ICTCA 2017 VIENNA

13th International Conference on Theoretical and Computational Acoustics

# Book of Abstracts

## 30 July - 3 August 2017

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Manfred Kaltenbacher
Florian Toth

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PART I

# Information

# Welcome to ICTCA2017

Dear Participant,

A warm welcome to Austria, to Vienna, and to the ICTCA2017, the 13th International Conference on Theoretical and Computational Acoustics, held at the Campus of TU Wien. We warmly welcome distinguished guest and speaker Dr. Allan D. Pierce, a distinguished member of the ICTCA.

With the total of 214 papers, 6 keynote lectures, 17 structured sessions, and 6 regular sessions the ICTCA2017 is a forum for active researchers from different areas of science related to acoustics, seismics, and wave propagation in general to discuss state-of-the-art developments and results in their work. The ICTCA2017 Program also includes two special sessions: one entitled *Past, Present, and Future of the ICTCA* dedicated to the memory of Dr. Ding Lee, founder of the ICTCA; the other entitled *Advances in Selected Topics in Acoustics, Applied Mechanics, and Mechatronics* dedicated to the memory of Dr. Franz Ziegler, Professor of the TU Wien.

The authors are encouraged to convert their presentations into manuscripts of full-length research papers and the Journal of Computational Acoustics (JCA) will be accepting such manuscripts for Special Issues on topics specified by the Guest Editors.

The ICTCA2017 will give an award of 450 € to each of the four best papers presented by graduate students. A Committee formed by Dr. Megan Ballard, Dr. Piotr Borejko, and Prof. Manfred Kaltenbacher will conduct evaluation and present the awards at the closing ceremony on Thursday afternoon.

We would like to thank the Office of Naval Research (ONR) and the Office of Naval Research Global (ONRG) for support and generous financial contributions of the past and present ICTCAs.

We would also like to thank all the other sponsors listed on the conference website for their support and financial contributions. We welcome our exhibitors; their participation in the ICTCA2017 is greatly appreciated. We also appreciate sponsoring of the ICTCA2017 by the societies: Acoustical Society of America (ASA), Canadian Acoustical Society (CAA), European Acoustics Association (EAA), Deutsche Gesellschaft für Akustik DEGA e.V., and Austrian Acoustics Association (AAA). We would also like to acknowledge the support of TU Wien.

The success of ICTCA2017 is due to efforts and hard work of the Special and

Structured Session Organizers and their invitees; we are most grateful to them. Finally, a warm thank you to all members of the Advisory, Technical, and Organizing Committees for their helpful suggestions and advices.

We wish you an interesting and fruitful ICTCA2017 and an enjoyable stay in Vienna.

Piotr Borejko
Co-Chairman

Manfred Kaltenbacher
Co-Chairman

# General Information

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# Plenary Speakers

**Ching-Sang Chiu** (Naval Postgraduate School, USA) will lecture about *Progresses in the Understanding of the Northeastern South China Sea Sound Field: Experimentations and Modeling*.

Ching-Sang Chiu is a Distinguished Professor Emeritus of the Oceanography Department at the Naval Postgraduate School in Monterey, California, USA, a Fellow of the Acoustical Society of America, and an Editor-in-Chief of the Journal of Computational Acoustics. He received a Doctor of Science degree in 1985 from the Massachusetts Institute of Technology and Woods Hole Oceanographic Institution joint program. Chiu's research specialities include ocean acoustics, acoustical oceanography, and coastal ocean processes. His research interests include measurement, analysis, modeling and prediction of sound propagation in spatially and temporally varying oceans, and ocean monitoring and process studies using underwater acoustical remote sensing techniques. He has authored and co-authored sixty refereed publications in those subject areas.

**Dan Givoli** (Technion—Israel Institute of Technology, Israel) will lecture about *Computational Time Reversal for Source and Scatterer Identification*.

Dan Givoli is a Professor at the Department of Aerospace Engineering, Technion—Israel Institute of Technology. He holds the Lawrence and Marie Feldman Chair in Engineering at the Technion is a fellow of the International Association for Computational Mechanics (IACM) as well as the former President and one of the three founders of the Israel Association for Computational Methods in Mechanics (IACMM), which is affiliated with ECOOMAS and with IACM. He is an associate Editor of two journals: Wave Motion and Journal of Computational Acoustics and a member of the Editorial Board of seven other journals, including Int. J. Numerical Methods in Engineering (IJNME) and Computer Methods in Applied Mechanics and Engineering (CMAME) and a member of the Solid and Structural Mechanics Committee (ECCSM) of ECCOMAS. He served as an elected member of the IACM General Council for 16 years.

Dan Givoli completed his PhD degree at Stanford University in 1988 and has won several Excellent Teaching awards at the Technion. He held Visiting Professor positions at four other universities: Tel Aviv U., RPI, NPS and TU Delft. During 2004–2005 he served as the Dean of the Dept. of Aerospace Engineering, Technion and since Jan. 2017 he has been serving as the Dean of the Graduate School of the Technion (for 3 years).

He published over 100 papers in scientific journals, including four highly-cited review papers, and many more papers in conference proceedings and edited books. Dan Givoli wrote the monograph “Numerical Methods for Problems in Infinite Domains” that was published by Elsevier in 1992 and soon after became out-of-print and has co-edited several books and Special Issues in scientific journals. He constantly writes ”popular science” articles on computational mechanics related topics, and is the permanent writer of the Book Review section in IACM Expressions. His field of interest are: developing computational methods in mechanics and aerospace engineering, especially in the area of wave propagation, and in particular computational methods for waves in solids and structures.

**Steffen Marburg** (Technical University of Munich, Germany) will lecture about *Contribution Analysis Using Non-Negative Intensity*.

Professor Steffen Marburg obtained his PhD from the Technische Universität (TU) Dresden in Germany. From 2010 until 2015, he held the Chair for Engineering Dynamics at the Universität der Bundeswehr (University of the Federal Armed Forces) in Munich, Germany. In July 2015, he took over the Gerhard Zeidler endowed Chair for Vibroacoustics of Vehicles and Machines of the Technical University of Munich. His research interests include simulation and simulation methods of vibroacoustics, uncertainty quantification, experimental identification of parameters and parameter distributions, damage detection and other problems of vibroacoustics. Steffen Marburg is one of the chairs of the EAA technical committee for Computational Acoustics and associate editor of Acta Acustica united with Acustica, editor for the Journal of Computational Acoustics (JCA) and Acoustics Australia. He is author of nearly 90 peer reviewed journal papers and 7 book chapters. Furthermore, he is editor of a book on finite and boundary element methods and has worked as a guest editor for six special issues of JCA. Professor Marburg is a well-known expert in computational acoustics.

**Martin Schanz** (Graz University of Technology, Austria) will lecture about *Variable Time Steps in Time Domain Boundary Elements*.

Martin Schanz is Professor of Mechanics at the Department of Civil Engineering at Graz University of Technology. He studied mechanical engineering at the University of Karlsruhe (Germany) and earned his Diploma degree in 1990. From 1990 he investigated in improving the BEM formulation for wave propagation problems. His doctoral thesis is about viscoelastic BEM formulations in time domain. He received his habilitation in Mechanics in 2001 with a thesis on a visco- and poroelastodynamic BEM formulation. He had research stays at the University of Delaware (USA), the University of Campinas (Brazil), the Hong Kong University of Science and Technology (China) and the University of Zurich (Switzerland). He has authored and co-authored more then 50 journal papers, four books, and several book chapters. His research interests cover visco- and poroelasticity and the acoustic behaviour of such materials. The main focus lies on the development of Boundary Element Methods with focus on wave propagation, which includes also fast methods like FMM and ACA. He is actually president of the International Association for Boundary Element Methods (IABEM) and associate editor of Applied Mechanics Reviews beside other services at Graz University of Technology.

**Yu-Chiung Teng** (Columbia University, USA) will lecture about *The Elasto-Dynamic Transient Problem for a Fluid/Solid Coupled Medium*.

Yu-Chiung Teng is a retired senior research scientist and Adjunct Professor of Columbia University. Her research has been in the field of elasto-dynamic wave propagation both analytically and numerically. She earned her doctoral degree from the Aldridge Laboratory of Applied Geophysics, Henry Krumb School of Mines, Columbia University, New York, N.Y. in 1971. Previously, she received her M.A. and B.S. in physics from the State University of New York (SUNY) at Buffalo, N.Y. and National Cheng Kung University, Taiwan, Republic of China, respectively. She was the executive chairperson for the 3rd International Conference on Theoretical and Computational Acoustics (ICTCA), Newark, New Jersey, USA July, 1997. She also co-chaired the 2nd ICTCA in Honolulu, Hawaii, USA, two years earlier in 1995; and subsequently, the 5th in Beijing, 2001; the 6th in Honolulu, Hawaii, 2003; the 7th in Hangzhou, China, 2005; and, most recently, the 11th in College Station, Texas, USA, 2014.

After graduation from Columbia University, she had worked at her alma mater and concentrated her research in the area of forward modeling in elastodynamics and poro-elastodynamics. While at Columbia before her retirement, she had been invited as the visiting scholar to Taiwan's Earthquake Research Center, Institute of Physics, Academia Sinica (1974–1975) and the Institute of Geology and Geophysics, the Chinese Academy of Science, Beijing, China (2000–2001). In addition, from 1987–1990, the Department of Technical Co-operation Development of the United Nations invited her as a consultant for seismological studies at varies academic institutions in China. Currently, she is the visiting professor of the following universities in China: Chang An University, Xian, Shanxi,China; Xian Jiaotong University, Xian, Shanxi,China; and ShanDong University of Science and Technology, Qingdau, Shandong, China.

**Sean F. Wu** (Wayne State University, USA) will lecture about *Interrelationships Among Force Excitation, Structural Vibration, and Sound Radiation*.

Sean F. Wu received his BSME from Zhejiang University (China); MSME and Ph.D. from Georgia Institute of Technology, USA. Dr. Wu joined the Department of Mechanical Engineering at Wayne State University (WSU) as an Assistant Professor for Research in 1988; became a tenure-track Assistant Professor in 1990;

Associate Professor in 1995, and a Professor in 1999. He was voted unanimously as the Charles DeVlieg Professor of Mechanical Engineering in 2002; and was appointed and re-appointed by the Board of Governors to the rank of University Distinguished Professor every year since 2005. Dr. Wu holds the rank of Fellow in the Acoustical Society of America (ASA) and the American Society of Mechanical Engineers (ASME), and is a member of the Society for Automotive Engineering (SAE). Currently, Dr. Wu serves as an Associate Editor for the Journal of the Acoustical Society of America (JASA), Express Letters Editor for JASA, Managing Editor and Co-Editor-in-Chief for the Journal of Computational Acoustics (JCA). Dr. Wu's areas of interest are acoustics, vibration, and noise control. He has over 60 refereed journal articles, 13 U.S. and International Patents, and is the author of the book, "The Helmholtz Equation Least Squares Method for Acoustic Radiation and Reconstruction," published by Springer (2015) in the Modern Acoustics and Signal Processing book series. Dr. Wu has mentored supervised more than 40 Ph.D. and MS students, who have won 24 the Best Student Papers Competitions at the professional conferences sponsored by the ASME, ASA, Institute of Noise Control Engineering International, and SAE. He was a co-founder of SenSound, LLC in 2003. In 2015, Dr. Wu founded Signal-Wise, LLC, a private company to provide disruptive technologies for tackling complex noise and vibration issues, and for conducting in-line and end-of-line product quality control tests.

# The conference is supported and sponsored by

# Practical Information

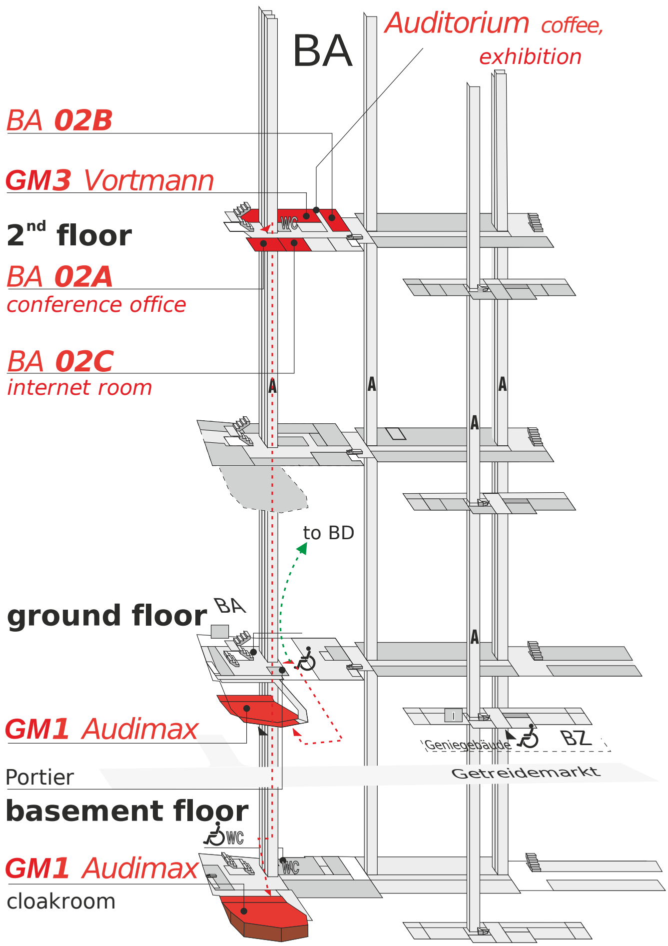
## Conference Venue: TU Wien

The Conference will be held at main campus of Faculty of Mechanical and Industrial Engineering, TU Wien (Getreidemarkt 9, 1060 Vienna). TU Wien (Vienna University of Technology) is located in the heart of Europe, in a cosmopolitan city of great cultural diversity. For more than 200 years, the TU Wien has been a place of research, teaching and learning in the service of progress. TU Wien is among the most successful technical universities in Europe and is Austria's largest scientific-technical research and educational institution.

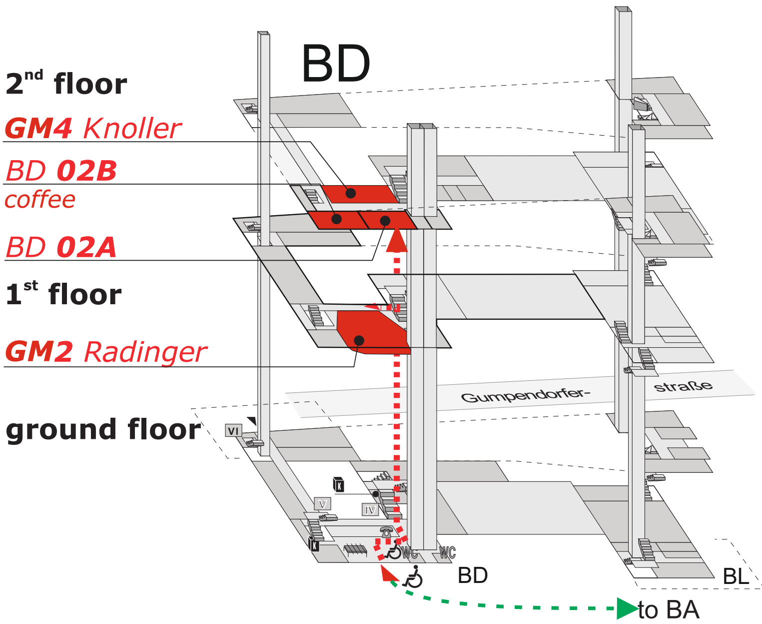
All sessions, coffee breaks and exhibitions will take place on campus in Getreidemarkt 9, 1060 Vienna in the following two locations:

- Building **BA**, with rooms
  - Seminar Room BA **02A**, 2nd floor: Conference office
  - Seminar Room BA **02B**, 2nd floor
  - Seminar Room BA **02C**, 2nd floor: Internet room
  - Auditorium of 2nd floor: Coffee, Exhibition
  - **GM1** Audimax, 1st basement floor (U1)
  - **GM3** Vortmann Lecture Hall, 2nd floor
- Building **BD**, with rooms
  - Seminar Room BD **02A**, 2nd floor
  - Seminar Room BD **02B**, 2nd floor: Coffee
  - Lecture hall **GM2** Radinger, 1st floor
  - Lecture hall **GM4** Knoller, 2nd floor


Surroundings of the conference venue




Rooms in building BA




Rooms in building BD

# Information for Presenters

All lecture rooms are equipped with projectors. A laptop computer and laser pointer will be provided by the conference organisation. Lecture rooms will be accessible 30 minutes prior to the start of the sessions. Our lecture room staff will be there to assist you. Please copy your presentation (PDF or PowerPoint) to the provided computer well before the session starts, and test if everything is working as expected.

# Coffee & Lunch

During the coffee breaks, there will be drinks, coffee and snacks provided on the second floor of building BA, and on the second floor of building BD, in seminar room BD **02B**.

For lunch, there are several restaurants in walking distance. The famous *Naschmarkt*, located between the streets *Rechte Wienzeile* and *Linke Wienzeile*, is a market with over 100 different market stalls and offers food from traditional Austrian to Japanese buffet. Furthermore Austria's biggest shopping street, the *Mariahilfer Straße* offers a large variety of restaurants and shops. Both places are just five minutes away.

# WiFi at the Venue

WiFi is available at the whole university. Conference participants with an *eduroam* account can use it on the campus. All participants without access to *eduroam* can use their personalised account to access the network *tunetguest*. The required login credentials (username and password) can be found in the conference bag.

# Cloakroom

Since we expect that many partocipants will have their baggage with them on Thursday, 3. August 2017, you find a cloakroom in Building BA, basement floor (opposite of **GM1** Audimax). Opening times are 08:00–09:30, 11:30–12:30 and 16:00–17:00 on Thursday. On all other days during the conference you have the possiblility to store baggage at the conference office (Building BA, 2$^{nd}$ floor, room BA **02A**).

# Social Events

## Welcome Reception

**Sunday, 30 July 2017, 17.00-20.00:** The welcome reception (icebreaker) will be held at the entrance of the BA building, the main conference building, located at Getreidemarkt 9, 1060 Vienna. At the welcome reception drinks and finger food will be served, you will meet old and new friends, and you will have the possibility to get your conference bag. The BA building is an “energy-plus” office tower; it is the first office tower in the world capable to feed more energy into the power grid than is required to operate it. During the welcome reception, you will have the possibility to join a guided tour to discover the technical features necessary to achieve the “energy-plus” level.

## Mayor’s Reception

**Monday, 31 July 2017, 19.00, City Hall:** On Monday evening, the Mayor’s Reception will be held at the Vienna City Hall (Rathaus), located in the center of Vienna. The City Hall is one of the most beautiful buildings in Vienna and serves as the seat of both the mayor and the city council of the city of Vienna. It was designed by Friedrich von Schmidt and built between 1872 and 1883. The distinctive Neo-Gothic style of the City Hall with its magnificent and fabulous halls provides a perfect setting for the conference’s reception. Please do not forget to bring along the invitation you have recieved with your conference bag.

## Natural History Museum and Conference Banquet

**Wednesday, 2 August 2017, 16.00-23.00:** On Wednesday afternoon, the sessions end at about 15:45. Therefore, we have planned afterwards for you a visit to the Natural History Museum Vienna. Please do not forget to bring along the entrance card, you have received with your conference bag.

The museum is home to world-famous and unique objects, such as the 29,500-year-old Venus of Willendorf, the Steller’s sea cow that became extinct over 200 years ago, and enormous dinosaur skeletons. Further highlights in the 39 exhibit halls include the world’s largest and oldest public collection of meteorites, including the spectacular Tissint meteorite from Mars, as well as the permanent anthropological exhibition on the origins and development of humans, and the new prehistoric exhibition with the Venus Cabinet and the Gold Cabinet. Furthermore, on the occasion of the museum’s 125th anniversary a new Digital Planetarium has been opened, featuring full dome projection technology that will give visitors the chance to embark on fascinating virtual journeys in stunning scientific detail to the edge of the Milky Way galaxy or Saturn's rings.

**Starting at 18:00** you will have the possibility to take a guided walk up to the rooftop terrace with fantastic views of Vienna—guaranteed an unforgettable experience. In time intervals of 15 minutes a new group of about 15 people will start for the guided tour and have the possibility to enjoy a cocktail on the rooftop.

**The banquet will start at 20:00** and take placa on the second floor of the upper dome hall, the heart of the Natural History Museum. The famous architects Gottfried Semper and Carl von Hasenauer envisaged a "cathedral of the sciences" here. Their ambition is realized in this space: the extraordinary décor of the main dome translates a love of art and nature in equal measure, and the elegance of this place breathes the spirit of the time. Please do not forget to bring along your banquet ticket.

# Scientific Program

## Overview

### Monday

**09:30–10:15** Plenary Lecture

**Sean F. Wu** (Wayne State University, USA) *Interrelationships among force excitation, structural vibration, and sound radiation* in **GM1** Audimax, Building BA

**10:45–12:45** Morning Sessions

**Acoustic and Elastic Metamaterials** in **GM1** Audimax, Building BA

**Advances in Modeling of Wave Propagation in Time Domain and Applications** in Lecture Hall **GM2** Radinger, Building BD

**Aeroacoustics** in **GM3** Vortmann Lecture Hall, Building BA

**Attenuation and Dissipation of Vibrational and Acoustical Energy** in Lecture Hall **GM4** Knoller, Building BD

**Shallow-Water Acoustics** in Seminar Room BD **02A**, Building BD

**Acoustical Propagation through Internal Waves in an Ocean with an Irregular Bottom** in Seminar Room BA **02B**, Building BA

**14:15–15:00** Plenary Lecture

**Steffen Marburg** (Technical University of Munich, Germany) *Surface Contribution Analysis Using Non-Negative Intensity* in **GM1** Audimax, Building BA

**15:30–17:30** Afternoon Sessions

**Acoustic and Elastic Metamaterials** in **GM1** Audimax, Building BA

**Advances in Modeling of Wave Propagation in Time Domain and Applications** in Lecture Hall **GM2** Radinger, Building BD

**Aeroacoustics** in **GM3** Vortmann Lecture Hall, Building BA

**Attenuation and Dissipation of Vibrational and Acoustical Energy** in Lecture Hall **GM4** Knoller, Building BD

**Shallow-Water Acoustics** in Seminar Room BD **02A**, Building BD

**Panel Contribution Analysis** in Seminar Room BA **02B**, Building BA

## Tuesday

**09:00–09:45** Plenary Lecture

**Yu-Chiung Teng** (Columbia University, USA) *The Elasto-Dynamic Transient Problem for a Fluid/Solid Coupled Medium* in **GM1** Audimax, Building BA

**10:15–12:15** Morning Sessions

**Acoustic and Elastic Metamaterials** in **GM1** Audimax, Building BA

**Seismic Attenuation and Seismic Data Processing** in Lecture Hall **GM2** Radinger, Building BD

**Advances in Selected Topics in Acoustics, Applied Mechanics, and Mechatronics** in **GM3** Vortmann Lecture Hall, Building BA

**Ocean Acoustic and Geoacoustic Inversion** in Seminar Room BD **02A**, Building BD

**Seismo-Acoustics, Electromagnetics, and Multiphysics Coupling** in Lecture Hall **GM4** Knoller, Building BD

**Model Order Reduction and Numerical Acoustics** in Seminar Room BA **02B**, Building BA

**13:45–14:30** Plenary Lecture

**Martin Schanz** (Graz University of Technology, Austria) *Variable Time Steps in Time Domain Boundary Elements* in **GM1** Audimax, Building BA

**15:00–17:00** Afternoon Sessions

**Acoustic and Elastic Metamaterials** in **GM1** Audimax, Building BA

**Seismic Attenuation and Seismic Data Processing** in Lecture Hall **GM2** Radinger, Building BD

**Advances in Selected Topics in Acoustics, Applied Mechanics, and Mechatronics** in **GM3** Vortmann Lecture Hall, Building BA

**Seismo-Acoustics, Electromagnetics, and Multiphysics Coupling** in Lecture Hall **GM4** Knoller, Building BD

**Ocean Acoustic and Geoacoustic Inversion** in Seminar Room BD **02A**, Building BD

## Wednesday

**09:00–09:45** Plenary Lecture

**Ching-Sang Chiu** (Naval Postgraduate School, USA) *Progresses in the Understanding of the Northeastern South China Sea Sound Field: Experimentations and Modeling* in **GM1** Audimax, Building BA

**10:15–12:15** Morning Sessions

**Acoustic and Elastic Metamaterials** in **GM1** Audimax, Building BA

**Seismic Attenuation and Seismic Data Processing** in Lecture Hall **GM2** Radinger, Building BD

**Modern Mathematical Methods for Signal Processing in Audio and Acoustics** in **GM3** Vortmann Lecture Hall, Building BA

**Acoustical Modeling for Applications Related to the Comprehensive Nuclear-Test-Ban Treaty International Monitoring System** in Lecture Hall **GM4** Knoller, Building BD

**Vibration Mitigation and Sound Absorbers** in Seminar Room BD **02A**, Building BD

**Inverse Problems in Acoustics** in Seminar Room BA **02B**, Building BA

**13:45–15:45** Afternoon Sessions

**Acoustic and Elastic Metamaterials** in **GM1** Audimax, Building BA

**Seismic Attenuation and Seismic Data Processing** in Lecture Hall **GM2** Radinger, Building BD

**Modern Mathematical Methods for Signal Processing in Audio and Acoustics** in **GM3** Vortmann Lecture Hall, Building BA

**Acoustical Modeling for Applications Related to the Comprehensive Nuclear-Test-Ban Treaty International Monitoring System** in Lecture Hall **GM4** Knoller, Building BD

**Modeling and Numerical Simulation of Waves in Moving and Inhomogeneous Media** in Seminar Room BD **02A**, Building BD

**Sound, Vibration, and Excitation** in Seminar Room BA **02B**, Building BA

## Thursday

**09:00–09:45** Plenary Lecture

**Dan Givoli** (Technion—Israel Institute of Technology, Israel) *Computational Time Reversal for Source and Scatterer Identification* in **GM1** Audimax, Building BA

**10:15–12:15** Morning Sessions

**Acoustic and Elastic Metamaterials** in **GM1** Audimax, Building BA

**Physical Acoustics** in Lecture Hall **GM2** Radinger, Building BD

**Acoustical Boundary Elements and Related Topics** in **GM3** Vortmann Lecture Hall, Building BA

**Acoustical Propagation in an Ice-Covered Environment** in Lecture Hall **GM4** Knoller, Building BD

**Numerical Simulation Methods for Ultrasonic Applications** in Seminar Room BD **02A**, Building BD

**Musical Instruments and Loudspeaker Modelling** in Seminar Room BA **02B**, Building BA

**13:30–15:30** Afternoon Sessions

**Past, Present, and Future of the ICTCA** in **GM1** Audimax, Building BA

**Physical Acoustics** in Lecture Hall **GM2** Radinger, Building BD

**Acoustical Boundary Elements and Related Topics** in **GM3** Vortmann Lecture Hall, Building BA

**Acoustical Propagation in an Ice-Covered Environment** in Lecture Hall **GM4** Knoller, Building BD

**Guided Wave Propagation** in Seminar Room BD **02A**, Building BD

# Plenary Lectures and Sessions

## Plenary Lectures

**Interrelationships among force excitation, structural vibration, and sound radiation** by **Sean F. Wu** (Wayne State University, USA) on Monday, 09:30–10:15, in **GM1** Audimax, Building BA.

**Surface Contribution Analysis Using Non-Negative Intensity** by **Steffen Marburg** (Technical University of Munich, Germany) on Monday, 14:15–15:00, in **GM1** Audimax, Building BA.

**The Elasto-Dynamic Transient Problem for a Fluid/Solid Coupled Medium** by **Yu-Chiung Teng** (Columbia University, USA) on Tuesday, 09:00–09:45, in **GM1** Audimax, Building BA.

**Variable Time Steps in Time Domain Boundary Elements** by **Martin Schanz** (Graz University of Technology, Austria) on Tuesday, 13:45–14:30, in **GM1** Audimax, Building BA.

**Progresses in the Understanding of the Northeastern South China Sea Sound Field: Experimentations and Modeling** by **Ching-Sang Chiu** (Naval Postgraduate School, USA) on Wednesday, 09:00–09:45, in **GM1** Audimax, Building BA.

**Computational Time Reversal for Source and Scatterer Identification** by **Dan Givoli** (Technion—Israel Institute of Technology, Israel) on Thursday, 09:00–09:45, in **GM1** Audimax, Building BA.

## Special Sessions

**Advances in Selected Topics in Acoustics, Applied Mechanics, and Mechatronics**
Organised by Piotr Borejko, Rudolf Heuer and Franz Rammerstorfer.
The session contains 10 talks at Tuesday, 10:15; Tuesday, 15:00 in **GM3** Vortmann Lecture Hall, Building BA.

Special session dedicated to the memory of Dr. Franz Ziegler, Professor of the TU Wien.

**Past, Present, and Future of the ICTCA**
Organised by Chifang Chen.
The session contains 3 talks at Thursday, 13:30 in **GM1** Audimax, Building BA.

Special session dedicated to the memory of Dr. Ding Lee, founder of the ICTCA.

## Structured Sessions

**Acoustic and Elastic Metamaterials**
Organised by Andrew Norris.
The session contains 32 talks at Monday, 10:45; Monday, 15:30; Tuesday, 10:15; Tuesday, 15:00; Wednesday, 10:15; Wednesday, 13:45; Thursday, 10:15 in **GM1** Audimax, Building BA.

**Acoustical Boundary Elements and Related Topics**
Organised by Martin Ochmann and Rafael Piscoya.
The session contains 9 talks at Thursday, 10:15; Thursday, 13:30 in **GM3** Vortmann Lecture Hall, Building BA.

This session will focus on new developments and practical applications in acoustic boundary elements including but not limited to sound radiation and scattering, modelling of sources, halfspace problems, special Green's functions, etc. Exterior, interior, and inverse acoustical problems may be considered. Related methods like the local BEM, the dual reciprocity BEM, the viscous BEM and others which extend the applicability of the traditional boundary elements to new problems arising, e.g., in flow acoustics, metamaterials or ultrasonics as well as improvements in numerical techniques e.g. fast multipole methods are encouraged. Also welcomed are papers combining boundary elements with other approaches like statistical or energy methods.

**Acoustical Modeling for Applications Related to the Comprehensive Nuclear-Test-Ban Treaty International Monitoring System**
Organised by Mario Zampolli, Georgios Haralabus and Peter Nielsen.
The session contains 7 talks at Wednesday, 10:15; Wednesday, 13:45 in Lecture Hall **GM4** Knoller, Building BD.

The International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) monitors the world for signs of nuclear explosions under water, in the earth, and in the atmosphere. It encompasses three waveform technologies, namely, (i) hydroacoustics, (ii) seismic, and (iii) infrasound. Radionuclide technology for the detection of radioisotopes associated with nuclear explosions is the fourth pillar of the IMS. The 85% of the waveform stations are already installed, certified, and providing real-time data to Vienna. Once completed, the IMS will consist of 337 monitoring stations distributed around the globe. Archived data is available to the scientific community on a zero-cost basis for studies pertaining to the Treaty, and also for topics of broader scientific or public interest. The purpose of this session is to present advances in acoustical modeling techniques relevant to the primary mission of the IMS and to the numerous scientific applications of IMS data.

**Acoustical Propagation in an Ice-Covered Environment**
Organised by Marcia Isakson and Megan Ballard.
The session contains 9 talks at Thursday, 10:15; Thursday, 13:30 in Lecture Hall **GM4** Knoller, Building BD.

**Acoustical Propagation through Internal Waves in an Ocean with an Irregular Bottom**
Organised by Ching-Sang Chiu.
The session contains 5 talks at Monday, 10:45 in Seminar Room BA **02B**, Building BA.

Recent discoveries of large-amplitude ocean internal waves, sand dunes and sand waves on the continental slope and shelf in some marginal seas and estuaries have generated substantial scientific interest in the international ocean acoustics communities to study the effects of these ocean structures on underwater acoustic propagation. The intent of this proposed special session is to provide a scientific forum for acousticians to present and review the up-to-date research results and findings from recent experimental, modeling and data-model-comparison efforts pertaining to this topic, as well as underscoring the outstanding research issues.

**Advances in Modeling of Wave Propagation in Time Domain and Applications**
Organised by Geza Seriani and Saulo P. Oliveira.
The session contains 11 talks at Monday, 10:45; Monday, 15:30 in Lecture Hall **GM2** Radinger, Building BD.

**Aeroacoustics**
Organised by Stefan Becker.
The session contains 9 talks at Monday, 10:45; Monday, 15:30 in **GM3** Vortmann Lecture Hall, Building BA.

The session ”Aeroacoustics” will present a view of new developments in the CAA-simulation techniques. The challenge is the strong connection between fluid and acoustic simulation on different scales. The session covers new complementary methods, basics of hybrid algorithm and monolithic solutions in the simulation tools but also applications for simplified geometries and rotating systems. Additional a special issue is the connection to combustion and thermoacoustic problems.

**Attenuation and Dissipation of Vibrational and Acoustical Energy**
Organised by Allan D. Pierce and Adnan Akay.
The session contains 8 talks at Monday, 10:45; Monday, 15:30 in Lecture Hall **GM4** Knoller, Building BD.

Session will focus on the research frontiers regarding the theoretical and computational modeling of energy dissipation associated with vibrations and wave propagation. Scope will include all types of media, with possible emphasis on mems- and nano-structures, and also metamaterials.

**Modeling and Numerical Simulation of Waves in Moving and Inhomogeneous Media**
Organised by Manfred Kaltenbacher and Drasko Masovic.
The session contains 7 talks at Wednesday, 13:45 in Seminar Room BD **02A**, Building BD.

The focus of the session are modeling and numerical simulation of all sound propagation phenomena which take place in moving and/or inhomogeneous media, both fluid and solid. Topics include high-frequency (ray acoustics) and low- to mid-frequency solutions of sound propagation problems involving mean flow and/or temperature gradient, convection, refraction, diffraction/scattering from foreign objects, visco-thermal effects and dissipation, non-linear propagation, dispersion, interface and boundary conditions in inhomogeneous media, and acoustic feedback.

**Modern Mathematical Methods for Signal Processing in Audio and Acoustics**
Organised by Georg Tauböck and Peter Balazs.
The session contains 8 talks at Wednesday, 10:15; Wednesday, 13:45 in **GM3** Vortmann Lecture Hall, Building BA.

The aim of this session is to present modern mathematical methods for signal processing and their applications to problems in audio and acoustics. In particular, the talks will focus on recent advancements in frame theory, time-frequency analysis, compressive sensing and sparsity, harmonic analysis, etc. illustrating the benefits of the tools developed in these research areas for acoustic applications. The session will include both overview/introductory talks as well as presentations concerning more specific (application) scenarios.

**Numerical Simulation Methods for Ultrasonic Applications**
Organised by Jens Prager and Fabian Krome.
The session contains 6 talks at Thursday, 10:15 in Seminar Room BD **02A**, Building BD.

The focus of this session is on methods for modeling and numerical simulation of ultrasonic wave propagation. These methods are mainly used for designing ultrasonic non-destructive testing methods and ultrasonic measurement technologies. For these applications, adapted approaches are required to handle the unfavorable ratio of wavelength caused by high frequencies and geometrical dimension as well as to minimize the computational cost. Different methods using semi-analytical approaches or Finite Elements will be presented.

**Ocean Acoustic and Geoacoustic Inversion**
Organised by Stan Dosso.
The session contains 7 talks at Tuesday, 10:15; Tuesday, 15:00 in Seminar Room BD **02A**, Building BD.

Because electromagnetic radiation is strongly attenuated in seawater while sound propagates to long ranges, acoustics plays a vital role in sensing and operating within the ocean environment. Estimating physical properties of the environment (seabed and/or water column), localizing sound sources (natural or anthropogenic), and high-precision surveying/positioning are common applications in ocean acoustics that require solving an inverse problem. Such problems are inherently nonlinear and non-unique, and estimating parameter values and uncertainties can be challenging. This session is intended to bring together a wide range of work in ocean acoustic and geoacoustic inversion, including theoretical and computational developments, as well as experiments, surveys and practical applications.

**Panel Contribution Analysis**
Organised by Steffen Marburg.
The session contains 4 talks at Monday, 15:30 in Seminar Room BA **02B**, Building BA.

The session on panel contribution analysis will be focused on the question of which source regions of the computational domain or/and the boundary are most relevant for a certain objective function such as sound pressure at certain points, the radiated or scattered sound power into certain directions etc. The contributions to this session are all related to computational applications. Most of them discuss special software solutions whereas one is related to a quantity which is known as non-negative intensity.

**Seismic Attenuation and Seismic Data Processing**
Organised by Jinghuai Gao and Yu-Chiung Teng.
The session contains 20 talks at Tuesday, 10:15; Tuesday, 15:00; Wednesday, 10:15; Wednesday, 13:45 in Lecture Hall **GM2** Radinger, Building BD.

Seismic attenuation, quantified by the quality factor Q, has a considerable impact on seismic reflection data. Attenuation is usually considered to be associated with properties such as lithological information, porosity, permeability, viscosity, and the degree of saturation of rocks; and it can thus act as a useful tool for reservoir characterization. Therefore, reliable methods for Q estimation are needed to be developed. The recent achievements of seismic applications in applied geophysics of Xian Jiaotong University and Chang An University, both in XiAn China, will be presented in this session.

**Seismo-Acoustics, Electromagnetics, and Multiphysics Coupling**
Organised by Yuefeng Sun and Qing Huo Liu.
The session contains 7 talks at Tuesday, 10:15; Tuesday, 15:00 in Lecture Hall **GM4** Knoller, Building BD.

**Shallow-Water Acoustics**
Organised by Er-Chang Shang and Juan Zeng.
The session contains 12 talks at Monday, 10:45; Monday, 15:30 in Seminar Room BD **02A**, Building BD.

**Sound, Vibration, and Excitation**
Organised by Pan Zhou.
The session contains 3 talks at Wednesday, 13:45 in Seminar Room BA **02B**, Building BA.

This session is focused on the interrelationships among sound radiation, structural vibration, and their excitations. The intent is to help practitioners to better understand the characteristics of these very different, but closely related phenomena. Such an understanding will help engineers to come up with better ways to reveal the root causes to vibro-acoustic problems encountered in engineering practice, and to tackle these problems in the most cost-effective manner.

## Regular Sessions

**Guided Wave Propagation**
The session contains 5 talks at Thursday, 13:30 in Seminar Room BD **02A**, Building BD.

**Inverse Problems in Acoustics**
The session contains 5 talks at Wednesday, 10:15 in Seminar Room BA **02B**, Building BA.

**Model Order Reduction and Numerical Acoustics**
The session contains 6 talks at Tuesday, 10:15 in Seminar Room BA **02B**, Building BA.

**Musical Instruments and Loudspeaker Modelling**
The session contains 3 talks at Thursday, 10:15 in Seminar Room BA **02B**, Building BA.

**Physical Acoustics**
The session contains 11 talks at Thursday, 10:15; Thursday, 13:30 in Lecture Hall **GM2** Radinger, Building BD.

**Vibration Mitigation and Sound Absorbers**
The session contains 7 talks at Wednesday, 10:15 in Seminar Room BD **02A**, Building BD.

# Monday

## **09:00–09:30** Opening

**GM1** Audimax, Building BA

## **09:30–10:15** Plenary Lecture

**GM1** Audimax, Building BA Chaired by P. Borejko

**Sean F. Wu** (Wayne State University, USA) *Interrelationships among force excitation, structural vibration, and sound radiation*

## **10:15–10:45** Coffee Break

Building BA, 2nd floor and building BD, 2nd floor

## Shallow-Water Acoustics

Seminar Room BD **02A**, Building BD Chaired by E. Shang and J. Zeng

**10:45** *Sound intensity fluctuations in the presence of moving nonlinear internal waves in shallow water* (invited)
**Boris Katsnelson**, Yanyu Jiang

**11:05** *Monitoring Internal Wave with Broadband Interference Pattern of Normal Mode Amplitude* (invited)
**Shengchun Piao**, Shizhao Zhang, Jiaqi Liu, Xiaoman Li

**11:25** *Maximum Entropy Method for Reconstruction of Ocean Current Field* (invited)
Shuai Shentu, **Hangfang Zhao**

**11:45** *Tomographic Inverting for Intrinsic Attenuation of Sea-bed Sediment*
**Z. D. Zhao**, J. Zeng, L. Ma, E. C. Shang

**12:05** *Sequential processing of multiple explosive sources for bottom characterization in shallow waters*
**Qunyan Ren**, Licheng Lu, Li Ma, Tianjun Liao

**12:25** *The Frequency Dependence of the Effective Seabed Sound Speed Inverted from 2016 Yellow Sea Experimental data*
**Juan Zeng**, D. Y. Peng, W. Y. Zhao, H. J. Liu

## Attenuation and Dissipation of Vibrational and Acoustical Energy

Lecture Hall **GM4** Knoller, Building BD Chaired by A. D. Pierce

**10:45** *A Prototypical Example for Damping and Dissipation* (invited)
**Adnan Akay**

**11:15** *Nonlinear damping in piezoelectric vibrational energy harvesters excited by Brownian and Lévy stable stochastic processes* (invited)
**Subramanian Ramakrishnan**

**11:45** *Numerical Analysis of a Piezoelectrically Modulated Oscillator Array* (invited)
**Joseph Vignola**, John Sterling, Aldo Glean, Teresa Ryan, John Judge, Diego Turo

**12:15** *Behavior of Sound Waves at the Vapor-liquid Interface Accompanied with Evaporation and Condensation* (invited)
**Shigeto Nakamura**, Takeru Yano

## Acoustical Propagation through Internal Waves in an Ocean with an Irregular Bottom

Seminar Room BA **02B**, Building BA — Chaired by C.-S. Chiu

**10:45** *Observations of Shoaling Internal Solitary Waves and their Properties in the Sand-wave Area on Upper Continental Slope of Northern South China Sea* (invited)
**Yiing Jang Yang**, Steven R. Ramp, Ching-Sang Chiu, D. Benjamin Reeder, Chen-Hao Hsueh

**11:15** *Sound propagation of the continental slope and sand dunes in the north-eastern South China Sea* (invited)
Andrea Y. Y. Chang, Linus Y. S. Chiu, **Chi-Fang Chen**, Ching-Sang Chiu

**11:45** *Measurement of Transmission Loss Using an Inexpensive Mobile Source on the Upper Slope of the South China Sea* (invited)
**Christopher W. Miller**, Ching-Sang Chiu, Chi-Fang Chen, Linus Y. S. Chiu, Ying-Jang Yang

**12:15** *Acoustic field horizontal variability and direction of arrival estimation in a canyon with internal tides* (invited)
**Timothy F. Duda**, Bruce D. Cornuelle, Ying-Tsong Lin

**12:45** *Three-Dimensional Sound Propagation and Scattering in an Oceanic Wave-guide with Surface and Internal Gravity Waves over Range-Dependent Seafloor* (invited)
**Ying-Tsong Lin**, James F. Lynch

## Advances in Modeling of Wave Propagation in Time Domain and Applications

Lecture Hall **GM2** Radinger, Building BDChaired by G. Seriani and S. P. Oliveria

**10:45** *Salvus: An Open-Source Package for Time-Domain Waveform Modeling and Inversion Across the Scales* (invited)
**Christian Boehm**, Michael Afanasiev, Martin van Driel, Lion Krischer, Dave A. May, Max Rietmann, Andreas Fichtner

**11:05** *Error Analysis of Non-Conforming FE Methods for Wave-Type Problems and its Application to Heterogeneous Multiscale Methods* (invited)
David Hipp, Marlis Hochbruck, **Christian Stohrer**

**11:25** *Error Analysis of Spectral Element Methods for the Acoustic Wave Equation in Heterogeneous Media*
**Saulo P. Oliveira**, Stela A. Leite

**11:45** *Mixed-Dimensional Modeling of Time-Dependent Wave Problems Using the Nitsche Method* (invited)
**Hanan Amar**, Dan Givoli

**12:05** *A modal-based partition of unity finite element method for layered wave propagation problems* (invited)
P. Destuynder, L. Hervella-Nieto, P. M. López-Pérez, J. Orellana, **Andres Prieto**

**12:25** *A high-order discontinuous Galerkin method for 1D-3C wave propagation in nonlinear heterogeneous media* (invited)
**Simon Chabot**, N. Glinsky, ED. Mercerat, LF. Bonilla-Hidalgo

## Acoustic and Elastic Metamaterials

**GM1** Audimax, Building BA Chaired by J.-P. Groby

**10:45** *Rainbow-trapping absorbers for transmission problems: Broadband and perfect sound absorbing panels* (invited)
Noé Jimenez, Vicente Roméro-Garcìa, Vincent Pagneux, **Jean-Philippe Groby**

**11:15** *Decorated Membrane Resonators* (invited)
**Z. Yang**, Kayan Auyeung, Suet To Tang, L. Sun, Ying Li, Yibin Li

**11:45** *Controlling and absorbing mechanical waves*
**Muamer Kadic**

**12:05** *Low frequency and nonlinear acoustical behaviour of plates with perforations bearing periodically spaced flat resonators*
**Philippe Leclaire**, Olga Umnova, Thomas Dupont, Raymond Panneton

**12:25** *Multi-dimensional Low-frequency Suspension via synthesizing high-static-low-dynamic stiffness isolator and pendulum system*
**Guangxu Dong**, Xinong Zhang, Yajun Luo, Yahong Zhang, Shilin Xie

## Aeroacoustics

**GM3** Vortmann Lecture Hall, Building BA — Chaired by S. Becker

**10:45** *Simulation of Sound Radiation based on PIV Measurements* (invited)
Alexander Lodermeyer, Matthias Tautz, Emen Bagheri, Manfred Kaltenbacher, Michael Döllinger, Stefan Kniesburges, **Stefan Becker**

**11:05** *On The Computaional Performance Of The Hybrid Aeroacoustic Solver Applied To Confined Flows* (invited)
**Vyacheslav Korchagin**, Wim De Roeck, Wim Desmet

**11:25** *Helmholtz-Hodge decomposition of compressible flow data on homologically trivial domains* (invited)
**Stefan Schoder**, Manfred Kaltenbacher

**11:45** *Acoustic response of a flat plate due to a turbulent boundary layer excitation*
**Mahmoud Karimi**, Paul Croaker, Alex Skvortsov, Nicole Kessissoglou

**12:05** *Noise Sources from Flow over a Forward-Facing Step* (invited)
Alexander Kolb, **Michael Gruenewald**

**12:25** *Direct aeroacoustic simulation of whistling noise at a side mirror using a high order discontinuous Galerkin method* (invited)
Hannes Frank, **Claus-Dieter Munz**

## **14:15–15:00** Plenary Lecture

**GM1** Audimax, Building BA — Chaired by M. Kaltenbacher

**Steffen Marburg** (Technical University of Munich, Germany) *Surface Contribution Analysis Using Non-Negative Intensity*

## **15:00–15:30** Coffee Break

Building BA, 2$^{nd}$ floor and building BD, 2$^{nd}$ floor

## Shallow-Water Acoustics

Seminar Room BD **02A**, Building BD — Chaired by J. Zeng and E. Shang

**15:30** *Analytical and numerical solution for whispering gallery waves near curved isobaths in shallow water*
**Boris Katsnelson**, Pavel Petrov

**15:50** *Characteristic acoustic impedance for more reliable environmental characterization*
**Qunyan Ren**, Licheng Lu, Li Ma, Shengming GUO, Tianjun LIAO

**16:50** *Spatial Variability of Ocean Ambient Noise Spectrum in China Offshore*
**Xin Yi Guo**, Guoli Song, Li Ma

**17:10** *Reverberation intensity decaying in range-dependent waveguide*
**Jin Rong Wu**, T. F. Gao, E. C. Shang

## Acoustic and Elastic Metamaterials

**GM1** Audimax, Building BA Chaired by C. Rubio

**15:30** *An open acoustic barrier. Design and characterization* (invited)
**Constanza Rubio**, Sergio Castiñeira-Ibáñez, Pilar Candelas, Francisco Belmar, Antonio Uris

**16:00** *On the use of the dynamic mass of metamaterials to calculate the transmission loss based on the acoustic mass law* (invited)
**N. G. R. de Melo Filho**, Lucas Van Belle, Claus Claeys, Elke Deckers, Wim Desmet

**16:30** *Manipulation of Acoustic Waves using Deformationdriven Tunable Auxetic Metamaterials*
**Hsin-Haou Huang**

**16:50** *Soft matter based hypersonic phononic hybridization gaps*
**George Fytas**

**17:10** *Soft active material based acoustic filter*
**Kun Jia**, Mian Wang, Xueya Liang

## Advances in Modeling of Wave Propagation in Time Domain and Applications

Lecture Hall **GM2** Radinger, Building BDChaired by S. P. Oliveira and G. Seriani

**15:30** *Stable Perfectly Matched Layers for a Class of Metamaterials* (invited)
Eliane Bécache, **Maryna Kachanovska**

**15:50** *FEM solution of exterior problems with weakly enforced integral non reflecting boundary conditions* (invited)
**Silvia Falletta**

**16:10** *Analysis of the cumulant lattice Boltzmann method for acoustics problems* (invited)
Ehsan Kian Far, **Sabine Langer**

**16:30** *A Gaussian wave packets approach for transient ultrasonic NDE modeling*
**Olivier Jacquet**, Nicolas Leymarie, Didier Cassereau

**16:50** *Modeling Longitudinal Wave Propagation in Solids with Slow Dynamics: Application to DAE Experiments*
**Harold Berjamin**, Bruno Lombard, Guillaume Chiavassa, Nicolas Favrie

## Aeroacoustics

**GM3** Vortmann Lecture Hall, Building BA Chaired by S. Becker

**15:30** *Finite Element Simulations of Flow Induced Sound from Blowers* (invited)
**J. Grabinger**, M. Kaltenbacher, A. Hüppe, A. Reppenhagen, M. Springer, S. Becker

**15:50** *Aeroacoustic Simulation of Complex HVAC Components* (invited)
**Matthias Tautz**, Andreas Hüppe, Kerstin Besserer, Manfred Kaltenbacher, Stefan Becker

**16:10** *Determination of Acoustic Scattering Matrices from Linearized Compressible Flow Equations*
**Max Meindl**, Malte Merk, Fabian Fritz, Wolfgang Polifke

## Attenuation and Dissipation of Vibrational and Acoustical Energy

Lecture Hall **GM4** Knoller, Building BD Chaired by A. Akay

**15:30** *Band Gap and Dispersion Characteristics of Structures with Viscoelastically Damped Resonant Periodic Inserts* (invited)
Hajid Alsupie, Sadok Sassi, **Amr Baz**

**16:00** *Radiative Decay and Relaxation Processes in Vibrational and Acoustical Energy Dissipation* (invited)
**Allan D. Pierce**

**16:30** *Nonlinear dissipation in the classical dynamics of a nanomechanical resonator coupled to a single electron transistor* (invited)
**Subramanian Ramakrishnan**

**17:00** *Seismic Modulus Response of Asphalt Pavement in Accelerated Loading Tests with Rayleigh Wave* (invited)
**J. T. Wu**, F. Ye, J. X. Li

## Panel Contribution Analysis

Seminar Room BA **02B**, Building BA Chaired by S. Marburg

**15:50** *Panel Contribution Analysis based on FEM and Numerical Green's Function Approaches* (invited)
Mads J. Herring Jensen, **Kirill Shaposhnikov**

**16:10** *Panel Contribution Analysis, One of the Tools to Diagnose the Energy Transfer* (invited)
**Arnaud Caillet**, Lassen Mebarek, Joe Venor, Marc Dutilly, Bryce Gardner

**16:30** *Non-Negative Intensity for Structures with Inhomogeneous Damping* (invited)
**Daipei Liu**, Steffen Marburg, Nicole Kessissoglou

# Tuesday

## **09:00–09:45** Plenary Lecture

**GM1** Audimax, Building BA — Chaired by P. Borejko

**Yu-Chiung Teng** (Columbia University, USA) *The Elasto-Dynamic Transient Problem for a Fluid/Solid Coupled Medium*

## **09:45–10:15** Coffee Break

Building BA, 2nd floor and building BD, 2nd floor

### Acoustic and Elastic Metamaterials

**GM1** Audimax, Building BA — Chaired by A. Krokhin

**10:15** *Nonreciprocal transmission of sound through a 2D phononic crystal with viscous background and broken P-symmetry of the unit cell* (invited)
**Arkadii Krokhin**, Arup Neogi, Ezekiel Walker, Jesús Arriaga

**10:45** *Topological wave transport in acoustic systems*
**Romain Fleury**

### Seismic Attenuation and Seismic Data Processing

Lecture Hall **GM2** Radinger, Building BD — Chaired by Y.-C. Teng and H. Zhao

**10:15** *Variable-order Besov Bayesian theory for full waveform inversion of seismic data* (invited)
Jigen Peng, **Junxiong Jia**

**10:45** *Analysis of the Viscoelastic Wave Propagation via the Adomian Decomposition Method* (invited)
**Xinhua Zhang**

**11:15** *Q Correction Based on Seismic Structure Constrained Molecular Decomposition*
**Lingling Wang**, Jinghuai Gao, Bing Zhang

**11:35** *Q Estimation using an improved frequency shift method*
**Qian Wang**, Jinghuai Gao

**11:55** *Modeling Attenuation of Diffusive-viscous Wave Using Reflectivity Method*
**Haixia Zhao**, Jinghuai Gao, Jigen Peng, Xiaokai Wang

### Advances in Selected Topics in Acoustics, Applied Mechanics, and Mechatronics

**GM3** Vortmann Lecture Hall, Building BA — Chaired by R. Heuer and C. Adam

**10:15** *Franz Ziegler - Renowned Teacher and Scholar* (invited)
**Rudolf Heuer**

**10:30** *An efficient model-reduction technique for computing the thermo-mechanical behaviour of the strand in a continuous casting machine.* (invited)
G. Simon, H. J. Holl, P. Wieser, A. Schiefermüller, **Hans Irschik**

**11:20** *Crack Detection in Beam Structures by Modal Identification* (invited)
Markus J. Hochrainer, Markus Hauser, Florian Tschürtz, **Peter A. Fotiu**

**11:45** *Reliability Analysis of Ballasted Steel Bridges Crossed by High-Speed Trains* (invited)
**Christoph Adam**, Patrick Salcher, Benjamin Hirzinger

## Ocean Acoustic and Geoacoustic Inversion

Seminar Room BD **02A**, Building BD — Chaired by S. Dosso

**10:15** *Shallow Water Geoacoustic Inversion: a Sequential Filtering Approach* (invited)
**Zoi-Heleni Michalopoulou**, Andrew Pole

**10:45** *Broadband measurements of the seabed critical angle – inferences for sound speed dispersion in a sandy sediment* (invited)
**Charles W. Holland**, Samuel Pinson, Derek Olson

**11:15** *Sediment Parameter Inversions in the East China Sea* (invited)
Gopu R. Potty, James H. Miller, **Stan E. Dosso**, M. J. Isakson

**11:45** *Implications of vector-scalar reciprocity for acoustic inversion processing* (invited)
Thomas Deal, **Kevin B. Smith**

## Seismo-Acoustics, Electromagnetics, and Multiphysics Coupling

Lecture Hall **GM4** Knoller, Building BD — Chaired by Y. Sun and Q. H. Liu

**10:15** *A Data Driven Representation Method for Nonstationary Convolution Seismic Trace Model with Application to Enhancing Resolution of Seismic Data* (invited)
**Jinghuai Gao**, Lingling Wang, Bing Zhang

**10:45** *Discontinuous Galerkin Algorithm for Elastic Wave Scattering by Arbitrary Discrete Fractures* (invited)
Qiwei Zhan, Qingtao Sun, Qiang Ren, Yiqian Mao, Yuan Fang, **Qing Huo Liu**

**11:15** *Theoretical and Numerical Simulations of the Indirect Collar Waves in Sonic Logging While Drilling* (invited)
**Xiao He**, Xiuming Wang, Hao Chen, Xiumei Zhang

**11:45** *Sensitivity of Biot Slow Wave to Fluid Content and Pore Structure of Fractured Porous Rocks* (invited)
**Yuefeng Sun**

## Model Order Reduction and Numerical Acoustics

Seminar Room BA **02B**, Building BA — Chaired by S. Marburg

**10:15** *Automatic Model Reduction and Error Estimation for Vibro-Acoustic Models Using Krylov Subspaces*
**Axel van de Walle**, Wim Desmet

**10:35** *Efficient Vibro-acoustic Model Updating of Localized Properties using Low-Rank Parametric Model Order Reduction Schemes*
**Sjoerd van Ophem**, Axel van de Walle, Elke Deckers, Wim Desmet

**10:55** *Normal Modes and Modal Reduction in Exterior Acoustics*
**Lennart Moheit**, Steffen Marburg

**11:15** *Virtual Microphone Sensing for Vibro-Acoustics*
**Axel van de Walle**, Wim Desmet

**11:35** *Diffraction Model for Propagation over Realistic Terrain*
**Subhashini Chitta**, John Steinhoff

## **13:45–14:30** Plenary Lecture

**GM1** Audimax, Building BA — Chaired by M. Kaltenbacher

**Martin Schanz** (Graz University of Technology, Austria) *Variable Time Steps in Time Domain Boundary Elements*

## **14:30–15:00** Coffee Break

Building BA, 2nd floor and building BD, 2nd floor

## Acoustic and Elastic Metamaterials

**GM1** Audimax, Building BA — Chaired by B. Popa

**15:00** *Soda Cans Metamaterial: A Subwavelength-Scaled Phononic Crystal* (invited)
**Fabrice Lemoult**, Simon Yves, Nadège Kaina, Mathias Fink, Geoffroy Lerosey

**15:30** *Anti-tetrachiral Lattices as Acoustic Metamaterials*
**Theodore P. Martin**, Kristin Charipar, Matthew D. Guild, Charles A. Rohde, Alberto Pique, Gregory J. Orris

**15:50** *Nonlinear Waves in a Lattice of Magnetic Dipoles*
L. Salmerón-Contreras, N. Jiménez, **V. J. Sánchez-Morcillo**, L. M. Garcia-Raffi, R. Picó, J. F. R. Archilla

**16:10** *Design and characterization of ultrasonic lenses based on generalized Cantor sets*
Sergio Castiñeira-Ibáñez, Pilar Candelas, Jose Miguel Fuster, Daniel Tarrazó-Serrano, **Constanza Rubio**

**16:30** *Nonlinear Waves in Layered Ionic Crystals*
**Juan F. R. Archilla**, Yuriy A. Kosevich, Yaroslav O. Zolotaryuk, Víctor Sánchez-Morcillo, Noé Jiménez, Luis M. García-Raffi

## Seismic Attenuation and Seismic Data Processing

Lecture Hall **GM2** Radinger, Building BD Chaired by J. Gao and H. Li

**15:00** *Q Estimation from the Envelope Peak Instantaneous Frequency based on Generalized Seismic Wavelet*
**Guowei Zhang**, Jinghuai Gao

**15:20** *Anti-aliasing in Kirchhoff beam migration*
**Bangyu Wu**, Hui Yang, Jinghuai Gao

**15:40** *Seismic Instantaneous Attributes Extraction and Applications to Reservoir Characterization*
Naihao Liu, Jinghuai Gao, Bo Zhang, Xiudi Jiang, **Qian Wang**

**16:00** *A robust and precise seismic dip estimation method based on instantaneous phase*
Xiaokai Wang, Wenchao Chen, Jinghuai Gao, **Haixia Zhao**, Changchun Yang

**16:20** *The DAS coupling noise removal using alternating projection iteration with united sparse transforms*
Jianyou Chen, Wenchao Chen, Xiaokai Wang, Dawei Liu, **Bangyu Wu**

**16:40** *Random noise attenuation of seismic data using variational mode decomposition and time-frequency peak filtering*
**Zhen Li**, Jinghuai Gao

## Advances in Selected Topics in Acoustics, Applied Mechanics, and Mechatronics

**GM3** Vortmann Lecture Hall, Building BA Chaired by C. Adam and R. Heuer

**15:00** *Propagation of a Kind of Surface Waves in Case of Rigid Boundary* (invited)
**Amares Chattopadhyay**, A. K. Singh

**15:25** *Nonlinear electro-elastic shells: Modelling and stability analysis* (invited)
**Michael Krommer**, Elisabeth Staudigl, Yury Vetyukov

**16:10** *Simple Mechanical Modelling Applied to Dynamic Roller Compaction*
**Johannes Pistrol**, Dietmar Adam

**16:30** *Estimation of small failure probabilities in high dimensions by asymptotic sampling*
**Christian Gasser**, Christian Bucher

## Seismo-Acoustics, Electromagnetics, and Multiphysics Coupling

Lecture Hall **GM4** Knoller, Building BD Chaired by Q. H. Liu and Y. Sun

**15:00** *Overview of Applications of Microwaves in Medicine* (invited)
**Jan Vrba**

**15:45** *Piezoelectric Transducer Modeling in Anisotropic Media* (invited)
Mingwei Zhuang, Qingtao Sun, Mengqing Yuan, Chunhua Deng, **Qing Huo Liu**

**16:30** *Dielectric Signature of Living Microorganisms in Sediments and Rocks: Theoretical Model and Numerical Results* (invited)
**Yuefeng Sun**

## Ocean Acoustic and Geoacoustic Inversion

Seminar Room BD **02A**, Building BD Chaired by S. Dosso

**15:00** *Similarity Measurements of Acoustic and Seismic signals* (invited)
Costas Smaragdakis, John Mastrokalos, **Michael Taroudakis**

**15:30** *Direct method for solving coefficient inverse problems for hyperbolic equations, based on Gelfand-Levitan approach*
**Nikita S. Novikov**, Maxim A. Shishlenin

**15:50** *Gradient-based Model Parameterizations in Bayesian Geoacoustic Inversion*
**Stan E. Dosso**, Hefeng Dong

# Wednesday

## **09:00–09:45** Plenary Lecture

**GM1** Audimax, Building BA Chaired by P. Borejko

**Ching-Sang Chiu** (Naval Postgraduate School, USA) *Progresses in the Understanding of the Northeastern South China Sea Sound Field: Experimentations and Modeling*

## **09:45–10:15** Coffee Break

Building BA, 2nd floor and building BD, 2nd floor

## Acoustic and Elastic Metamaterials

**GM1** Audimax, Building BA Chaired by A. Baz

**10:15** *Achieving Negligible Shear in Mechanically Robust Acoustic Metamaterials for Underwater Operation* (invited)
**Bogdan-Ioan Popa**

**10:45** *Active Acoustic Metamaterial with Tunable Effective Density using A Disturbance Rejection Controller* (invited)
**Amr Baz**

**11:15** *Design and Demonstration of an Underwater Acoustic Carpet Cloak*
Yafeng Bi, **Han Jia**, Jun Yang

**11:35** *Active Cloaking for Flexural Waves in a Pinned Kirchhoff Plate*
Jane O'Neill, **Özgür Selsil**, Stewart G. Haslinger, Natasha V. Movchan, Richard V. Craster

**11:55** *Highly Directional Source Radiation using Isotropic Transformation Acoustics*
**Andrew Norris**, Xiaoshi Su

## Seismic Attenuation and Seismic Data Processing

Lecture Hall **GM2** Radinger, Building BD Chaired by J. Gao and J. Peng

**10:15** *Seismic Source Simulation for Poroelastic Wave Equations*
**Yijie Zhang**, Jinghuai Gao, Jigen Peng

**10:35** *The difference and correlation between the static modulus and dynamic modulus*
**Hui Li**, De-hua Han, Luanxiao Zhao, Jinghuai Gao

**10:55** *The reflection of the inhomogeneous seismic wave in the generalized viscoelastic model*
**Fengyuan Sun**, Jinghuai Gao

**11:15** *Simulation of Elastic Wave Propagation in Media with an Elastic-poroelastic Interface Using COMSOL Multiphysics*
**Yanbin He**, Tianning Chen, Jinghuai Gao, Yijie Zhang

## Modern Mathematical Methods for Signal Processing in Audio and Acoustics

**GM3** Vortmann Lecture Hall, Building BA — Chaired by G. Tauböck

**10:15** *Modern Mathematical Methods for Signal Processing in Audio and Acoustics*
**Georg Tauböck**

**10:35** *The Inverse Short-Time Fourier Transform (ISTFT) and its applications* (invited)
**Jont B. Allen**

**10:55** *Accelerating Matching Pursuit In Gabor Dictionaries*
**Zdeněk Průša**

**11:15** *Applications of the SWAG Penalty to Audio Reconstruction Problems* (invited)
**İlker Bayram**

**11:35** *Frame Mask for Robust Representation of Speaker Characteristics*
**Feng Huang**, Peter Balazs

**11:55** *Frames in boundary element methods*
**Wolfgang Kreuzer**, Tomasz Hrycak

## Acoustical Modeling for Applications Related to the Comprehensive Nuclear-Test-Ban Treaty International Monitoring System

Lecture Hall **GM4** Knoller, Building BD — Chaired by M. Zampolli

**10:15** *Early Developments in the Modeling of Infrasound Propagation from Atmospheric Nuclear Explosions* (invited)
**Allan D. Pierce**

**10:45** *Numerical Simulations of T-wave Generation and Propagation: Comparison Between Earthquake and Explosion-generated T-waves.* (invited)
**Alexis Bottero**, Paul Cristini, Dimitri Komatitsch

**11:15** *Insights into the modeling of seismic waves for the detection of underground cavities* (invited)
Götz Bokelmann, **Sofi Esterhazy**, Ilario Mazzieri, Ilaria Perugia, Felix Schneider

## Vibration Mitigation and Sound Absorbers

Seminar Room BD **02A**, Building BD — Chaired by M. Kaltenbacher

**10:35** *Prediction of the vibration response of the seat back with variable stiffness*
**Hyukju Ham**, Deokman Kim, Chunkyu Park, Junhong Park

**10:55** *Effects of the rotational stiffness affecting on the dynamic characteristics of the vehicle seat back*
**Deokman Kim**, Hyukju Ham, Chunkyu Park, Junhong Park

**11:15** *FEM modeling and analysis on the mechanism of vibration reduction of railway with impact absorber*
**Jin Jie**, Wonsuk Yang, Hyoin Koh, Junhong Park

**11:35** *Application of an equivalent fluid model for the simulation of sound absorption properties of microperforated panels in 3D environments*
**Sebastian Floss**, Manfred Kaltenbacher

**11:55** *Extended analytical Model for the Transmission Loss of a Plate Silencer in a Flow Duct*
**Roman Kisler**, Ennes Sarradj

## Inverse Problems in Acoustics

Seminar Room BA **02B**, Building BA — Chaired by D. Givoli

**10:15** *Acoustic Source Localization from Microphone Measurements using an Inverse Scheme based on Finite Element Simulations*
**Barbara Kaltenbacher**, Manfred Kaltenbacher, Stefan Gombots

**10:55** *Robust Multiple Time-Reversal Focusing*
**Gi Hoon Byun**, Donghyeon Kim, Jeasoo Kim

**11:15** *Implementation of a Bandpass Filter and Beamforming Algorithms for Source Direction Finding for an ROV*
**Sea-Moon Kim**, Sung-Hoon Byun, Kihun Kim, Chong-Moo Lee

**11:35** *Modelling and Simulation of Musical Instruments*
Lukas Larisch, Martin Rupp, Rossitza Piperkova, **Gabriel Wittum**

## Acoustic and Elastic Metamaterials

**GM1** Audimax, Building BA — Chaired by M. Smith

**13:45** *Metamaterials for enhanced acousto-optic interactions* (invited)
**M. J. A. Smith**, C. Wolff, C. M. de Sterke, M. Lapine, C. G. Poulton

**14:15** *Scattering from Bianisotropic Acoustic Media* (invited)
Michael B. Muhlestein, Benjamin M. Goldsberry, Caleb F. Sieck, **Michael R. Haberman**

**14:45** *Understanding the Willis elastodynamics equations with the displacement coupling terms*
**Ruiwen Yao**, Zhihai Xiang

**15:05** *Non-conventional dynamic behaviour of highly contrasted structured plates*
**Claude Boutin**, K. Viverge, P. Fossat, M. Ichchou

**15:25** *Propagation of coherent transverse waves in composite materials containing hard spherical inclusion*
**Tony Valier-Brasier**, Jean-Marc Conoir

## Seismic Attenuation and Seismic Data Processing

Lecture Hall **GM2** Radinger, Building BD Chaired by Y.-C. Teng and Y. Wu

**13:45** *Several Problems on Numerical Simulation for Seismic Source Loading* (invited)
**Hongjuan Quan**, Guangming Zhu, Yinting Wu

**14:15** *The Comparison of Zero Phase Wavelet after 90 Degree Phase Shift and the Trace Integration Method in Seismic Interpretation*
**Shuhong Zhao**

**14:35** *Modified Forward of Zero-offset VSP Record with Attenuation based on Ganley's Theory*
**Yinting Wu**, Guangming Zhu

**14:55** *A Mathematical Morphology Method for Denoising and Fracture Characterization in Seismic Exploration*
**J. T. Wu**, F. Ye

**15:15** *Location of Acoustic Emission Microseismic Events based on Phase-only Correlation and Genetic Algorithm*
**Yinting Wu**, Guangming Zhu

## Modern Mathematical Methods for Signal Processing in Audio and Acoustics

**GM3** Vortmann Lecture Hall, Building BA Chaired by G. Tauböck

**13:45** *Kernel-based Reconstruction of Solutions of the Helmholtz Equation*
**Manuel Gräf**, Martin Ehler, Wolfgang Kreuzer, Markus Noisternig, Peter Balazs

**14:05** *Time-frequency analysis and determinantal point processes*
**Luís Daniel Abreu**, Karlheinz Gröchenig, João M. Pereira, José L. Romero, Salvatore Torquato

## Acoustical Modeling for Applications Related to the Comprehensive Nuclear-Test-Ban Treaty International Monitoring System

Lecture Hall **GM4** Knoller, Building BD Chaired by G. Haralabus

**13:45** *A Theoretical Model of 3-D Acoustical Propagation on the Continental Shelf* (invited)
**Piotr Borejko**

**14:45** *Numerical and experimental modeling of 3-D ocean acoustics problems* (invited)
**Michael D. Collins**, David C. Calvo, Michael Nicholas

**15:15** *On the Application of Resonance Seismometry for Cavity Detection* (invited)
Götz Bokelmann, Sofi Esterhazy, **Felix Schneider**, Ilaria Perugia

## Modeling and Numerical Simulation of Waves in Moving and Inhomogeneous Media

Seminar Room BD **02A**, Building BDChaired by D. Masovic and M. Kaltenbacher

**13:45** *Propagation of infrasonic impulsive signals in the Earth's atmosphere* (invited)
Roberto Sabatini, Olivier Marsden, **Christophe Bailly**, Olaf Gainville

**14:05** *Comparison of Different Approaches for Calculation of Sound Radiation from an Open Pipe with a Flow*
**Drasko Masovic**, Eugene Nijman, Jan Rejlek, Robert Höldrich

**14:25** *Dissipation of infrasound and acoustic-gravity waves in inhomogeneous, moving fluids*
**Oleg A. Godin**

**14:45** *Numerical Simulation of the effect of cement defects on flexural wave logging*
Ruolong Song, **Hefeng Dong**, Xueshan Bao

**15:05** *3D-Soundfield-Simulations for Ultrasonic Flowmeters*
**H. Landes**, M. Meiler, J. Grabinger

**15:25** *Solving Galbrun's Equation with a Discontinuous Galerkin Approach* (invited)
**Marcus Guettler**, Steffen Marburg

**15:45** *Investigation of the Acoustic Flame Response in Turbulent Combustion* (invited)
**Konrad Pausch**, Sohel Herff, Stephan Schlimpert, Wolfgang Schröder

## Sound, Vibration, and Excitation

Seminar Room BA **02B**, Building BA — Chaired by S. F. Wu

**13:45** *Wave Attenuation in Metamaterial Beams* (invited)
**Jung-San Chen**, I-Ting Chien

**14:15** *The noise reduction using meta impact damper for water spray induced vibration* (invited)
**Dongki Min**, Jewon Lee, Yeonuk Seong, Junhong Park

**14:45** *Research on the Finite-amplitude Sound Pressure in the Membrane-sealed Pistonphone* (invited)
**Wen He**, Junjie Zhong, Fan Zhang

# Thursday

## **09:00–09:45** Plenary Lecture

**GM1** Audimax, Building BA — Chaired by M. Kaltenbacher

**Dan Givoli** (Technion—Israel Institute of Technology, Israel) *Computational Time Reversal for Source and Scatterer Identification*

## **09:45–10:15** Coffee Break

Building BA, 2nd floor and building BD, 2nd floor

## Acoustic and Elastic Metamaterials

**GM1** Audimax, Building BA — Chaired by A. Maurel

**10:15** *Effective behavior of periodic arrays of resonators* (invited)
**Agnès Maurel**, Jean-Jacques Marigo, Jean-François Mercier, Kim Pham, Baidey

**10:45** *Superdimensional Metamaterial Resonators From Sub-Riemannian Geometry* (invited)
**Allan Greenleaf**, Henrik Kettunen, Yaroslav Kurylev, Matti Lassas, Gunther Uhlmann

**11:15** *Group-Theoretic symmetry and Acoustic Metamaterial properties*
**Jont B. Allen**

**11:35** *On the Influence of Boundary Conditions on the Predicted Stop Band Width of Finite Size Locally Resonant Metamaterials*
**Luca Sangiuliano**, Claus Claeys, Elke Deckers, Wim Desmet

## Physical Acoustics

Lecture Hall **GM2** Radinger, Building BD — Chaired by P. Borejko

**10:15** *Study of the resonant interaction between two gas bubbles by using the spherical harmonics expansion*
**Tony Valier-Brasier**, Jean-Marc Conoir, Régis Marchiano

**10:35** *The Forward and Inverse Scattering Analysis of Love Waves due to A Cavity at the Interface*
**Bin Wang**, Chen Yang, Yihui Da, Zhenghua Qian

**11:35** *Coupling Coefficient for Flux Density and Density Gradient of Reflected Sound Energy in Quasidiffuse Sound Fields*
Alexander Antonov, Vladimir Ledenev, Igor Shubin, **Ilya Tsukernikov**, Tatiana Nevenchannaya

**11:55** *Plane wave kinedynamics in fluid continuum, and at a boundary delimiting two fluids*
**Henryk Lasota**

## Acoustical Boundary Elements and Related Topics

**GM3** Vortmann Lecture Hall, Building BA Chaired by R. Piscoya and H. Dogan

**10:15** *The Abused Can - A comparison of the results from numerical simulations and measurements of scattered sound pressure field on a "special" object within the higher frequency range* (invited)
**Ralf Burgschweiger**, Ingo Schäfer, Arne Stoltenberg, Martin Ochmann

**10:35** *A pollution effect in the boundary element method* (invited)
**Steffen Marburg**

**10:55** *Boundary Element Method with Viscous and Thermal Losses: A Calibration Microphone Test Case* (invited)
**Vicente Cutanda Henríquez**, Salvador Barrera Figueroa, Peter Risby Andersen

**11:15** *An Acoustic Hypersingular Boundary Element Formulation Including Viscous and Thermal Losses* (invited)
**Peter Risby Andersen**, Vicente Cutanda Henríquez, Niels Aage, Steffen Marburg

**11:35** *The implementation of the local boundary integral equation method for flow acoustics* (invited)
**Hakan Dogan**, Martin Ochmann, Chris Eisenmenger, Stefan Frank

**11:55** *Study of the numerical stability of different representations of the three-dimensional half-space Green's function* (invited)
**Rafael Piscoya**, Martin Ochmann

## Acoustical Propagation in an Ice-Covered Environment

Lecture Hall **GM4** Knoller, Building BD Chaired by M. Isakson and M. Ballard

**10:15** *Three-Dimensional Propagation Induced by the Rough Sea Ice Interface* (invited)
**Megan S. Ballard**, Jason D. Sagers

**10:45** *Range-Dependent Acoustic Propagation in the Arctic* (invited)
**Michael D. Collins**, Altan Turgut

**11:15** *Finite Element Modeling of Acoustic Scattering from First- and Multi-year Ice Keels in the Arctic* (invited)
**Marcia J. Isakson**, Megan Ballard

**11:45** *Modeling Acoustic Propagation in a Tidewater Glacial Fjord Environment, LeConte Glacier, Alaska* (invited)
**Matthew C. Zeh**, Megan S. Ballard, Erin C. Pettit, Preston S. Wilson

## Numerical Simulation Methods for Ultrasonic Applications

Seminar Room BD **02A**, Building BD — Chaired by J. Prager and F. Krome

**10:15** *A numerical and asymptotic framework for modelling ultrasonic non-destructive testing* (invited)
**Alexandre Imperiale**, Sylvain Chatillon, Edouard Demaldent, Pierre Calmon

**10:35** *Ultrasonic Finite Element Simulations on GPUs with Pogo* (invited)
**Peter Huthwaite**

**10:55** *Wave propagation in prismatic structures modeled using image-based homogenization* (invited)
**Fabian Krome**, Albert Saputra

**11:15** *The Scaled Boundary Finite Element Method to Model Contact Acoustic Nonlinearity* (invited)
**Jannis Bulling**, Jens Prager

**11:35** *Ultrasonic evaluation using FE-based resonance elastic spectroscopy*
Faezeh Sheikhnezhad, **Sina Sodagar**

**11:55** *Effective acoustic modeling of fluid-filled elastic tubes* (invited)
**Sebastian Wöckel**

## Musical Instruments and Loudspeaker Modelling

Seminar Room BA **02B**, Building BA — Chaired by M. Kaltenbacher

**10:15** *3d Modeling and Simulation of a Harpsichord*
**Lukas Larisch**, Rossitza Piperkova, Martin Rupp, Sebastian Reiter, Gabriel Wittum

**10:35** *Piezoelectrically Driven MEMS for Digital Sound Reconstruction*
**Yauheni Belahurau**, Manfred Kaltenbacher, David Tumpold, Christoph Glacer, Alfons Dehé

**10:55** *Numerical Analysis of Sound Wave Generated by a Parametric Speaker with Divergence Control of Directivity*
**Hideo Furuhashi**, Geer Cheng, Xiuming Wu, Madoka Oi, Yuki Matsui

## Past, Present, and Future of the ICTCA

**GM1** Audimax, Building BA — Chaired by C.-F. Chen

**13:30** *Ding Lee and the Early History of the ICTCA's and of the Journal of Computational Acoustics* (invited)
**Allan D. Pierce**

**13:50** *ICTCA Conferences : An unforgettable experience for organizers and participants* (invited)
**Michael Taroudakis**

**14:10** *My Interaction with Dr. Ding Lee since 1996* (invited)
**Chi-Fang Chen**

## Physical Acoustics

Lecture Hall **GM2** Radinger, Building BD Chaired by F. Toth

**13:30** *Layered Structures with Obstacles and Embedded Guides: FEM-Analytic Approach*
**Evgeny Glushkov**, Natalia Glushkova, Alexander Evdokimov

**13:50** *Wave Generation and Source Energy Distribution in Acoustic Fluid with an Immersed Plate*
Evgeny Glushkov, **Natalia Glushkova**, Olga Miakisheva

**14:10** *Guided wave based damage localization in isotropic thin-walled structures with time-reversal approach and linear resonance scattering*
**Artem Eremin**, Evgeny Glushkov, Natalia Glushkova, Rolf Lammering

**14:30** *Analysis the Size Effect on the Vibration of Flexible Core Micro Sandwich Beams based on High Order Nonlocal Theory*
**Omid Rahmani**, Solmaz Ghaffari

**14:50** *Causal-feedback phenomena as the essence of bi-field relations describing linear acoustics*
**Henryk Lasota**

## Acoustical Boundary Elements and Related Topics

**GM3** Vortmann Lecture Hall, Building BA Chaired by R. Piscoya and H. Dogan

**13:30** *Time varying loads and white noise on a SDOF system with Bouc hysteresis using Gaussian Closure* (invited)
**Holger Waubke**, Christian Kasess

**13:50** *Bouc Hysteresis under White Noise Excitation using Non-linear Mapping and the Beta Distribution* (invited)
**Christian H. Kasess**, Holger Waubke

**14:10** *Efficient BEM Simulation of Absorbing Layered Systems*
**Paul Reiter**, Harald Ziegelwanger

## Acoustical Propagation in an Ice-Covered Environment

Lecture Hall **GM4** Knoller, Building BD Chaired by M. Ballard and M. Isakson

**13:30** *Acoustic Communications and Propagation Under Greenland Shore-Fast Ice* (invited)
**Lee Freitag**, Andreas Muenchow, Peter Washam, Kevin Heaney, Mohsen Badiey

**14:00** *Multi-Modal and Short-Range Transmission Loss in Ice-Covered, Near-Shore Arctic Waters.* (invited)
**Miles Penhale**, Andrew Barnard

**14:30** *Glider Navigation using Low-Frequency Acoustic Sources in an Open-Water Arctic Environment with an Eye Towards Glider Navigation Under Ice* (invited)
**Lora J. Van Uffelen**, Sarah E. Webster, Lee E. Freitag, Peter F. Worcester, Matthew A. Dzieciuch

**15:00** *Spatio-temporal correlation of under-ice noise in the Chukchi Sea 2012-2013* (invited)
Bruce Martin, **Christopher Whitt**, Briand Gaudet

**15:30** *The Impact of Oceanographic Variability on Broadband Acoustic Propagation through the Iceland-Faeroe Front* (invited)
**Yong-Min Jiang**

## Guided Wave Propagation

Seminar Room BD **02A**, Building BD — Chaired by A. Chattopadhyay

**13:50** *A Uniform Formalism for Acoustic Wave Propagation in a Mixed Liquid-Solid-Porous Viscoelastic Multilayered Structure*
**Sandrine Matta**, Weijian Xu, Georges Nassar, Antoine Abche

**14:50** *Dispersion of Rayleigh-type wave in an exponentially graded incompressible Crustal layer resting on yielding foundation*
**Amit K. Verma**, Amares Chattopadhyay, Abhishek K. Singh

## **15:30–15:45** Coffee Break

Building BA, 2nd floor and building BD, 2nd floor

## **15:45–16:15** Closing

**GM1** Audimax, Building BA

- Award ceremony for the winners of the student paper competition
- Announcement of ICTCA2019

PART II

# Abstracts

# Interrelationships among force excitation, structural vibration, and sound radiation

Sean F. Wu[1], Pan Zhou[2]

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[2] College of Power and Energy Engineering, Harbin Engineering University, Harbin, China

This paper presents the general theory of using NAH to uncover the root causes of sound and vibration of a structure, namely, the excitation force acting behind a vibrating structure. The input data are the acoustic pressures collected on a hologram surface in the near field in front of the structure. These data are utilized to reconstruct the normal surface velocity distribution. Once this is done, the excitation force acting behind the vibrating surface is determined by synthesizing the normal modes of the structure. Specifically, the characteristics of the excitation force such as its location, type, and amplitude distribution are identified, as if one could “see” the force acting behind a structure based on the acoustic pressure measured on the opposite side. It is shown that such an approach is of generality because vibro-acoustic responses on the surface of a vibrating structure can always be reconstructed, exactly or approximately by using NAH. With these vibro-acoustic responses, the excitation forces acting behind the structure can always be determined, analytically or numerically, given any set of boundary conditions. The second part of this paper examines the interrelationships among excitation, structural vibration and acoustic radiation. For simplicity yet without loss of generality, we consider a finite plate mounted on an infinite rigid baffle subject to an arbitrary force acting on its backside. We demonstrate that the excitation force is not the direct cause of acoustic radiation, but rather the source of mechanical energy supply to a vibrating plate. The direct cause of acoustic radiation is the normal component of the surface velocity, which can be obtained by synthesizing the normal modes of a structure. It is emphasized that these normal modes do not contribute equally to acoustic radiation however. In other words, at any excitation frequency, only a small number of natural modes can produce sound effectively, and the rest do not, including resonance modes. Therefore, the conventional thinking that because the amplitudes of structural vibrations at resonances are maximal, they are primarily responsible for resultant acoustic radiation is not true at all.

Monday, 09:30, **GM1** Audimax, Building BA

# Surface Contribution Analysis Using Non–Negative Intensity

Steffen Marburg[1], Daipei Liu[2], Herwig Peters[2], Nicole Kessissoglou[2]

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[2]School of Mechanical and Manufacturing Engineering, The University of New South Wales, Sydney, Australia

Surface or panel contribution analysis based on numerical methods has a history of approximately three decades [1, 2]. Soon after the first publications, panel contribution analysis became a feature of commercial software tools [3]. For this, the nodal contributions from surface regions with respect to the sound pressure at a single point were summed up over a predefined panel for interior problems. For exterior problems, a similar procedure was executed for nodal intensities of predefined panels. In 2013, the authors proposed a new approach to surface contribution analysis by introducing a non–negative quantity [4] which was later on referred to as non–negative intensity [5]. Non–negative intensity showed similarities to supersonic intensity [6, 7], which is another approach to identify wave components of sound field propagating to the far field. Indeed, the authors could show that under certain conditions, both quantities are coinciding [8]. It is one advantage of the non–negative intensity that it detects acoustic short circuits and directly reveals the regions which are the actual source for sound radiation into the far field. Furthermore and other than acoustic intensity, it identifies surface regions which are important for the overall radiated sound power, even if this region is not moving at all. The concept of surface contribution analysis based on non–negative intensity has been extended to scattering problems [9]. For both, scattering and radiation, it is easily possible to determine non–negative surface contributions with respect to certain directivity patterns with scattering effects or radiation into predefined directions. Non–negative surface contributions can be determined in a similar way with respect to other energy quantities. This presentation will give a survey of the recent developments and the future potential of this approach.

**References**

[1] S.-I. Ishiyama, M. Imai, S.-I. Maruyama, H. Ido, N. Sugiura, and S. Suzuki. The application of Acoust/Boom – a noise level prediction and reduction code. *SAE–paper 880910*, pages 195–205,1988.

[2] S. Marburg. Developments in structural–acoustic optimization for passive noise control. *Archives of Computational Methods in Engineering. State of the art reviews*, 9(4):291–370, 2002.

[3] R. A. Adey, S. M. Niku, J. Baynham, and P. Burns. Predicting acoustic contributions and sensitivity application to vehicle structures. In C. A. Brebbia, editor, *Computational Acoustics and its Environmental Applications*, pp. 181–188. Computational Mechanics Publications, 1995.

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[5] E. G. Williams. Convolution formulations for non-negative intensity. *Journal of the Acoustical Society of America*. 134:1055–1066. 2013.

Monday, 14:15, **GM1** Audimax, Building BA

[6] E. G. Williams. Supersonic acoustic intensity. *Journal of the Acoustical Society of America*, 97:121–127, 1995.

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[9] D. Liu, H. Peters, S. Marburg, and N. J. Kessissoglou. Surface contributions to scattered sound power using non-negative intensity. *Journal of the Acoustical Society of America*, 140:1206–1217, 2016

Monday, 14:15, **GM1** Audimax, Building BA

# The Elasto-Dynamic Transient Problem for a Fluid/Solid Coupled Medium

Yu-Chiung Teng[1,2,3,4]

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The purpose of this paper is to emphasize the importance of the physical modeling through the problem of elasto-dynamic wave propagation for a fluid/solid coupled medium. Roever, Vining, and Strick(1959) have experimentally and analytically investigated the problem of wave propagation from an impulsive source along a fluid/solid interface. Their duel attack of the problem certainly led to a better understanding of the solution and the nature of the complexity of the influence of the elasticity on the wave motion in an acoustic/elastic coupled medium. In this study we simulate their problem numerically by means of the finite element method. Two different approaches are used. The first approach is accomplished by modeling the small acoustic disturbance in the fluid medium with pressure type fluid elements and the small elastic deformation in the solid medium by elastic displacements type solid elements. In the second approach, both the fluid and solid medium are modeled by the displacement solid element. In this second approach, an energy-sharing-nodal-point technique is introduced to simulate an omni-directional source for generating the compressional waves in the fluid. And also the double-layer technique is used to remove the unnecessary continuity in tangential displacements at the fluid/solid interface. It is hoped that the experiment with the finite element simulation would not only provide a more detail results in this fluid/solid problem but could also be extended to solving physically realistic problem of more complex fluid/solid interfaced media arising in ocean acoustics.

Tuesday, 09:00, **GM1** Audimax, Building BA

# Variable Time Steps in Time Domain Boundary Elements

Martin Schanz[1]

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In acoustics often infinite or semi-infinte domains has to be treated, e.g., scattering. As long as travelling waves are considered a time domain calculation is advantageous. A preferable method to simulate the waves in such domains is the Boundary Element Method in time domain. The radiation condition is fulfilled in this method, but the numerical effort is high. Especially in time domain, efficient methods are challenging. The quadratic complexity in the spatial variable may be reduced by so-called fast methods. However, to keep the linear complexity in time a constant time step size is required, which is not a suitable choice for all problems. If a non-smooth time behavior has to be captured a variable step size would be the better choice.

A variable time step size for BEM has been proposed by Sauter and Veit [3] using a global shape function in time and by Lopez-Fernandez and Sauter [1, 2] with a generalized convolution quadrature method (gCQM). Both approaches are formulated for the single layer potential in acoustics. The gCQM approach shares all benefits of the original convolution quadrature method but allows a variable time step size. The complexity in time is $\mathcal{O}(N \log N)$. This approach is used in this presentation to establish BE formulations for an acoustic domain with absorbing boundary conditions. Numerical studies will show the behaviour of this formulation with respect to temporal discretization. The sound pressure in a building will serve as real world application [4].

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Tuesday, 13:45, **GM1** Audimax, Building BA

# Progresses in the Understanding of the Northeastern South China Sea Sound Field: Experimentations and Modeling

Ching-Sang Chiu

Since 2000, a series of integrated oceanographic and acoustics field studies have been carried out jointly by Taiwan and US scientists to investigate the dominant oceanographic and geological processes and their major impacts on underwater sound transmissions in the northeastern South China Sea. Under joint sponsorship by the Taiwan Ministry of Science and the US Office of Naval Research, these collaborative field studies include the Asian Sea Acoustics Experiment in 2001 encompassing the shelf break; the Windy Island Soliton Experiments in 2005 and 2006, with the former on the outer shelf and latter in the deep basin; the Non-Linear Internal Wave shelf experiment in 2007, and most recently, the Sand Dunes Experiments in 2013 and 2014 on the upper slope. Each of these experiments was designed to study different important aspects of the complex environmental and acoustical variabilities unique to this region. In this paper, an overview of the objectives, design and measurements of each of these experiments is provided. Significant scientific results pertaining to the acoustical effects of the observed transbasin depression nonlinear internal waves in the basin, on the slope and near the shelfbreak, depression and elevation nonlinear internal waves on the shelf, and large sand dunes on the upper slope are highlighted. An emphasis in the discussion is placed on the use of acoustic propagation models to assimilate and interpret the measurements in elucidating the linkages between the observed environmental and acoustic propagation phenomena.

Wednesday, 09:00, **GM1** Audimax, Building BA

# Computational Time Reversal for Source and Scatterer Identification

Dan Givoli[1]

[1]Dept. of Aerospace Engineering, Technion, Haifa, Israel

Inverse wave problems are characterized by the fact that part of the information usually needed for well-posedness of the problem (for example the material properties or a part of the geometry) is unknown, and on the other hand certain physical measurements provide some information on the wave field. The problem of identifying a crack in a structure based on sound measurements belongs to this category of problems. One may distinguish between passive identification (e.g., identification of a wave source) and active identification (e.g., identification of a scatterer when the source is given).

This talk will start with a short introduction to inverse wave problems of both kinds, followed by a discussion on the use of Time Reversal (TR) as a computational tool to solve such problems. Source and scatterer identification in structures and unbounded media will be focused on. The capability of TR in identifying damage in structures as well as obstacles in the ground will be demonstrated. Ongoing work will be described.

Thursday, 09:00, **GM1** Audimax, Building BA

# An efficient model-reduction technique for computing the thermo-mechanical behaviour of the strand in a continuous casting machine.

G. Simon [1], H.J. Holl[1], P. Wieser[2], A. Schiefermüller[3], H.Irschik[1]

[1]Institute for Technical Mechanics, Johannes Kepler University Linz, Austria
[2]Primetals Technologies Austria GmbH, Linz, Austria
[3]Voestalpine GmbH, Linz, Austria

The realistic and effective computation of the thermo-mechanical behaviour of the strand in a continuous casting machine is a complex task. The strand-shell is transported over a large number of unevenly distributed rolls in a high-temperature regime, such that a non-linear, inelastic constitutive behaviour of the solidified shell must be taken into account. The inelastic constitutive behaviour varies over the shell thickness and length due to a varying temperature field. The thickness of the strand shell increases over the length of the machine, from the mould to the completely solidified part of the strand, where thickness variations may occur, a fact that must be taken into account in order to estimate mould level variations. Even in the light of the nowadays-available large computer power, it is not possible to study the problem by means of three- or two-dimensional Finite Element formulations in a computation time acceptable for studying the influence of parameter changes, not to talk about the coupling to a closed-loop controller. It is therefore necessary to perform a problem-oriented model reduction.

The model reduction strategy used in the present paper for the strand dates back to a solution method originally developed by the late Professor Franz Ziegler and his co-workers for the dynamics of elasto-plastic and visco-plastic solids and structures, see e.g. [1] – [3]. In this strategy, non-linear effects are treated as fictitious eigenstrains (sources of self-stress) acting upon a properly defined linear elastic background structure. This allows using efficient linear solution techniques in the non-linear context, where the fictitious eigenstrains are computed in an iterative time-stepping procedure. In the present contribution, this solution strategy, which was originally applied to more simple structures, is extended to the complex problem of computing the thermo-mechanical behaviour of the strand in a continuous casting machine. The method allows to estimate also non-stationary bulging caused e.g. by casting speed variations, variations of the strand-shell thickness, strand still-stand and roll misalignment, it is capable to investigate the mechanism of unsteady bulging and mould level variations, and it is simple and accurate enough to couple it with a mould level controller.

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Tuesday, 10:30, **GM3** Vortmann Lecture Hall, Building BA

# Crack Detection in Beam Structures by Modal Identification

Markus J. Hochrainer, Markus Hauser, Florian Tschürtz, Peter A. Fotiu

Department of Applied and Numerical Mechanics
University of Applied Sciences Wiener Neustadt, Austria

Detecting cracks in a vibrating structure is an inverse problem where changes in natural frequencies and mode shapes can be used to estimate the location and the depth of the crack.

This contribution presents a robust two-step method for identification of the crack position via measured frequencies and mode shapes. The first step consists of an analytic model, where the weakened cross-section is represented by a rotational spring. The stiffness of this spring is found from a static finite element simulation. Therefore arbitrary cross-sectional geometries can be considered, where classical analytic results from elastic fracture mechanics are not available.

After a derivation of an analytic relation between the frequency dependent crack stiffness and its location, a matching procedure delivers a first estimate of the crack position and from a subsequent comparison to the static FE simulation, the depth can be estimated as well. These results will be introduced in a modal identification procedure in state space, using a cost function for the deviations between calculated and measured frequencies and mode shapes. The optimization procedure yields a refined result which is both robust and reliable for the determination of localized damage in vibrating structures.

Tuesday, 11:20, **GM3** Vortmann Lecture Hall, Building BA

# Reliability Analysis of Ballasted Steel Bridges Crossed by High-Speed Trains

Christoph Adam[1], Patrick Salcher[2], Benjamin Hirzinger[3]

[1,2,3]Unit of Applied Mechanics, University of Innsbruck, Innsbruck, Austria

This contribution addresses the reliability analysis of high-speed railway bridges with stochastic methods to account for uncertainties in the mechanical model. The emphasis is on ballasted steel bridges. The acceleration response of the bridge deck is assumed to be the governing response quantity for bridge serviceability, and thus, defines in the reliability assessment the limit state of the bridge. The uncertainties for this specific interaction problem are identified and modeled as random variables with appropriate distributions. The effect of uncertain track quality is considered via random rail profiles. A stochastic model is proposed to account for the environmental impact of seasonal temperature changes on the bridge structure. In a parametric study, the contribution of the random variables on the uncertain bridge response of a case study problem is quantified. The probability of exceeding the serviceability limit state is predicted using crude Monte Carlo simulations and Latin Hypercube samples. These predictions are set in contrast to outcomes of a traditional code-based deterministic design procedure.

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Tuesday, 11:45, **GM3** Vortmann Lecture Hall, Building BA

# Propagation of a Kind of Surface Waves in Case of Rigid Boundary

Amares Chattopadhyay, A. K. Singh

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The present study investigates that propagation of Love/SH, Rayleigh, Torsional and Stoneley wave in a medium with a rigid upper boundary is not possible. Some distinct cases have been studied exclusively in the present paper. In all the cases, it has been considered that displacements vanishes at the rigid boundary whereas at the common interface, displacements and tractions are continuous.

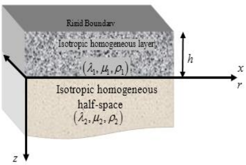


**Fig. 1**

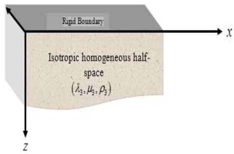


**Fig. 2**

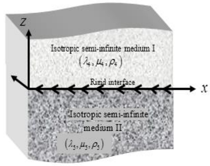


**Fig. 3**

**Case I** discusses Love/SH wave propagation in an isotropic layer with rigid boundary lying over a half space (See Fig. 1). On solving, the dispersion equation is obtained as

$$\tan\left(kh\sqrt{c^2/\beta_1^2-1}\right) = -\mu_1\left(\sqrt{c^2/\beta_1^2-1}\right)/\,\mu_2\sqrt{1-c^2/\beta_2^2} \tag{1}$$

where $\beta_1 = \sqrt{\mu_1/\rho_1}$ and $\beta_2 = \sqrt{\mu_2/\rho_2}$, which is not classical Love wave equation.

**Case II** depicts the propagation of Rayleigh wave in an isotropic half space with rigid boundary (See Fig. 2). The obtained velocity equation is found to be as

$$c^2/c_1^2 = (\lambda_3+3\mu_3)/(\lambda_3+2\mu_3) = 1.156 \text{ for } \lambda_3=\mu_3 \text{ when } \sigma = 0.25 \tag{2}$$

where $c_1 = \sqrt{(\lambda_3+2\mu_3)/\rho_3}$. As $c/c_1 > 1$, therefore, Rayleigh wave cannot propagate in this case.

**Case III** articulates Rayleigh wave propagation in an isotropic layer with a rigid boundary lying over a half space (See Fig. 1). In this case, on deduction frequency equation only contains the imaginary part (attenuation), therefore, Rayleigh wave cannot propagate in such medium.

**Case IV** deliberates the propagation of Torsional surface wave in an isotropic layer with rigid boundary lying over a half space (See Fig. 1). The obtained results are found to be similar as in Eq. (1) which states Torsional surface wave doesn't propagate in such medium.

**Case V** studies Stoneley wave propagation at the rigid interface of two isotropic semi-infinite mediums (See Fig. 3). This case yields $\sqrt{(\lambda_4+2\mu_4)/\mu_4} = \sqrt{(\lambda_5+2\mu_5)/\mu_5} = 0.5 \pm i\sqrt{3}/2$ which indicates that Stoneley wave does not propagate in such mediums.

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Tuesday, 15:00, **GM3** Vortmann Lecture Hall, Building BA

# Nonlinear electro-elastic shells: Modelling and stability analysis

Michael Krommer[1], Elisabeth Staudigl[1], Yury Vetyukov[1]

[1]Institute of Mechanics and Mechatronics, TU Wien, Vienna, Austria

In the present contribution thin electro-elastic shells undergoing large deformations are studied. Such shells are made of dielectric materials, which can be used for both, sensing and actuation. In particular, we consider two types of materials: (1) Anisotropic piezoeleastic materials, for which the classical linear piezoelectric effect dominates the electro-elastic response, and (2) isotropic dielectric elastomers, in which pondomotive and electrostatic forces in combination with the quadratic electrostrictive effect provide the actuation authority.

Based on the theory of nonlinear electro-elasticity, thin shells are introduced as material surfaces with mechanical and electrical degrees of freedom, see [1] for purely elastic shells and piezoelectric shells and [2] for dielectric elastomer shells. The present contribution extends our previous work concerning constitutive coupling. In particular, piezoelectricity and electrostriction are accounted for by means of a hybrid multiplicative / additive decomposition of the deformation measures of the material surface; previously, piezoelectricity was only considered within an additive decomposition and electrostriction was not accounted for at all. The resulting nonlinear electromechanically coupled shell theory is discretized using Finite Elements.

Case studies are presented, in which the electro-active materials are used as actuators to control the deformation of the shell. We are especially interested in problems, in which the actuators are used to control the switching between two non-neighbouring stable configurations of the shell. It will be shown that active switching can be enabled either by means of a snap-through instability or by means of a snap-buckling instability, see [3],[4] for preliminary results concerned with piezoelectric plates. This is true for both actuator materials, piezoelectric actuators and dielectric elastomer actuators. Stability and post-buckling behaviour are discussed by semi-analytical methods - e.g. the Galerkin procedure - and the results are verified against the numerical Finite Element computations. Possible applications of the discussed systems are e.g. micro-bumps, buckling actuators or highly dynamic switching devices for loudspeakers.

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Tuesday, 15:25, **GM3** Vortmann Lecture Hall, Building BA

# Simple Mechanical Modelling Applied to Dynamic Roller Compaction

Johannes Pistrol[1], Dietmar Adam[1]

[1]Institute of Geotechnics, TU Wien, Vienna, Austria

In the scope of the special session dedicated to the memory of Dr. Franz Ziegler the paper provides an overview of the research activities in the field of soil dynamics performed over the recent 25 years at the worldwide first Institute of Soil Mechanics established at the Technische Hochschule Wien. The contribution focuses on a current research project, which deals with the dynamic near-surface compaction by oscillatory rollers.

Compaction is usually accomplished by vibratory rollers; the vibration of the drum is generated by rotating eccentric masses. Moreover, dynamic rollers with different types of excitation have been developed in the last decades, including rollers with directed vibration, feedback controlled rollers and oscillatory rollers.

A high-levelled quality management requires continuous control all over the compacted area, which can be achieved only by work-integrated methods. Roller integrated measurement and continuous compaction control (CCC) result in time and cost savings.

The basic principle of CCC systems is the assessment of the soil stiffness or compaction respectively based on an evaluation of the motion behaviour of the dynamically excited roller drum. CCC has become the state of the art method for an assessment of the compaction success over the past decades. Since it is a continuous roller- and work-integrated method, it is much more efficient compared to spot-like testing methods.

However, the application of CCC systems was limited to vibratory rollers. Therefore, the German roller manufacturer HAMM AG and the Vienna University of Technology launched a research project to investigate the motion behaviour of oscillatory rollers and the aim of developing the first functional CCC system for oscillating rollers.

Large-scale in situ tests were performed as well as theoretical investigations by means of a simple mechanical model, which resulted in the first functional CCC system for oscillating rollers. The study covers the basic principles of CCC systems, a description of the novel CCC value for oscillating rollers and a validation of the CCC system for oscillating rollers on the example of three roller types. Finally, recommendations for an ideal application of the new CCC system are provided.

Tuesday, 16:10, **GM3** Vortmann Lecture Hall, Building BA

# Estimation of small failure probabilities in high dimensions by asymptotic sampling

Christian Gasser[1], Christian Bucher[1]

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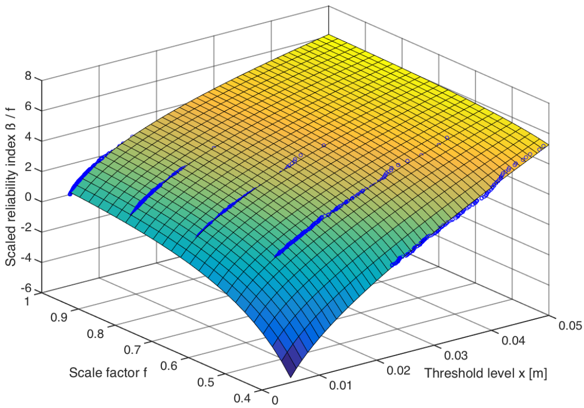
The reliability of high-dimensional nonlinear systems can be analysed by applying Monte Carlo simulation. Whereas the computational effort of crude Monte Carlo is not adversely affected by the dimensionality of the problem, it becomes prohibitively expensive when very small failure probabilities are to be calculated. For example, for a failure probability of $10^{-5}$, the number of samples should be at least $10^{6}$ to obtain enough failures.

A recently developed method to overcome these deficiencies is the so-called asymptotic sampling. The method aims at obtaining more failures by artificially increasing the variance of the basic variables. The scale factor $f$ shown in the figure below is the inverse of the standard deviation. Asymptotic properties of the reliability index regarding the scaling of the basic variables are exploited to construct a regression model which allows to determine the reliability index for extremely small failure probabilities by extrapolation.




A somewhat alternative regression approach in the sense that a regression surface is applied is presented. For that purpose, the Monte Carlo samples for each investigated scale level are expressed as cumulative distribution function over the threshold level. The reliability index for high threshold levels of the original system is then obtained by extrapolation in two directions, see figure above.

Strategies to reduce computation time and to extend the applicability are shown.

Tuesday, 16:30, **GM3** Vortmann Lecture Hall, Building BA

# Ding Lee and the Early History of the ICTCA's and of the Journal of Computational Acoustics

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Professor Emeritus, Boston University

Ding Lee excelled at organizing meetings and in enticing people to come to meetings and participate in special sessions. The present author interacted extensively with Ding Lee over the period 1983 to 1999, but much of this time period was before the advent of e-mail — the author's recollections are somewhat murky, and he welcomes corrections and additions to his remarks.

The present paper discusses several meetings in which Ding Lee was involved prior to the first *International Conference on Theoretical and Computational Acoustics* (ICTCA). These include the *Workshop on Computational Ocean Acoustics* (Yale, 1984), the *Workshop on Numerical Fluid Mechanics* (Georgia Tech, 1985), and the three *IMACS Symposium(s) on Computational Acoustics* (Yale, 1986; Princeton, 1989; and Harvard, 1991). It also discusses the three *World Congress(es) on System Simulation and Scientific Computation* for which Ding Lee organized special sessions on computational acoustics. These were the 11-th (Oslo, 1985), the 12-th (Paris, 1988), and the 13-th (Dublin, 1991). The present author attended all of these conferences.

The present talk also discusses Ding Lee's extraordinary collegiality and how he reached out to many people outside of his organization (Naval Underwater Systems Center, NUSC, New London) and initiated collaborative research with them. Those involved in his early years at NUSC include John Papadakis, Suzanne McDaniel, Fred Tappert, Bill Siegmann, Greg Kriegsmann, Ken Gilbert, Donald St. Mary, George Knightly, and Ray Nagem. Ding's special relationship with the Computer Science Department at Yale is also discussed, including his long association with Martin Schultz of Yale. The paper also describes just how the current author became closely involved with Ding Lee, starting with a meeting of the Acoustical Society of America in 1983.

The paper speculates on the origins of the early association of the computational acoustics conferences in which Ding Lee was involved with the *International Association for Mathematics and Computers in Simulation* (IMACS). Two prominent individuals in the formation of this association were William F. Ames (Georgia Tech) and Robert Vichnevetsky (Rutgers). The latter was, since 1973, the President of IMACS, and extremely active in organizing and chairing all IMACS-related conferences.

The impetus to found a new journal, subsequently known as the *Journal of Computational Acoustics* (JCA) was strongly championed by Ding Lee, William Ames, and Robert Vichnevetsky, and the present author was tapped to serve with Ding Lee as Co-Editor-in-Chief. The first issue appeared in March 1993, and the journal was formally published as an IMACS journal, with Vichnevetsky serving as Consulting Editor.

The launching of JCA, with IMACS sponsorship, was fairly well-set by the time of the third *IMACS Symposium on Computational Acoustic* in 1991, but shortly thereafter Ding Lee and his colleagues decided that future conferences in this general vein would be without IMACS sponsorship, with Ding Lee being the person primarily responsible for the organizing. The title was broadened to include theoretical acoustics, and shortly thereafter the first *International Conterence on Theoretical and Computational Acoustics* was held, in Mystic, CT, in July 1993. The subsequent ICTCA's have been regularly held at two year intervals at various places all over the world.

Thursday, 13:30, **GM1** Audimax, Building BA

# ICTCA Conferences : An unforgettable experience for organizers and participants

Michael Taroudakis[1,2]

[1]Department of Mathematics and Applied Mathematics, University of Crete, Heraklion, Greece

[2]Institute of Applied and Computational Mathematics, FORTH, Heraklion, Greece

The ICTCA series of Conferences have already marked a successful course in the field of acoustics. The original idea of Ding Lee to bring together scientists working on computational aspects of acoustics with those working on theoretical aspects, resulted in gatherings of extremely high scientific output and to the osmosis of people having different research priorities but the same objective: Quality in science. The inclusion in the list of thematic priorities, areas linked with acoustics through their corresponding computational methods (e.g seismology) led to meetings of people who not only discussed on the similarity of the computational tools they have developed or applied, but also shared novel ideas on the analysis of the actual problems encountered in their fields. The ICTCA conferences combined a high scientific level with an atmosphere of warm friendship. It is not strange that new collaborations had as their starting point some ICTCA conference.

For the Organizers of the ICTCA Conferences, the job was highly challenging but very enjoyable. The size of the Conference, which is reasonable and manageable, in connection with the strong links between the participants resulted every time in a scientific event to be kept in their memories as one of their major contributions in the dissemination of the research outcome.

I believe that keeping the flavour of the ICTCA Conferences as it was set by Ding Lee, they will remain in the history of Acoustics as among the most successful medium-sized thematic conferences in this field. Of course everybody should be adjusted to the needs of the current scientific and social situations. It therefore necessary for the ICTCA Conferences to follow the trends, keeping however the tradition of quality they have created.

Thursday, 13:50, **GM1** Audimax, Building BA

# My Interaction with Dr. Ding Lee since 1996

Chi-Fang Chen

Department of Engineering Science and Ocean Engineering, National Taiwan University, Taipei, Taiwan, Republic of China

I have the privilege to know Dr. Ding Lee for 23 years. I first met him in the 1993 ASA meeting held in Boston, and my second encounter with him was in the 1995 2nd ICTCA (International Conference on Theoretical and Computational Acoustics), in Hawaii, which he was the founder. He was a pioneer in his field even back in 1980s. I became a faithful attendee of ICTCA ever since, only missed the meeting in 1999 due to arrival of my third child. Before long, Dr. Ding Lee became my mentor when I started my academic career back home in Taiwan. His FOR3D was the focus of my work. Our collaborative effort expedited improvement of the code and other aspect of propagation modeling. In retrospect, that had been an extremely rich and enjoyable experience. This talk will present the collaboration with Dr. Ding Lee and the past experiences of interactions during each ICTCA.

Thursday, 14:10, **GM1** Audimax, Building BA

# Rainbow-trapping absorbers for transmission problems: Broadband and perfect sound absorbing panels

Noé Jimenez[1], Vicente Roméro-Garcìa[1], Vincent Pagneux[1], Jean-Philippe Groby[1]

[1]Laboratoire d'Acoustique de l'Université du Maine, UMR6613 CNRS, Université du Maine, Le Mans, France

Broadband and perfect sound absorption by subwavelength panels for transmission problems is reported. The asymmetric panels are composed of a periodic array of open waveguides loaded by Helmholtz resonators (HRs) with slightly different dimensions along the structure depth. In each waveguide, the deepest resonator generates a low cut-off frequency, reducing drastically the transmission. The geometry of the preceding HR is designed to possess a slightly higher resonance frequency and is tuned to match the structure impedance with the surrounding one, thanks to the critical coupling condition. Therefore, reflection vanishes and the structure becomes critically coupled to the incident wave, resulting in perfect sound absorption. This process is repeated by adding HRs, whose resonance frequency is slightly higher than the preceding one, to each waveguide. The last added HR fixes the high cut-off frequency of the perfect absorption band in such a way that slow sound condition is achieved within each open waveguide over a broadband frequency range. We experimentally, theoretically and numerically report perfect sound absorption for two panels: (1) at 300 Hz for a transparent panel of total thickness 2.8 cm, i.e., 40 times smaller than the wavelength, (2) from 350 to 1000 Hz for a transparent panel composed of 9 resonators with a total thickness of 12 cm, i.e., 10 times smaller than the wavelength and covering almost two octaves.

Monday, 10:45, **GM1** Audimax, Building BA

# Decorated Membrane Resonators

Z. Yang[1], Kayan Auyeung[1], Suet To Tang[1], L. Sun[1], Ying Li[1,2], and Yibin Li[1,2]

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[2]Center for Composite Materials and Structures, Harbin Institute of Technology, Harbin 150080, People's Republic of China

Although the decorated membrane resonators (DMR's) were first discovered for their sound wave blocking capability [1], the wide range of tunability of their effective impedance was soon recognised [2] and put to good use. Hybrid membrane resonators (HMR's) made by a DMR backed by a rigid air cavity could provide an effective perfect absorption area several times larger than the physical area of the devices [3]. When such an HMR is mounted on the sidewall of a clear duct, it functions as a super Helmholtz resonator (HR) [4], in that it can perform all the functions as a HR, while having larger oscillation strength so it can block sound waves through ducts with larger cross section area, and it can operate at multiple frequencies. Dark acoustic metamaterials (DAM) made by DMR's with multiple asymmetric decorating platelets could achieve total absorption via curvature energy dissipation at resonance to maximize acoustic wave absorption while achieving impedance match to eliminate reflection [5]. Each unit cell of the DAM is also an excellent vibration damper when mounted on a host structure [6]. Compact and light weight sound shields made by damped plates show excellent performance in blocking audible noise when applied in realistic settings, such as a music box and a 10-square-meter in area by 2-meter in height shed made by conventional gypsum boards. Compare to the bare shed, the installation of sound shields on the walls of the shed brought over 20 dB of additional transmission loss across the frequency range from 50 to 2000 Hz, breaking the mass density law below 200 Hz by a great margin.

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Monday, 11:15, **GM1** Audimax, Building BA

# Controlling and absorbing mechanical waves

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In this talk we will see how to guide or to absorb elastic waves using mechanical metamaterials. We will first show that using transformational elastodynamics [1,2] or the neutral inclusion concept [3] one can design cloaking devices for static and dynamic mechanical phenomena. This methodology requires the design of extremal anisotropic mechanical metamaterials [4].

Second, structures and materials absorbing mechanical (shock) waves commonly exploit either viscoelasticity or destructive modifications. Here, we will present a class of uniaxial light-weight geometrically nonlinear mechanical microlattices [5] which using buckling of inner elements, achieve repeatable energy absorption that can be used for wave phenomena.
Proof-of-principle experiments on three-dimensional polymer microstructures will be presented.

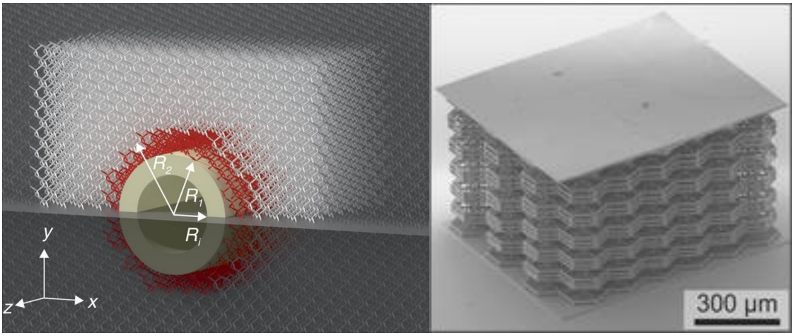


Figure 1: (left) design of a mechanical cloaking device using neutral inclusion concept and pentamode metamaterials. Taken from [3]. (right) buckling metamaterials for shock absorption. Taken from [5].

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Monday, 11:45, **GM1** Audimax, Building BA

# Low frequency and nonlinear acoustical behaviour of plates with perforations bearing periodically spaced flat resonators

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Recent theoretical developments have shown that perforated materials with periodically spaced lateral resonators along the main perforation could result in low frequency absorption peaks even for main perforations, resonators and periods of millimetric or submillimetric sizes.

Based on the modeling and in particular on a low frequency asymptotic development, a new material design involving a collection of resonators with the shape of periodically spaced very flat rings saturated by air was proposed so that from the outside, the absorber system resembles a perforated pancake pile. Experimental results are presented and these confirm the theoretical prediction. These materials are capable of creating absorption peaks at a few hundred Hz for overall material thicknesses of a few cm.

The current development of the research is concerned with the behaviour of these new type of absorber under high sound levels and sound blasts. Based on previous works on periodically spaced flat resonators and on experiments under high sound levels in absorber or muffler applications, modeling of these phenomena is currently studied.

A new design involving a tapered central pore combined with periodically spaced lateral flat ring cavities is also investigated to study the interactions between the behaviour of this type of resonator with the black hole effect under high sound levels and blasts.

Monday, 12:05, **GM1** Audimax, Building BA

# Multi-dimensional Low-frequency Suspension via synthesizing high-static-low-dynamic stiffness isolator and pendulum system

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**Abstract:** This paper systematically investigates the dynamic behaviors of a low-frequency suspension system by exploiting the dynamic coupling between the vibration mode and pendulum mode. The remarkable features of the proposed mount is to configure high-static-low-dynamic stiffness (HSLDS) systems vertically [1], together with a space pendulum [2] to realize multi-dimensional low frequency vibration protecting suspension in passive manner. By combining the mechanisms of the HSLDS isolators and the space pendulum, the mathematical modeling of the present mount is developed. The stiffness and damping properties are nonlinear due to the multi-dimensional coupling and both can be tuned via structural parameters. Then the harmonic balance method (HBM) is applied to solve the dynamic equations of the motion of the suspension system, and corresponding numerical analysis are conducted simultaneously. The results reveal that (a) the proposed system can achieve high-static-low-dynamic stiffness in the vertical direction and quasi-zero stiffness characteristics in the two horizontal directions; (b) compared with the traditional suspension structures, the proposed suspension system can have good vibration suppression in three perpendicular directions, and the nonlinearity of the HSLDS structure can enhance the suspension system to have much better vibration suppression performance.

**Key words:** low frequency suspension, high-static-low-dynamic stiffness, space pendulum, vibration isolation

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Monday, 12:25, **GM1** Audimax, Building BA

# An open acoustic barrier. Design and characterization

Constanza Rubio[1], Sergio Castiñeira-Ibáñez[2], Pilar Candelas[1], Francisco Belmar[1], Antonio Uris[1]

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Nowadays, due to the problems that exist in terms of noise pollution and its impact on health, it is common to use acoustic barriers[1]. Traditionally, these barriers consisted of rigid and continuous materials that are interposed between the source and the receiver[2]. However, there are situations in which the characteristics of the problem necessitate the use of new noise shielding systems. The design and characterization of open acoustic barriers is presented in this work. These are tunable acoustic barriers based on periodic arrays of subwavelength slits[3]. The acoustic response of periodically arranged rectangular scatterers with a subwavelength separation between them and embedded in air is discuss. The results point out that these systems can be tuned to attenuate specific band noise and can be used instead of classical barriers.

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Monday, 15:30, **GM1** Audimax, Building BA

# On the use of the dynamic mass of metamaterials to calculate the transmission loss based on the acoustic mass law

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Lightweight materials are increasingly used in recent years for ecological reasons. Due to increasing ratio of stiffness over mass, those materials often do not reach the noise and vibration performance required by customers or by acoustic norms. Given the well-known shortcomings of classical acoustic solutions, being their mass and/or volume, novel solutions are sought. In this scenario, resonant metamaterials are gaining interest as lightweight noise and vibration solution, be it only in dedicated and tunable frequency zones. Since the goal of resonant metamaterials is to improve the transmission loss of the structure, prediction of this improvement is of high importance.

The paper proposes a method to predict the transmission loss of resonant metamaterials based on the negative mass effect of these materials. Current methods are generally either computational expensive due to very large coupled vibro-acoustic finite element models or the model is oversimplified, in order to derive an analytical solution, jeopardizing the representation of the real model.

The proposed method comprises three steps. First, unit cell modelling is used to calculate the dispersion diagram of the resonant metamaterial to predict the stopband region. Second, the dynamic mass formula of a 1 degree of freedom (1dof) system connected with an undamped spring, is used to calculate the effective resonant mass of the resonant metamaterial using the stopband limits obtained from the dispersion diagram as these limits are the same as those of the negative mass effect [1]. Finally, the dynamic mass formula of a 1dof system connected with a damped spring, is used to calculate the mass per area of the resonant metamaterial and this dynamic mass is used in the mass law formula of the acoustic transmission loss.

This method leads to a computationally cheap and accurate estimation of the transmission loss of resonant metamaterials considering the damping present in the resonant structure. Since in the first step, finite element models are used to derive the dispersion diagram, the method is applicable for multi-material metamaterials with complex geometries. The method is validated through a comparison with results obtained from a coupled vibro-acoustic finite element model.

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Monday, 16:00, **GM1** Audimax, Building BA

# Manipulation of Acoustic Waves using Deformation-driven Tunable Auxetic Metamaterials

Hsin-Haou Huang

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In the first part, a tunable planar auxetic metamaterial (PAM) for controlling and filtering acoustic waves was investigated. The basic unit of the PAM possesses a central node with four tangentially attached ligaments arranged in such a way that the basic unit exhibits rotational symmetry of order four [1]. This basic unit contains equal amounts of left-handed and right-handed basic units and is antitetrachiral. Numerical results for deformed and undeformed PAMs were obtained from several finite element analyses based on Bloch–Floquet theory. Tunable bandgaps in certain frequency ranges were generated by various deformations applied to the PAMs. Wave attenuation in experimental transmission spectra at specific frequencies was demonstrated, showing favorable agreement with the bandgaps obtained from numerical calculations.

In the second part, a three-dimensional antitetrachiral auxetic metamaterial (3DAAM) was proposed [2]. The rules and procedures for designing a 3DAAM that achieves a negative Poisson's ratio are presented. Numerical analysis and experimental validation showed good agreement between the deformations and Poisson's ratios. Specifically, the 3DAAM displayed anisotropic behavior in the in-plane directional compression as well as isotropic behavior in the out-of-plane directional compression. Next, the 3DAAM was used as the deformation-driven tunable metamaterial that can deform in the linearly elastic region, leading to changes of its static and dynamic properties. A series of finite element simulations were performed as well as validated and found to be in favorable agreement with the experimental observations. Moreover, the 3DAAM was shown capable of turning on or off the bandgaps directionally such that two distinct bandgap frequencies can be manipulated by applying deformation in different directions.

In summary, both the numerical and experimental results indicate that the PAMs and the 3DAAMs can be tuned for controlling sound wave propagation. The study opens a new possibility to manipulate acoustic wave propagation, and sheds light on the design of acoustic devices such as acoustic controllers and switches.

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Monday, 16:30, **GM1** Audimax, Building BA

# Soft matter based hypersonic phononic hybridization gaps

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Phononic structures, i.e. composite materials in which a periodic distribution of elastic parameters facilitates control of the propagation of phonons, hold the promise to enable transformative material technologies in areas ranging from sound and heat management. Realizing these opportunities requires strategies to deliberately ‘engineer’ the phononic band structure of materials in the frequency range of interest. The study of hypersonic phononic crystals (hPnC) imposes substantial demand on fabrication and characterization techniques. Colloid and polymer science offer methods to create novel materials that possess periodic variations of density and elastic properties at mesoscopic length scales commensurate with the wave length of hypersonic phonons and hence photons of the visible light. The key quantity is the dispersion ω(k) of high frequency (GHz) acoustic excitations with wave vector k which is measured by the noninvasive high resolution spontaneous Brillouin light scattering. The typical approach involves the exploitation of Bragg-type phononic band gaps (BGs) that result from the destructive interference of waves in periodic media. However, the sensitivity of BG formation to structural disorder limits the application of self-assembly methods that are generally susceptible to defect formation. Phononic hybridization gaps (HG), originating from the anti-crossing between local resonant and propagating modes, are robust to structural disorder and occur at wavelengths much larger than the size of the resonant unit. Here, two examples based on hierarchical structures will be highlighted:

(i) In hard colloid based phononics, ω(k) has revealed both type of band gabs. For the HG, the colloidal shape (spherical, ellipsoid, dumbbell) is crucial since it controls the particle eigenmodes and the direction-dependent mechanical properties of the assembled structures.1-3 Recent progress in surface-initiated polymerization has enabled the synthesis of particle brush materials with controlled architecture of the grafted chains. A new type of HG materials was realized by harnessing the anisotropic elasticity across the particle-polymer interface.4This is contrasted to structures based on core-shell particle topology for which displayed the hypersonic BG at hypersonic frequencies can be reversibly tuned by a solid-solid phase transition.

(ii) Elastic wave propagation through hierarchically nanostructured matter can involve unprecedented mechanisms as observed in the dispersion diagram of the spider dragline silk.5 A delicate combination of mechanical non-linearity and nonlocal spatial distribution of pre-strain led to an intriguing ω(k) with a unidirectional HG-type.

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Monday, 16:50, **GM1** Audimax, Building BA

# Soft active material based acoustic filter

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Locally resonant acoustic metamaterials(LRAMs) have been extensively studied since the first demonstration of low-frequency sound wave regulation with such small-sized artificial structures. However, most of the available metamaterials suffer from the deficiency that the outstanding sound attenuation properties are confined in a fixed frequency band. Thus, LRAMs are not effective to deal with non-stationary noise source, such as rotating machinery which always has speed up or slow down working processes. Polymers with long cross-inked network have been widely used to fabricate sound absorbers and filters, and the desired acoustic performance is related with the energy dissipative mechanism accompanying the wave propagation process in these materials. Besides the absorptive behavior, recently emerged soft active materials possess overwhelming actuation performance. The electrically deformable dielectric elastomer and conductive hydrogel, two commonly used soft materials, are promising to be employed in active acoustic metamaterial, making up for the insufficiency of traditional ones[1-2]. Recently, we have presented a smart membrane-type filter, consisting of a pre-stretched dielectric elastomer membrane (VHB49xx, from 3M corporation) with two compliant electrodes coated on the both sides, to suppress the low frequency noise[1]. By adjusting the voltage applied to the dielectric elastomer, the filter band-gap can be tuned according to the frequency variation of sound source. More than 60 Hz band-gap shift have been achieved by a 3 times pre-stretched VHB4910 specimen with 85mm diameter. To further investigate the mechanism of electrically controlled sound insulation behaviors, the vibro-acoustic characteristics of the specimen under different actuation voltage are experimentally analyzed in an impedance tube((model 4206-T, Bruel & Kjaer Sound and Vibration Measurement). Since incident wave only result small amplitude deflection of the dielectric membrane, complicated acoustic-electric-elastic coupling effects can be theoretically analyzed by a simplified vibro-acoustic model, where the applied electric field only interacts with the membrane stress in one way form. The predicted sound transmission loss(STL) of specimens with various actuation areas on the dielectric membrane shows little differences, which accords well with the experiments.

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Monday, 17:10, **GM1** Audimax, Building BA

# Nonreciprocal transmission of sound through a 2D phononic crystal with viscous background and broken *P*-symmetry of the unit cell

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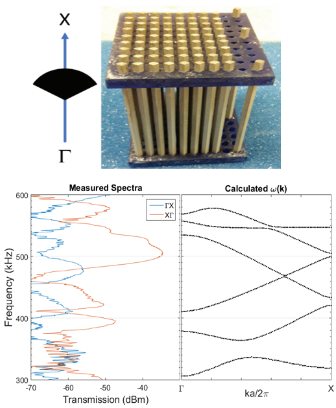


Figure 1: PhC with broken *P*-symmetry. The nonreciprocal direction is labeled by arrow on the left together with the cross-section of the scatterers. Measured transmission along the $\Gamma - X$ and $X - \Gamma$ directions showing nonreciprocity (left). The band structure (right) calculated for inviscid water. Nonreciprocity is suppressed within the band gap, $330 < f < 360$ kHz.

Nonreciprocal propagation of sound becomes possible if the *T*-symmetry of elastic medium is broken. Recent methods of *T*-symmetry breaking are based on scattering actuated by nonlinear electric circuits or spinning of fluid, see reviews [1, 2]. Here we report nonreciprocity in sound propagation in a phononic crystal (PhC) with broken *PT*-symmetry. *T*-symmetry is naturally broken in any fluid due to viscosity. Dissipation leads to irreversibility but not necessary to nonreciprocity. The latter becomes possible if *P*-symmetry is also broken. We study nonreciprocal propagation of sound through a PhC of asymmetric metal cylinders (Figure) imbedded in water. The transmission spectra exhibit strong nonreciprocity reaching 30 dBm for some frequencies. Sound wave propagating along $\Gamma - X$ direction hits a sharp corner where strong gradients of velocity lead to enhanced viscous attenuation. A wave propagating in the opposite direction decays much weaker since the field of velocities is formed by reflection at streamlined surfaces.

Experiment is supported by analytical and numerical calculations based on the solution of the Navier-Stokes equation. It is shown that the viscous corrections to the spectrum of eigenfrequencies of a PhC with broken *P*-symmetry are nonreciprocal. The imaginary part of these corrections gives the attenuation coefficient and the real part – the red shift. Due to nonreciprocity in the red shift there is a principle possibility for engineering of a new class of *nonreciprocal hyperbolic metamaterials* where sound exhibits elliptic and hyperbolic dispersion for propagation along two opposite directions.

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Tuesday, 10:15, **GM1** Audimax, Building BA

# Topological wave transport in acoustic systems

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The recent discovery of topological phases of condensed matter has recently spawned a quest for their classical analogs in other branches of physics. In wave physics, in particular, several proposals have been put forward to obtain artificial periodic materials with a topologically nontrivial band structure, leading to metamaterial analogs of topological insulators. In particular, these materials support backscattering-immune chiral wave transport on their edges, along with a remarkable topological resilience against a large class of defects and disorder. In this presentation, we review our recent theoretical and experimental work on acoustic topological insulators. We discuss our strategies to break time-reversal symmetry to induce a non-zero Chern invariant in nonreciprocal acoustic metamaterials, and pseudospin engineering methods to induce topologically nontrivial subwavelength acoustic states without breaking time-reversal symmetry. Our results may lead to a novel class of system that exploits topological protection to guide and manipulate waves in unprecedented ways.

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Tuesday, 10:45, **GM1** Audimax, Building BA

# *Soda Cans Metamaterial: A Subwavelength-Scaled Phononic Crystal*

Fabrice Lemoult[1], Simon Yves[1], Nadège Kaina[1], Mathias Fink[1], Geoffroy Lerosey[1]

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In this talk, we review our results obtained on a very simple acoustic metamaterial made of soda cans [1]. Indeed, each soda can behaves as a Helmholtz resonator and consistutes the unit cell of a propagation medium with interesting properties. Going beyond the homogenization paradigm usually introduced in the context of locally resonant metamaterials we show that it permits to enrich the physics associated with such a medium in a drastic way. We first underline that the physics can be entirely understood at the light of polaritons in solid state physics. We show, using a microscopic approach based on the transfer matrix that the metamaterial properties are strictly governed by interferences and propagation effects [2]. Namely, the physics of the system solely depend on Fano interferences between the scattered and the unscattered, and multiple scattering of waves between the unit cells of the metamaterial.

We then demonstrate how this observation allows one to tailor this kind of composite medium at the scale of the unit cell, hence going much further than the homogenization approximation. Specifically, we show how this allows one to design various components such as cavities, waveguides, filters, that present deep subwavelength dimensions, much smaller than that of their phononic crystal counterparts [2].

Starting again from our microscopic approach of locally resonant metamaterials, we show how it can underline new effects that are totally hidden by other ones. In particular, we explain how a single negative metamaterial can be turned on a double negative medium thanks to multiple scattering, provided that it is rightly structured [3].

Finally, to conclude, we present a few exotic ideas that are direct consequences of the previous results and of a relatively new understanding of the physics of locally resonant metamaterials. For instance, we show how a 2D soda can metamaterials can be turned into a sheet of "acoustic graphene" whose Dirac cone can be positioned at will within a given frequency range [4].

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Tuesday, 15:00, **GM1** Audimax, Building BA

# Anti-tetrachiral Lattices as Acoustic Metamaterials

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We report the application of anti-tetrachiral elastic lattices as dynamic components in acoustic metamaterials. Anti-tetrachiral lattices have auxetic properties and relatively low Young's modulus compared to other hierarchical lattices. We use geometric engineering of the anti-tetrachiral unit cell to identify a number of extraordinary acoustic propagation phenomena associated with metamaterials, including effective negative index, slow sound, and hyperbolic dispersion. Furthermore, we use finite element analysis to extract effective medium properties from the elastic band structure of the lattice. We extend the theory to predict the appropriate lattice boundaries that enable coupling to acoustic fluids.

Work supported by the Office of Naval Research.

# Nonlinear Waves in a Lattice of Magnetic Dipoles

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We consider a lattice of nonlinearly coupled oscillators, where the masses interact with their nearest neighbors by repulsive forces. Such physical system is realized experimentally, with an array of cylindrical magnets (magnetic dipoles), forming a nearly one dimensional chain of masses coupled by its magnetic fields. The magnetic moments of neighbor magnets are oriented in the same directions, so they experience repulsive forces dependent on the separation between poles. Each magnet is the mass of a pendulum, which is forced to oscillate around an equilibrium position. This system may be considered as a toy model of matter at the microscopic scale, with atoms or ions interacting via coulomb potentials [1]. The chain of oscillating magnets is set at a distance from a periodic array of fixed magnets, with the same periodicity, that mimics the presence of a neighbour layer of atoms, and results in an additional substrate or onsite potential. We report a theoretical and experimental study of nonlinear waves propagating in the magnetic chain. We study in particular the existence of localized traveling perturbations, in the form of solitons or kinks, that propagate along the chain without distortion [2]. These properties of such localized perturbations are investigated for the bare chain, and also for the chain under effect of the substrate potential. Their principal characteristics, as the amplitude and velocity, are determined and compared with the theoretical modeling. Other features of nonlinear waves explored in the setup are the generation of higher harmonics, subharmonics, or the existence of an acoustic dilatation mode, corresponding to an expansion of the chain induced by the acoustic excitation.

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Tuesday, 15:50, **GM1** Audimax, Building BA

# Design and characterization of ultrasonic lenses based on generalized Cantor sets

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The interest of passive focusing lenses for ultrasonic use has grown in the last decade. Traditional acoustic lenses are capable of modulating the ultrasonic beam, where their ability to focus and guide waves comes from the fact that they are constructed of refractory materials with curved surfaces. In this work, lenses capable of modulating the ultrasonic beam in a different way compared to conventional lenses are presented [1]. Its design is based on Polyphonic Cantor Fractals (PCFL) [2-3]. These types of fractals are the simplest to construct, resulting in a completely flat surface. The objective of this work, therefore, is to present the generation and characterization of these fractal structures. We present a complete analysis of these lenses demonstrating that the variation of the PCFL design parameters affects the modulation of the acoustic beam formation. This dynamic control is critical in certain medical applications where the focus of an ultrasonic beam allows thermal ablation of tumours.

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Tuesday, 16:10, **GM1** Audimax, Building BA

# Nonlinear Waves in Layered Ionic Crystals

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Ionic crystal force fields are dominated at intermediate distances by Coulomb interaction. Typical layered structures like some silicates are composed of ions of the same sign, as for example, cations, surrounded by layers of ions with opposite sign, i.e., negative. Short range forces are also predominantly Coulomb repulsion between the nuclei screened by the ion electrons and Pauli repulsion. Therefore, the in-layer interaction is repulsive and the interaction between the cation layer and the sheets is a combination of electric attraction and short-range repulsion with a equilibrium distance. The out-of-plane layers provide an on-site potential which breaks the translational invariance in the plane with a periodic potential, which produces significant changes in the properties of propagation of nonlinear waves. The finite potential barriers between sites allow for the movement of ions at high energies. The different types of nonlinear waves that occur in the cation layers can be classified as extended nonlinear waves, nanopterons, intrinsic localized modes, solitons and kinks or shock waves. The latter have the property of transporting mass and charge, which allow for experimental measurements of currents. The physical implications of the existence of these different waves are analyzed.
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Tuesday, 16:30, **GM1** Audimax, Building BA

# Achieving Negligible Shear in Mechanically Robust Acoustic Metamaterials for Underwater Operation

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Acoustic metamaterials promise to provide an unparalleled level of control over the propagation of sound. Significant research on the topic has focused on aero-acoustics in which solid metamaterials function as effective fluids whose material parameters can be designed to cover a large range of values around the material parameters of air. As a result of this research, applications such as cloaking [1, 2] and lens-based imaging [3] have been successfully demonstrated in air. However, most acoustics applications such as ultrasound imaging, sonar, underwater communications involve water-based environments. Unfortunately, transitioning air-based metamaterial designs to water is not a straightforward task because mechanically robust structures typically contain solid inclusions whose shear modes start to play a significant role in dense environments and in many cases severely complicate the design [4, 5]. Avoiding shear is desirable but difficult especially in self-contained, compact metamaterials. In this presentation I will discuss several techniques to overcome the shear challenge. I will illustrate these methods in an application that (1) serves as a good example of why transitioning air-based metmaterial designs to water is difficult and (2) shows that, surprisingly, carefully designed passive metamaterials surrounding hydrophones increase the hydrophone sensitivity in a broad band of frequencies.

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Wednesday, 10:15, **GM1** Audimax, Building BA

# Active Acoustic Metamaterial with Tunable Effective Density using A Disturbance Rejection Controller

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Extensive efforts are exerted to develop various types of acoustic metamaterials to effectively control the flow of acoustical energy through these materials. However, all these efforts are focused on passive metamaterials with fixed material properties. In this paper, the emphasis is placed on the development of a new class of one-dimensional acoustic metamaterials with tunable effective densities in an attempt to enable the adaptation to varying external environment. More importantly, the active acoustic metamaterials (*AAMM*) can be tailored to have increasing or decreasing variation of the material properties along and across the material volume. With such unique capabilities, physically realizable acoustic cloaks can be achieved and objects treated with these active metamaterials can become acoustically invisible. The theoretical analysis of this class of active acoustic metamaterials is presented and the theoretical predictions are determined for an array of cavities separated by piezoelectric boundaries. These boundaries control the stiffness of the individual cavity and in turn its dynamical density.

In this paper, a disturbance rejection control strategy is formulated to achieve a closed-loop control of the effective density of this class of acoustic metamaterials. The time and frequency response characteristics of a unit cell of the *AAMM* are investigated for various parameters of the controller in an attempt to optimize the cell performance.

A natural extension of this work is to include active control capabilities to tailor the bulk modulus distribution of the metamaterial in order to build practical configurations of acoustic cloaks.

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Wednesday, 10:45, **GM1** Audimax, Building BA

# Design and Demonstration of an Underwater Acoustic Carpet Cloak

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The carpet cloak, which is designed to hide the objects placed on a reflecting surface, has become a topic of considerable interest[1]. Inspired by those theoretical works, the experimental realization of acoustic carpet cloak in air host has been reported[2]. However, due to the difficulty in obtaining the unit cell in reality, the underwater carpet cloak still remains in simulation thus far[3]. Here, we present a design approach of an underwater carpet cloak which is much easier to realize. By introducing a scaling factor, a modest impedance mismatch is brought in to simplify the structure of the carpet cloak. The quasi-two-dimensional device, which is made up of layered brass plates, has surprising low complexity. We verify our method by designing and fabricating a realizable acoustic carpet cloak, and investigate its effectiveness through experiments. The measured results confirm that the carpet cloak can hide the information of the bump on the reflecting plane in a wide frequency range. The proposed carpet cloak, whose unit cell size is close to one fortieth of the wavelength, shows the ability to control the underwater acoustic wave in the deep subwavelength scale. This may bring great potential engineering applications in the practical underwater devices.

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Wednesday, 11:15, **GM1** Audimax, Building BA

# Active Cloaking for Flexural Waves in a Pinned Kirchhoff Plate

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We present new results for the active cloaking of flexural waves in a structured Kirchhoff plate. A cluster of periodically spaced pins is surrounded by active sources, represented by the non-singular Green's function for the two-dimensional biharmonic operator. The sources possess complex amplitudes that are determined by solving an algebraic system of equations enforcing the cancellation of selected multipole orders of the scattered wave field.

For frequencies in the zero-frequency stop band, a characteristic feature of a pinned plate, we find that only a small number of active sources are sufficient for efficient cloaking, and may be placed at nearest-neighbour lattice sites exterior to the cluster. For higher frequencies, active cloaking is achieved by positioning the sources on a circle surrounding the cluster. We demonstrate the cloaking efficiency with several numerical illustrations, considering key frequencies from band diagrams and dispersion surfaces for a Kirchhoff plate pinned in a doubly periodic fashion.

# Highly Directional Source Radiation using Isotropic Transformation Acoustics

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Recent developments in transformation acoustics (TA) have taken advantage of the isotropic nature of conformal mappings to form gradient index lens devices, such as a two-dimensional monopole-to-quadropole lens [1]. While this TA precisely maintains the wave equation solution within the lens the radiated field is still multi-directional and not fully efficient due to impedance mismatch and non-planar radiation. A three-fold strategy is outlined here to achieve highly directional and impedance matched devices. First, most of the rays leaving the original circular region are mapped to a single face of a polygon. Secondly, the center of the radiating face is impedance matched by simply scaling the size up or down. Finally, the polygon is replaced by a two-sided crescent moon mapping which optimizes the radiation across the face of higher curvature, allowing near-field focusing and quasi-planar far-field radiation. These ideas are illustrated by example simulations. Practical design methods, including water matrix and solid matrix devices, will be discussed. The analysis and designs have potential applications beyond acoustic antenna design in beam-steering and wavefront manipulation. [Work supported through ONR MURI.]

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Wednesday, 11:55, **GM1** Audimax, Building BA

# Metamaterials for enhanced acousto-optic interactions

M. J. A. Smith[1,2,3], C. Wolff[2], C. M. de Sterke[1,3], M. Lapine[1,2], C. G. Poulton[1,2]

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Interactions between light and sound are described by processes such as piezoelectricity, electrostriction, and photoelasticity, and drive key technologies underpinning modern telecommunications systems, such as frequency filters, Brillouin lasers, and sensors [1]. However, the range of materials available for practical applications is small, as acousto-optic interactions are generally weak in technologically relevant materials, such as silicon [3]. Metamaterial structuring presents a new and unprecedented opportunity for enhancing light-sound interactions, ultimately reducing device sizes, and improving existing device performance for applications [4].

To this end, we investigate the photoelastic properties of structured materials with periodicities much smaller than all optical and acoustic wavelengths. Here we define photoelasticity via [2]

$$\Delta(\varepsilon^{-1})_{ij} = P_{ijkl}\,\frac{\partial u_l}{\partial x_k} = p_{ij(kl)}s_{kl} + p_{ij[kl]}r_{kl}, \tag{1}$$

where $\Delta(\varepsilon^{-1})_{ij}$ denotes an infinitesimal change in the inverse permittivity tensor, $P_{ijkl}$ is the full photoelastic tensor, and $\partial u_l/\partial x_k$ the gradient of the displacement from equilibrium. The full photoelastic tensor can be decomposed into symmetric $p_{ij(kl)}$ and anti-symmetric $p_{ij[kl]}$ tensors, acting on the linear strain $s_{kl}$ and infinitesimal rotation $r_{kl}$ tensors, respectively.

We show that metamaterial structuring can significantly enhance the symmetric photoelastic and antisymmetric photoelastic (or *roto-optic*) properties of conventional dielectric materials [4, 5]. Surprisingly, the photoelastic properties of metamaterials are not given by weighted averages of the constituent materials alone; they also include *artificial contributions*, and correspond to changes in permittivity arising purely from changes in filling fraction. This behaviour is not observed in the linear optical, acoustic, or thermal properties of metamaterials, and the contribution to the total photoelasticity can be significant [5]. We demonstrate this with a selection of metamaterial designs, including arrays of spheres and layered media.

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# Scattering from Bianisotropic Acoustic Media

Michael B. Muhlestein[1], Benjamin M. Goldsberry[2,3], Caleb F. Sieck[3,4], Michael R. Haberman[2,3]

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Scattering from fluid domains with dissimilar material properties is of foundational importance to many application areas in acoustics and elastic wave propagation. For example, biomedical ultrasound and sonar both make use of acoustic field scattering for localization, imaging, and identification of objects. The theory of acoustic scattering from fluid and elastic materials is well established and has been validated with numerical and physical experiments. Recent work in acoustic and elastic metamaterials has shown that materials with subwavelength asymmetry have a macroscopic response characterized by a scalar bulk modulus, a tensorial mass density, and a vector that couples the pressure-strain relationship with the momentum density-particle velocity relationship. This type of constitutive behavior is the acoustic analogue of bianisotropy in electromagnetism and has come to be known as Willis coupling in acknowledgment of the first description of this material response by J. R. Willis [1]. We present a theoretical description of acoustic scattering of a plane wave incident upon a cylinder exhibiting weak Willis coupling using a perturbation approach. The scattered field depends upon the orientation of the Willis coupling vector and is therefore anisotropic despite the symmetry of the geometry. The analytical model is validated through comparison with a finite element-based numerical experiment where the bianisotropic material response is introduced using a weak formulation of the constitutive equations.

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Wednesday, 14:15, **GM1** Audimax, Building BA

# Understanding the Willis elastodynamics equations with the displacement coupling terms

Ruiwen Yao[1], Zhihai Xiang[1]

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Homogeneity and being free of pre-stresses are two basic assumptions of the classical theory of linear elasticity. Relaxing these two assumptions will result in new equations in the Willis-form. This talk will give a detailed explanation not only under the original theoretical framework [1] but also from the energy point of view.

In this case, the elastic potential energy density $W$ is a field function varies in space, namely

$$W(\boldsymbol{\varepsilon}, \boldsymbol{x}) \equiv [W(\boldsymbol{x})](\boldsymbol{\varepsilon}) \ , \tag{1}$$

where the first independent variable $\boldsymbol{\varepsilon}$ is strain and the second independent variable $\boldsymbol{x}$ is spatial coordinate. A non-homogeneous $W$ contains the potential of intrinsic body forces and external body forces, so that the equilibrium equation of the pre-stress $\sigma_{ij}^0$ can be written as

$$\sigma_{ij,j}^0 - W_{,i}^0 = 0 \,. \tag{2}$$

Through the energy approach, one can obtain the incremental constitutive relation and equation of motion for non-homogeneous linear-elastic media:

$$\begin{aligned} \sigma_{ij} &= C_{ijkl} u_{k,l} + \sigma_{ij,k}^0 u_k \\ \sigma_{ij,j} + f_i &= \sigma_{kj,i}^0 u_{k,j} + \sigma_{ij,jk}^0 u_k + \rho_{ij} \ddot{u}_j \end{aligned} \,, \tag{3}$$

where $f_i$ is the incremental external body force.

The relations (3) are in accordance with the results of transformation elastodynamics [2, 3], which are in Willis-forms with the displacement coupling terms. We will show that they are also possible results under the original theoretical framework of Willis [1]. These findings could give another possibility to designing elastic metamaterials.

**Acknowledgment**

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Wednesday, 14:45, **GM1** Audimax, Building BA

# Non-conventional dynamic behaviour of highly contrasted structured plates

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This paper is devoted to the effective description of two types of highly contrasted structured plates that exhibit non-conventional dynamic behaviour. The first type corresponds to stratified (HCS) plates in which the mechanical properties of the layers are highly contrasted. The second type corresponds to plates stiffened by a periodic mono- or bi-dimensional array of beams clamped on it.

The effective HCS plate behaviour is derived from (i) the 3D constitutive law of the materials combined with (ii) an asymptotic expansion formulation and (iii) the appropriate scaling of the stiffness contrast. The different regimes of behaviour are specified, according to the mechanical and geometrical parameters of the layers, and to the loading. The analysis clearly evidences the enriched kinematics of such HCS plate and yields to a synthetic and analytic bi-torsor representation that encompasses the shear and bending mechanisms. It results in a tri-Laplacian plate formulation that provides a simple understanding of the behaviour and enables to derive analytical solutions under basic loadings. The theory is easily extended to viscoelastic material and has been validated experimentally on laminated glass made of two glass layers pasted with a soft viscoelastic interlayer.

The dynamic behaviour of a stiffened plate is established by up-scaling, through multi-scale asymptotic method, the linear local description of the plate and of the stiffening beams coupled together. The study focus on situations of inner resonance that corresponds to specific mechanical contrasts between the beam and plate parameters. In the case of mono-axial beam array, an effective hybrid beam/plate model is obtained. This un-usual model accounts from the coexistence of two types of dynamic regimes, namely one with active beams (and locally resonant plate), the other one with passive beams and confined dynamic of plates. The case of bi-axial beam array, yield to a non-conventional plate model with frequency dependent apparent mass. These results allow investigating the atypical dispersion relationship with respect to the geometrical and mechanical contrasts of the structural components. The validity of the model and its practical feasibility are also verified by comparing theoretical predictions with numerical FEM simulations.

Wednesday, 15:05, **GM1** Audimax, Building BA

# Propagation of coherent transverse waves in composite materials containing hard spherical inclusions

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This work deal with the propagation of coherent transverse waves through a homogeneous elastic medium containing randomly distributed spherical particles. In comparison with the numerous studies of the scalar case, corresponding to sound waves in fluid, multiple scattering of elastic waves involving both longitudinal and transverse bulk waves, with conversions between them, has received relatively little attention. In an elastic solid, two coherent transverse waves can propagate. The coherent transverse T wave which is the result of constructive interferences between longitudinal and transverse T bulk waves including conversions. The coherent transverse S wave which is a pure transverse wave without conversion. Their behaviors are compared with that of the coherent longitudinal wave for hard spherical inclusions. For such particles, strong dispersion and attenuation are observed, which are the signature of the sub-wavelength dipolar resonance. It is shown that the density contrast between the particles and the matrix is the key parameter explaining the behavior of this resonance.

Wednesday, 15:25, **GM1** Audimax, Building BA

# Effective behavior of periodic arrays of resonators

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We present the homogenization of an array of locally resonant structures. In the context of elasticity the resonances of the Mie type are considered [1], and in the context of acoustics, they are of the Helmholtz type [2].

In the low frequency regime, we define the small parameter $kh$, with $k$ the wavenumber and $h$ the array spacing. Besides, we are interested in configurations where the array thickness $e = O(h)$ is small compared to the wavelength. For both resonators, appropriate scalings of the physical parameters with respect to $kh$ allow us to identify the mechanism of the subwavelength resonance. For the Mie resonance, this scaling concerns the material properties of the inclusions and of the matrix in which they are embedded; and in the context of elasticity, it is specifically a scaling in the shear moduli. For the Helmholtz resonance, the scaling concerns the geometrical properties of the cavity and of the neck of the resonator.

The homogenization method is based on two scale expansions of the near and far fields of the array, and matching conditions are used to connect the two fields. In both cases, the homogenization leaves us with effective jump conditions across the array involving effective parameters among which one is frequency dependent and encapsulates the resonances. Validations of our models will be presented by comparison with direct numerics.

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Thursday, 10:15, **GM1** Audimax, Building BA

# Superdimensional Metamaterial Resonators From Sub-Riemannian Geometry

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Many of the basic properties of waves have power laws which are dimensional in nature. For example, in a conventional material the number of resonant frequencies less than Ω grows polynomi-ally in Ω, with the degree of the polynomial being equal to the physical dimension d (Weyl's Law). Similarly, the rate of blow up of a Green's function at a pole is either logarithmic (d = 2) or inversely proportional to the distance (d = 3). We introduce a fundamentally new method for the design of metamaterial arrays which behave superdimensionally, in that they exhibit power laws for the density of resonant frequencies in a band, and stronger blow up of Green's functions, than expected from the physical dimension. These behaviors are derived from the properties of rays and waves in sub-Riemannian geometry, a well-established area of pure mathematics. This approach, which allows planar designs to function effectively as three- or higher-dimensional media, and bulk material to acts as though of dimension four or higher, we call sub-Riemannian optics. The theoretical designs are valid for any waves modeled by the Helmholtz equation, including acoustics and scalar optics. They are composed of nonresonant metamaterial cells and thus are potentially broadband.



Thursday, 10:45, **GM1** Audimax, Building BA

# Group-Theoretic symmetry and Acoustic Metamaterial properties

Jont B. Allen[1]

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Group theory in physics classifies properties of physical systems. For example, conservation of energy is equivalent to time-invariance in the system equations. This follows from *Noether's Theorem*. When Emma Noether died, Einstein spoke at her funeral, noting that the theory of relativity would not have been possible without her deep insights and theorems. These contributions reach down to Acoustic Metamaterials. In fact there are 1:1 relations between symmetry and *system postulates* (Kim *et al.*, 2016). Six of these postulates are the best known (Carlin and Giordano, 1964): $P_1$: Causality, $P_2$: Linearity, $P_3$: Real time response, $P_4$: Passive/Active, $P_5$: Time-invariance, $P_6$: Reciprocity (Beranek and Mellow, 2012). These relations will be defined and discussed in the presentation, along with others, the most interesting being *Brune impedance* (Brune, 1931), which explains $P_4$. As noted, $P_5$ implies conservation of energy, which is also related to $P_4$. Additional postulates include $P_7$: reversibility and $P_8$: translational-invariance. We propose that all the postulates have a symmetry counter-part. For example, rotation and translation symmetries have corresponding momentum conservation laws. Since the mathematics of group-theoretic symmetry is a highly developed mathematical science, perhaps we might use such symmetry classification schemes to help us think about metamaterial properties.

**Relevant Links:**

*https://en.wikipedia.org/wiki/Group_theory#Physics*
*https://en.wikipedia.org/wiki/Noether%27s_theorem*
*https://todayinsci.com/N/Noether_Emmy/NoetherEmmy-Quotations.htm*
*https://en.wikipedia.org/wiki/Symmetry_(physics)#Spacetime_symmetries*
*https://www.washingtonpost.com/news/comic-riffs/wp/2015/03/23/...*
*emmy-noether-google-doodle-why-einstein-called-her-a-creative-mathematical-genius*

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Thursday, 11:15, **GM1** Audimax, Building BA

# On the Influence of Boundary Conditions on the Predicted Stop Band Width of Finite Size Locally Resonant Metamaterials

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Over the past decades, lightweight material design has gained a lot of importance due to ever more stringent environmental requirements. Moreover, the growing awareness of the impact of noise and vibrations exposure on health and the high customer expectations increase the requirements for noise, vibrations and harshness (NVH) behavior. To comply with NVH regulations, conventional designs consist of heavy and bulky solutions, especially for the low frequency range, since the NVH performance of a structure improves with its mass. This clearly conflicts with the trend towards lightweight design; therefore novel low mass and compact volume NVH solutions are sought to combine both lightweight design and favorable NVH behavior at low frequencies.

Recently, locally resonant metamaterials have shown great potential as an alternative lightweight NVH solution. These metamaterials enhance noise and vibration attenuation performance in some tunable frequency zones, known as stopbands, which can be obtained by adding elastic resonant structures to an elastic host structure on a subwavelength scale. The prediction of the stopbands of these often periodic systems is obtained using the so-called unit cell modelling approach. In this approach, the smallest representative portion of the infinite periodic structure, the unit cell, is modeled and periodic Bloch-Floquet boundary conditions are applied. This unit cell model allows to predict the wave propagation in the infinite periodic structure in a computationally fast and cheap way. However, in any practical application, structures have a finite size and their dynamic behavior is influenced by the boundary conditions. In view of designing metamaterial solutions for real-life applications, it is thus crucial to investigate to which extent a stop band, predicted for an infinite counterpart of the finite structure, is preserved. To this end, this paper presents a numerical study to provide insights on the dynamic performance of finite locally resonant metamaterials with different mechanical boundary conditions. The natural frequencies of the finite size metamaterial are compared to the stopband location prediction for the corresponding infinite metamaterial. The results demonstrate how different sets of boundary conditions affect the width of the stopbands as well as the vibration attenuation in these frequency zones for the finite metamaterial structures as compared to their infinite counterpart. This paper gives on overview on how to estimate the effect of the applied boundary conditions on the predicted stop band frequencies for the infinite structure and derives guidelines on how to preserve the stop band width in the finite case by changing the metamaterials lay out.

Thursday, 11:35, **GM1** Audimax, Building BA

# The Abused Can - A comparison of the results from numerical simulations and measurements of scattered sound pressure field on a “special” object within the higher frequency range

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In the high-frequency range, the simulation of the scattered sound pressure of complex structures, which can interact acoustically with each other and with the surrounding medium, results in high demands on the numerical methods used. Often there are qualitative deviations due to numerical inaccuracies or the required memory space exceeds the available capacities. In addition, the results obtained are often compared only between the different methods. Analytical models can serve as benchmarks when available, but experimental data are seldom used to verify the simulations.

In this paper, therefore, a comparison of the results of simulations of the sound pressure in the high-frequency range around 200 kHz using different numerical methods (BE, FE and raytracing methods) is presented.

In addition, the results are compared with results from practical measurements in a water tank for which a commercially available beverage can was modified with a conical "inner life" and served as the basis of the numerical model used.

The structural setup of the model will be presented in detail and the results and differences between the numerical methods and the measurements are shown and clarified.

Thursday, 10:15, **GM3** Vortmann Lecture Hall, Building BA

# A pollution effect in the boundary element method

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The pollution effect is a well-known and well-investigated phenomenon of the finite element method for wave problems in general and for acoustic problems in particular. It is understood as the problem that a local mesh refinement cannot compensate the numerical error which is generated and accumulated in other regions of the model. This is the case for the dispersion error of the finite element method which leads to a phase lag resulting in very large numerical errors for domains with many waves in them and is of particular importance for low order elements. Former investigations of the author have shown that a pollution effect resulting from a dispersion error is unlikely for the boundary element method. However, numerical damping in the boundary element method can account for a pollution effect. A further investigation of numerical damping reveals that it has similar consequences as the dispersion error of the finite element method. One of these consequences is that the number of waves within the domain may be controlling the discretization error in addition to the size and the order of the boundary elements. This will be demonstrated in computational examples discussing traveling waves in rectangular ducts. Different lengths, cross sections, element types and mesh sizes are tested for the boundary element collocation method.

Thursday, 10:35, **GM3** Vortmann Lecture Hall, Building BA

# Boundary Element Method with Viscous and Thermal Losses: A Calibration Microphone Test Case

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A Boundary Element Method implementation including viscous and thermal losses of sound waves at the boundaries was proposed [1,2] and applied successfully to a number of cases, e.g. acoustic metamaterials and measurement microphones [3,4]. As other implementations employing the Finite Element Method, the BEM with losses is based on the linearized Navier-Stokes equations with no flow. In this presentation, a full three-dimensional BEM model of a one-inch condenser microphone designed for primary calibration, the B&K 4160, will be used for the discussion of the shortcomings of the BEM with losses [5]. This test case is particularly challenging due to its size, internal intricacy and strong coupling of internal, external and membrane domains. This model will be compared with other simpler BEM models of condenser microphones. Based on the results, possible paths for further improvement of the BEM implementation with losses will be suggested.

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Thursday, 10:55, **GM3** Vortmann Lecture Hall, Building BA

# An Acoustic Hypersingular Boundary Element Formulation Including Viscous and Thermal Losses

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To correctly estimate the behavior of small complex acoustic devices, the inclusion of viscous and thermal losses becomes necessary. Practically all domain losses in small setups take place in very thin layers near boundaries. Finite Element formulations including losses exist where boundary layers need to be properly discretized, adding to the computational cost [1]. On the other hand, meshing of boundary layers can be avoided by using the Boundary Element Method [2,3]. However, the existing Boundary Element formulation with losses relies on the use of tangential finite difference pressure derivatives, which might lead to computational difficulties at low frequencies where the element size is much smaller than the wavelength.

This work presents a new implementation of the acoustic Boundary Element Method with losses, where by means of an extra set of hypersingular tangential derivative Boundary Element equations, it is possible to avoid the use of the troublesome first and second finite difference pressure derivatives in the coupling of the fundamental equations. The new proposed formulation introduces, however, hypersingular integration kernels that require nodal $C^1$ continuity [4]. These difficulties will be discussed and the new implementation will be evaluated through simple test cases.

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Thursday, 11:15, **GM3** Vortmann Lecture Hall, Building BA

# The implementation of the local boundary integral equation method for flow acoustics

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The local boundary integral equation (LBIE) method is a meshless Boundary Element Method (BEM), which is previously well-established e.g. for the Helmholtz, Laplace, Poisson type of problems [1]. It has a similar idea with the domain decomposition based (multi-domain) BEM methods. Though, in contrast to the multi-domain BEM, the subdomains may be overlapping and moreover, the singular integrals are avoided in the LBIE.

The noise generated during the air flow through a duct is a challenging problem in flow acoustics, because of the compressibility of the fluid, the turbulence and the vortexes. Therefore, a domain decomposition based method would be more favourable compared to the classical BEM, in order to account for the local variations of the field variables (e. g. velocity) within the domain. In the present work, the implementation of the LBIE for the acoustic propagation in three-dimensional uniform mean flow will be accomplished. The results obtained with this formulation will be compared with the analytical solution for the acoustic waves from a monopole or dipole source in low Mach number flow. Upon accurate implementation of the method, an example with non-uniform flow will be shown.

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Thursday, 11:35, **GM3** Vortmann Lecture Hall, Building BA

# Study of the numerical stability of different representations of the three-dimensional half-space Green's function

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In previous works [1], [2], a comparison of four different exact representations of the three dimensional half-space Green's function was performed. The formula derived by the second author as a contribution of complex multipoles [3] was taken as reference, since it converges for all types of impedances. The other three formulas were deduced by Koh and Yook [4] and Taraldsen [5]. In [4] and [5] it is claimed that the formulas are valid for all type of impedances, but the results of numerical experiments showed that the accuracy of the last three formulas depends on the value of the ground impedance and the position of source and field points. In the present work, a detailed analysis of the formulas is done and the origin of the errors is determined. Alternative expressions that extend the range of accuracy are given.

**References**

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Thursday, 11:55, **GM3** Vortmann Lecture Hall, Building BA

# Time varying loads and white noise on a SDOF system with Bouc hysteresis using Gaussian Closure

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In a recent publication [4] the response of a single degree of freedom system under Gaussian white noise and a constant dead load is presented. The method is based on an approximation of the Kolmogorov equation [3]. The used approximation is the Gaussian closure technique [2]. Both methods are based on the Ito differential equation. This equation is a vector differential equation of the first order with an explicitly given derivative of the state vector. For dynamical systems the derivative of the displacement, the velocity has to be added to the state vector. If the mass term is constant, the derivative of the velocity is given explicitly. The system will become non-linear, because instead of an elastic spring an elastic-plastic hysteretic model defined by Bouc [1] is used. This model introduces another state vector variable, a displacement proportional to the elastic plastic force. Assuming a multivariate Gaussian distribution all integrals for the derivation of the moments needed in the moment equations can be solved analytically. For the transient response only an explicit time step procedure is needed for the determination of the time variant moments.

The original Kolmogorov equation allows for time varying parameters. To extend the solution found in [4] a slowly varying deterministic load instead of a constant dead load is introduced. Such deterministic loads leads to an asymmetry of the moment equations. Therefore the mean values of the state vector variables have to be added to the variances and co-variances.

The deviations from the exact solutions caused by the Gaussian closure technique is evaluated by a comparison with the Monte-Carlo simulation. For softening behavior the approximation is good. The computational time for a SDOF system is about 10 times the time for a deterministic calculation or in other words the time for 10 realizations with the Monte-Carlo method. To receive a resolution with the Monte-Carlo method that allows to compare the results with the Gaussian closure technique 100.000 realizations are needed.

Possible applications of the presented tool are wind loads and earthquakes for multi-storey frames in civil engineering taking the hysteresis of concrete and steel into account or the simulation of the non-linearity of tires and dampers used in cars running on a rough pavement.

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Thursday, 13:30, **GM3** Vortmann Lecture Hall, Building BA

# Bouc Hysteresis under White Noise Excitation using Non-linear Mapping and the Beta Distribution

Christian H. Kasess[1] and Holger Waubke[1]

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Elastic elements used for decoupling of vibrating devices often exhibit hysteretic behavior. In order to take such hysteretic behavior into account, Bouc [1] developed a differential equation where an internal elasto-plastic force is added to the equation of motion. Using a suitable description of the force-displacement relationship hysteretic behavior is achieved. The Bouc model describes the hysteresis by a set of three partially non-linear first order differential equations for the displacement, the velocity, and the force-proportional displacement. Under white noise excitation the resulting stochastic differential equation can be written as a Fokker-Planck-Kolmogorov equation that describes the evolution of the probability density of the state variables. From this, a set of coupled differential equations for the statistical moments of this probability density can be derived. In order to use these equations, certain restrictions on the distribution have to be applied. In the Gaussian closure, for example, the density is assumed to be multivariate Gaussian and thus higher order moments are given by the first two statistical moments. For the Gaussian closure of the Bouc model all necessary integrals can be solved analytically making it extremely efficient [2]. However, in the softening regime of the Bouc model, the force-proportional displacement is restricted to an interval and thus for large excitation levels the Gaussian distribution is not a suitable assumption for this variable.

Here, a new moment closure approach was assessed where for the force-proportional displacement a beta distribution is assumed. Comparisons to Monte-Carlo simulations show that the beta distribution is suitable for a large range of parameter sets. The main issue is the necessity for a non-linear mapping from the force-proportional displacement to the displacement and the velocity. This mapping is of a sigmoidal shape, resulting in a multitude of different candidate functions. Here, the inverse hyperbolic tangent (atanh) was used together with a stretching and a shifting parameter. The atanh is a natural choice as it can be described by a difference of logarithms whose expected values under the beta distribution can be evaluated analytically. Thus, all except four 1D integrals can be calculated analytically making it still a quite efficient closure approach. Initial results show that higher order moments in the force-proportional displacement are in better agreement with Monte-Carlo simulations than the Gaussian closure. Although most of the moments are close to the Monte-Carlo simulations, at low mean loads the displacement and for high excitation levels the velocity based higher moments show deviations that exceed those of the Gaussian closure. The reason is probably that the non-linear hysteretic behavior cannot be properly captured for certain cases using the atanh making further investigations necessary. Still, the new closure approach yields promising results when dealing with hysteretic systems under random excitation.

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Thursday, 13:50, **GM3** Vortmann Lecture Hall, Building BA

# Efficient BEM Simulation of Absorbing Layered Systems

Paul Reiter[1,2] and Harald Ziegelwanger[2]

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The boundary element method (BEM) is a widely used simulation method in acoustics. It allows the calculation of the sound field in a homogeneous domain, while only requiring a discretization of the domain's boundaries. The Green's functions utilized by the BEM inherently fulfill the Sommerfeld radiation condition, which makes it ideal for unbounded domains. A coupling of multiple BEM domains with different physical properties (speed of sound, density, ...) is also possible and requires only a discretization of the domain interfaces. The combination with a complex wave number, which causes exponential damping of the sound pressure, enables the calculation of the sound field inside and around absorbing materials.

In this work, an efficient BEM formulation for axi-symmetric problems is presented which can be used to calculate the sound field in and around an absorbing layered system. The layered system hereby consists of multiple plane layers. One layer describes a homogeneous material (air, homogeneous absorbers, ...) of certain thickness in the z-direction and of infinite dimension in the x-y plane. In the BEM implementation, the interfaces between layers are discretized into ring-shaped elements. A coordinate transformation was used to eliminate any singular boundary integrals and to enable the analytical solution of the radial component of the integrals over the ring elements. Thus, only a one dimensional integral over the angular part remains in the BEM, which can be calculated efficiently by Gaussian quadrature. Theoretically, the discretization yields an infinite sum of ring element integrals, but in practice the sum can be truncated after a certain number of elements. The proposed BEM formulation can be interpreted as a numerical half space Green's function, which describes the sound reflection from the absorbing layered system.

Thursday, 14:10, **GM3** Vortmann Lecture Hall, Building BA

# Early Developments in the Modeling of Infrasound Propagation from Atmospheric Nuclear Explosions

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The author's first employment, beginning in October 1961, after completion of his doctoral thesis in physics at MIT was with the RAND Corporation in Santa Monica. His initial assignment had to do with the study of the far-field pressure waveforms caused by nuclear explosions in the atmosphere. The work continued on, with varying levels of effort, for roughly 15 years — at the Avco Corporation (Wilmington, MA), MIT, and Georgia Tech. At the time when he first joined RAND, his background in fluid mechanics, acoustics, and meteorology was virtually nonexistent. But the timing of the author's becoming immersed in this research was fortuitous. The Soviet Union had recently resumed atmospheric testing, and over the preceding three months, it had conducted 31 nuclear tests. These included the shot of October 30, 1961, the largest nuclear explosion in history, with an energy yield estimated to be equivalent to that of 50 megatons of TNT. Only a few months earlier, a former RAND employee, Herman Kahn, had published (late 1960) his controversial book *On Thermonuclear War*, which dispassionately discussed the mass destruction that was likely to occur in the event of such a war. The stage was thus well-set for some sort of a nuclear test ban, with the eventual agreement (July 25, 1963) that led to a *Limited Nuclear Test Ban Treaty* (signed in August by the USSR, the USA, and the UK).

In 1961, there were at least three papers (Yamamoto, 1957; Hunt et. al., 1960; Weston, 1961) already in the literature that pertained to the modeling of pressure pulse propagation from nuclear explosions, and the Soviet series of tests of very large thermonuclear explosions prompted the reporting in several papers (Carpenter et. al., Donn and Ewing, Oksman and Kataja, Wexler and Hass) of barograms received at a large number of places all over the world. The October 30-th explosion created a pressure wave that was observed to have circled the globe at least two times.

The author's efforts resulted in several achievements that are discussed in this paper. The earlier computational model of Press and Harkrider (J. Geophys. Res., 1962) was extended to include the presence of atmospheric winds, and an *adiabatic mode theory* was developed to explain and predict the horizontal refraction of the pulses as they traveled through a horizontally inhomogeneous atmosphere. An improved formulation was developed to account for the fact that the earth's gravity and associated density height dependence had a substantial effect (hence, *acoustic-gravity waves*) on the propagation. An improved source model was devised to take into account that nuclear explosions impart energy, rather than volume or mass, into the atmosphere, and judicious techniques for taking short-range nonlinear effects into account was devised. The modeling by Press and Harkrider of the atmosphere as a discrete series of isothermal horizontal layers had been criticized by Colin Hines (Radio Science, 1965) for not properly taking into account gravity effects, so the author published a paper that showed the Press-Harkrider formulation was correct and that it converged to the right answer when the layer thicknesses went to zero. Perhaps the highpoint of this work was the theory (developed with the author's student, Joe Posey, at MIT) that predicted the initial form of the atmospheric pressure pulse was conveyed by a single hybrid (and dispersive) mode that clung to the ground and which died out with height. This led to a simple and widely applicable scheme for estimating explosion energy yields (Pierce and Posey, Nature, 1971).

Wednesday, 10:15, Lecture Hall **GM4** Knoller, Building BD

# Numerical Simulations of T-wave Generation and Propagation: Comparison Between Earthquake and Explosion-generated T-waves.

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The term T-waves is generally associated to acoustic signals generated by earthquakes which end up traveling horizontally in the ocean at the speed of sound in the water. They travel over long ranges and reach the shore where they can be reflected or converted into (visco)elastic waves. For almost 90 years, T-waves have been the subject of numerous studies in order to identify their generation mechanisms. Generally, it is supposed that seismic waves are converted to horizontally propagating T-waves by a sloping sea bottom before entering the SOFAR channel. In this study we use a 2D spectral-element method that allows for full-waveform modeling of wave propagation for the analysis of T-waves generation and propagation in the ocean. We present results from a numerical simulation of earthquake-generated T-wave in the context of mid-ocean ridge seismicity and then compare it with a synthetic T-wave generated by an explosion within an atoll.

Wednesday, 10:45, Lecture Hall **GM4** Knoller, Building BD

# Insights into the modeling of seismic waves for the detection of underground cavities

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Motivated by the need to detect an underground cavity within the procedure of an On-Site-Inspection (OSI) of the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO), we investigate the scattering of the seismic wavefield in the presence of an acoustic inclusion. The underlying technical questions of the OSI are still quite new and there are only few experimental examples that have been suitably documented to build a proper scientific groundwork. This motivates the investigation of the wave field on a purely numerical level and the simulation of potential observations based on recent advances in numerical modeling of wave propagation problems.

As much as this is a challenging task in the applied fields, it is also interesting from a modeling and computational point of view. The classical scattering problem considers the wave propagation in an acoustic medium with an elastic obstacle, whereas we focus on the inverse situation of an elastic medium with an acoustic inclusion. With a free surface in place we also face additional objection for the numerical computations. To overcome this issue we split the total wavefield into an incident and a scattered wavefield. Given the incident wavefield, we examine the propagation of the scatted wavefield origin to a plane wave propagation from the bottom or the side of the domain as from a passive sources like teleseismic waves, or to a spherical wave scattering from the surface as from an active point sources like a vibroseis or an explosion. Further, we aim to demonstrate in more detail the specific characteristics of the scattered wavefield corresponding only to incident P-waves and S-waves, separately. For our numerical simulations in 3D, we use the discontinuous Galerkin Spectral Element Code SPEED developed by MOX (The Laboratory for Modeling and Scientific Computing, Department of Mathematics) and DICA (Department of Civil and Environmental Engineering) at the Politecnico di Milano. The computations are carried out on the Vienna Scientific Cluster (VSC).

The accurate numerical modeling can facilitate the development of proper analysis techniques to detect the remnants of an underground nuclear test, help to set a rigorous scientific base of OSI and contribute to bringing the Treaty into force.

Wednesday, 11:15, Lecture Hall **GM4** Knoller, Building BD

# A Theoretical Model of 3-D Acoustical Propagation on the Continental Shelf

Piotr Borejko[1]

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In a continental shelf environment acoustical propagation may be three-dimensional (3-D) due to sloping bottom bathymetry. The 3-D propagation in such an environment has been studied by applying a variety of theoretical and numerical modeling approaches since the early 1980s, but there have been few observations of the predicted 3-D effects. In 2007 and 2008 the 3-D propagation was quantitatively measured in a pair of acoustic transmission tests on the Florida shelf, and then in 2012 accurately modeled by applying the hybrid and adiabatic-mode based techniques.

During these tests, the recorded signals were produced by a low frequency source that was towed parallel to the shelf from a bottom-mounted receiving array. The measured data show the direct path arrival at the bearing of the tow ship and a second refracted path arrival coming from an angle inshore of the direct arrival. A significantly higher received level (RL) of the refracted arrival than that of the direct arrival is also observed in the data; the refracted arrival propagated over the sandy slope, whereas the direct arrival propagated over the limestone sediment.

In this paper, a representative model of an acoustic point source in a penetrable-bottom wedge is applied to explain the data. The theoretical modeling approach is based on the generalized ray technique, an outgrowth of research in geophysics from 1950 to 1970. In the technique the received signal is expressed as a sum of all acoustic fields generated by the source in the wedge. Each term of the sum is identified as a wave motion arriving at the receiver along a specific ray path, and is represented by the so-called “ray integral,” the first being the spherical wave from the source directly to the receiver, the next two being reflected once, etc. By following the paths of multiple reflections, the technique enables one to analyze in detail the acoustical signals recorded by a receiver. Each ray integral is evaluated exactly by applying the Cagniard’s method; thus the contribution of the entire field is included for the complete received signal, as opposed to the method of plane wave approximation (the geometrical acoustics approximation) evaluating the specular component of the field only.

Based on the geoacoustic properties of the seabed at the tests’ site, the limestone sediment is modeled as an elastic solid of shear wave speed which is slightly less than the water-column sound speed, and the sandy slope is modeled as a fluid of sound speed which is greater than that in the water-column. The observed direct arrival is modeled by a group of wave motions of a few bounces off the elastic bottom, thus coming in nearly at the bearing of the towed source; and the observed refracted arrival is modeled by a group of horizontally refracted wave motions of multiple bounces off the sloping fluid bottom, thus coming from angles in-shore of the source bearing. The so modeled direct and refracted arrivals show the same salient features as the measured data: the wave motions comprising the direct group are attenuated due to the shear conversion in the elastic bottom, whereas the RLs of the wave motions comprising the horizontally refracted group are preserved since they undergo total reflections at the fluid bottom.

Wednesday, 13:45, Lecture Hall **GM4** Knoller, Building BD

# Numerical and experimental modeling of 3-D ocean acoustics problems

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This paper will report on progress in the development of the 3-D parabolic equation and in laboratory experiments. For the 2-D case, large gains in efficiency were achieved in previous work by using non-uniforum spacing in the depth grid. For the 3-D case, additional gains in efficiency may be achieved by also using non-uniform spacing in the azimuth grid, with fine sampling used only in regions where propagation deviates from the radial direction. Cross terms make it challenging to extend 3-D parabolic equation solutions to higher order. An alternative to attempting to avoid these terms is to accept them and use higher-order depth numerics. The structure of the matrices in the numerical solution involves three diagonals in the middle that correspond to the depth operator and two diagonals remote from the middle that correspond to the azimuth operator. In solving such systems, the intermediate diagonals are initialized with zeros but become populated with non-zero values during elimination. By using higher-order depth numerics, the intermediate diagonals are initialized with non-zero values, which has no effect on efficiency. The advantage of this approach is that a much coarser depth grid has a large positive effect on efficiency. Due to the extreme difficulty of numerically modeling 3-D problems, especially when there is coupling to shear waves in the sediment, we are exploring the possibility of experimentally modeling such problems. With the advent of additive manufacturing, it has become possible to build highly-detailed scaled environmental models.
[This work was supported by the Office of Naval Research.]

Wednesday, 14:45, Lecture Hall **GM4** Knoller, Building BD

# On the Application of Resonance Seismometry for Cavity Detection

Götz Bokelmann[1], Sofi Esterhazy[1,2], Felix Schneider[1], Ilaria Perugia[2]

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If a suspicious seismic signal has been recorded by the International Monitoring System of the CTBTO, the responsibility of the On Site Inspection (OSI) division is the investigation of the source location area to collect evidence that reveals whether a nuclear test has been conducted and, if the circumstances permit, to get a final localization of ground zero. At the location of an underground nuclear explosion, a damaged zone is expected to be present, including a cavity. Thus, cavity detection might become a major tool for the OSI division. As one OSI-technique "Resonance Seismometry" is listed in the Comprehensive Nuclear Test Ban Treaty (CTBT). A proper definition of the term is still missing in the OSI manuals, but this will most likely comprise a number of techniques. In order to contribute to the method design, we focus here on “Resonance Seismometry” in the narrow sense, and we investigate the interaction of the seismic wave-field with underground cavities, with particular regard to effects of seismic resonances. Analytical elastic modeling of the seismic wave-field interacting with a spherical acoustic inclusion revealed the presence of resonance peaks. Such resonance peaks due to a cavity might be detected by spatial spectrograms and the interference pattern of the scattered field might be used to locate the cavity. If the cavity is air-filled, however, resonances occurring in its vicinity may be quite sharp and hard to resolve [1]. To verify the modeling with real data observations, we use a data set collected in Kylylahti, Finland above a cavern in the subsurface that was collected on behalf of the OSI division.

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Wednesday, 15:15, Lecture Hall **GM4** Knoller, Building BD

# Three-Dimensional Propagation Induced by the Rough Sea Ice Interface

Megan S. Ballard[1] and Jason D. Sagers[1]

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Sea ice ridges are typical features in the arctic ice pack accounting for 10-40% of the total ice mass [1]. For an acoustic signal propagating long ranges under the ice canopy, scattering of sound by the rough ice interface is a dominate loss mechanism. Both theoretical [2] and empirical models [3] for surface loss have been applied to explain measurements of transmission loss in Arctic environments. For these models, the surface loss was dependent on the statistics of the ice ridges, including average keel size and spatial frequency. The work presented in this talk examines out-of-plane scattering caused by the rough ice interface using an approximate normal mode/parabolic equation hybrid model that includes mode coupling in the out-going direction [4]. The model calculates the three-dimensional pressure field for a realization of the ice surface roughness derived from measurements or models of pressure ridges. Like the early scattering models [2], a pressure release surface is assumed such that scattering is the dominant loss mechanism rather than intrinsic attenuation or shear conversion by the ice canopy. The goal of this work is to characterizing the nature of the three-dimensional propagation under sea ice, and understand its effects on transmission loss fluctuations, including horizontal focusing and defocusing of sound waves. The examples considered in this work are focused on first-year ice which is of primary interest for the changing Arctic environment.

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Thursday, 10:15, Lecture Hall **GM4** Knoller, Building BD

# Range-Dependent Acoustic Propagation in the Arctic

Michael D. Collins[1] and Altan Turgut[2]

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Acoustic sources and receivers have been placed in the Arctic Ocean to transmit and record for an entire year. A propagation path that is about 345 km begins in deep water and ends on the continental shelf. There was open water along the entire path when the components of the system were deployed. Sea ice will cover the area within a few months, grow thicker during the winter, and then recede during the last few months before the hardware is recovered. This data set will represent a wide range of ice conditions between the sources and receivers in an environment that is highly range dependent even without ice cover. This paper will discuss the on-going development of the parabolic equation method for problems in Arctic acoustics and its application to this experiment. The approach is currently capable of accurately handling many problems involving sloping fluid-solid and solid-solid interfaces and variable topography, which occur at the various interfaces and boundaries that exist in problems involving ice cover and a seafloor that supports shear waves. Stability is always a key issue in the application of the parabolic equation method to problems involving solid layers. Stable results have been obtained for many problems in Arctic acoustics. Since stability is associated with non-propagating modes, however, it is difficult to predict regimes in which the approach will be stable. One of the objectives will be to develop rational approximations that provide accurate and stable solutions for the parameter ranges (frequency, ranges of bathymetry, and ice thickness) that are relevant for this experiment. [This work was supported by the Office of Naval Research.]

Thursday, 10:45, Lecture Hall **GM4** Knoller, Building BD

# Finite Element Modeling of Acoustic Scattering from First- and Multi-year Ice Keels in the Arctic

Marcia J. Isakson and Megan Ballard

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In ice-covered environments, pressure ridges form from the interaction of between ice flows as they collide with each other. Ice keels, the subsurface expression of ice ridges, differ in composition for First year ice (FYI) and multi-year ice (MYI). FYI keels are made up of large blocks of broken ice sheets partially frozen together with water in between. If the keel does not melt completely during the summer months, the blocks freeze into a strong solid MYI keel. Large MYI keels cannot be broken by conventional ice breakers and pose a threat to structures such as oil rigs in the Arctic. Although methods exist for aerial observation of sea ice, they have limited footprints and are constrained by weather. Low-frequency acoustic scattering may provide a method of wide area surveys to detect MYI keels.

In this study, a finite element model (FEM) was developed to calculate low- frequency acoustic scattering from FYI and MYI in order to determine a parameter space in which the FY and MY ice keels could be distinguished. Geo-acoustic ice properties such as compressional and shear wave speed and attenuation were derived from physical properties including brine content, temperature, salinity, and ice depth using empirical relationships [1]. For FYI, the ice blocks were simply modeled statistically based on ice sheet thickness and placed using a simple dynamics model [2]. MYI keels were based on a measurement using upward-looking sonar [3]. The FEM was meshed, assembled and solved using the commercial code, COMSOL [4]. The FEM was calculated time-harmonically and a time dependent model was determined via Fourier synthesis. The model showed that FYI keels had a longer coda while MYI keels exhibited an in-ice multipath. Results were dependent on the resolution of the sonar and were thus dependent on frequency and bandwidth. Results can be used to understand and predict reverberation from Arctic ice cover. [Sponsored by ExxonMobil and ONR Ocean Acoustics.]

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Thursday, 11:15, Lecture Hall **GM4** Knoller, Building BD

# Modeling Acoustic Propagation in a Tidewater Glacial Fjord Environment, LeConte Glacier, Alaska

Matthew C. Zeh[1,2], Megan S. Ballard[2], Erin C. Pettit[3], Preston S. Wilson[1,2]

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Glacierized fjords present a unique set of acoustic environments that are significantly louder than other ice-covered environments or nonglacierized fjords, with average sound pressure levels of 120 dB (re $1\,\mu\mathrm{Pa}$) with a broad peak between 1 and 3 kHz [1]. The intensity within this peak is due to the release of bubbles from compressed air-filled pores within melting glacier ice. Additionally, the propagation environment of glacierized fjords is complex. The glacier-ocean boundary is dynamic in nature, sensitive to fresh- and sea-water balances governed by submarine glacier melt from heat transfer between the glacier face and ocean [2]. Fresh- and sea-water circulation within the fjord contributes to variations of salinity and temperature resulting in a range dependent sound-speed profile. Further, regular calving events contribute to the clustering of icebergs within the fjord resulting in an ice mélange top boundary layer. This talk presents acoustic measurements recorded in LeConte Bay. Two- and three-dimensional acoustic propagation models using both ray and modal based approaches are applied to calculate the acoustic field in this environment. Melting icebergs and the glacier face are the sound sources, and measured water column data and bathymetry data are used to create a representation of the LeConte Bay environment. [Work supported by NDSEG Fellowship and ONR]

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Thursday, 11:45, Lecture Hall **GM4** Knoller, Building BD

# Acoustic Communications and Propagation Under Greenland Shore-Fast Ice

Lee Freitag[1], Andreas Muenchow[2], Peter Washam[2], Kevin Heaney[3], Mohsen Badiey[2]

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A small experimental network of ocean sensors linked by acoustic communications was tested in April of 2017 in shore-fast ice near Thule Air Base in northern Greenland. The objective was to simultaneously test a real-time communications system for under-ice sensors and to gather synoptic oceanographic and acoustic data to be used for improving under-ice propagation modeling. The work builds on previous experiments in long range, low-frequency under-ice communications and navigation north of Svalbard and in the Canada Basin north of Alaska [1], [2] which utilized frequencies between 700 and 900 Hz.

The experiment spanned approximately one week, and included tests at ranges from 3 to 35 km utilizing a carrier of 3.5 kHz and four-channel receivers at data rates from approximately 100-1000 bps. Initial results from the Micro-Modem real-time hardware used in the Thule test showed reliable links at 20-25 km at most data rates, and moderate connectivity from 25-35 km, depending on the path and data rate.

Communications performance is governed by several factors including: the relative depth of source and receiver, location within the fiords and proximity to glacial fronts with varying sound-speed profiles, *pinniped* (seal) vocalizations, pier-side machinery noise and occasional random impulsive noise events attributed to iceberg movement. The results show good link stability despite a spatially-variant sound speed field resulting from mixing of glacial and ocean waters.

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# Multi-Modal and Short-Range Transmission Loss in Ice-Covered, Near-Shore Arctic Waters.

Miles Penhale[1], Andrew Barnard[1]

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In the past century, extensive research has been done regarding the sound propagation in Arctic ice sheets. The majority of this research has focused on low frequency propagation over long distances. One of the most commonly used excitation method for air-ice-water layers has been explosives. However, environmental regulation has become more stringent, disallowing the use of almost all explosive excitation types. Due to changing climate conditions in these environments, new experimentation is warranted to determine sound propagation characteristics in, through, and under thin ice sheets, in shallow water, over short distances. In April, 2016 several experiments were conducted approximately 1 mile off the coast of Barrow, Alaska on shore-fast, first year ice, approximately 1 m thick. To determine the propagation characteristics of various sound sources, Frequency Response Functions (FRFs) were measured between a source location and several receiver locations at various distances from 50 m to 1 km. The primary sources used for this experiment were, an underwater speaker with various tonal outputs, an instrumented impact-hammer on the ice, and a propane cannon that produced an acoustic blast wave in air. In addition, several anthropogenic sources, namely a snowmobile, generator, and ice auger, were characterized. The transmission characteristics of the multipath propagation (air, ice, water) are investigated and reported.

Thursday, 14:00, Lecture Hall **GM4** Knoller, Building BD

# Glider Navigation using Low-Frequency Acoustic Sources in an Open-Water Arctic Environment with an Eye Towards Glider Navigation Under Ice

Lora J. Van Uffelen[1], Sarah E. Webster[2], Lee E. Freitag[3], Peter F. Worcester[4], Matthew A. Dzieciuch[4]

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[4]Scripps Institution of Oceanography, University of California San Diego, La Jolla, California, USA

An acoustic tomography array consisting of six broadband 250-Hz sources and a distributed vertical line array is currently deployed in the Arctic Ocean as part of the Canada Basin Acoustic Tomography Experiment (CANAPE). Two acoustic Seagliders were deployed for a short pilot study in late Summer 2016 in the vicinity of the array in anticipation of a longer deployment in Summer 2017. Acoustic source transmissions recorded on the gliders were used in real-time for glider navigation and analyzed in post-processing to determine the limits on underwater glider localization using the moored acoustic sources.

Techniques for subsea localization of Seagliders in a temperate environment have been employed for a similar dataset collected in the Philippine Sea. The gliders were localized in post-processing with horizontal uncertainties of approximately 80 meters [1] by taking advantage of the broadband nature of the same 250-Hz acoustic sources deployed in the Arctic. Here we evaluate these techniques in the context of a more complicated Arctic propagation environment with a pronounced surface duct.

It is anticipated that the 2017 Seaglider deployment will include under-ice acoustic propagation paths. Seagliders traveling under the ice are unable to rely on GPS for positioning and navigation. For nearly a decade, Seagliders have successfully navigated under-ice in Davis Strait using 780 Hz narrowband RAFOS sources with positioning errors of a few kilometers [2]. Here we employ navigation techniques used in [2] and take advantage of the broadband nature of the sources as in [1] to begin to explore the limits of glider navigation and positioning in an Arctic environment both in open-water and under ice.

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Thursday, 14:30, Lecture Hall **GM4** Knoller, Building BD

# Spatio-temporal correlation of under-ice noise in the Chukchi Sea 2012-2013

Bruce Martin[1,2], Christopher Whitt[1], Briand Gaudet[1]

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In the past several years, numerous teams have begun investigating whether it is possible to develop long range communications and navigation systems for under-ice operations of autonomous underwater vehicles. The ice cover is well known to limit long range acoustic propagation to frequencies below 200 Hz. As part of the design of the communications systems the following questions arise: what are the spatial and temporal variabilities in the noise levels, how often does ice cracking occur and how does it change the noise amplitude and spectrum? To investigate these questions, we revisited a data set from the Chukchi sea in the winter of 2012-2013. Fourteen recorders were deployed from October – June and sampled at 16 kHz on a duty cycle of 40 minutes every four hours. The correlations between stations in decade bands and octave bands were computed and showed two clusters of results. One group of seven stations had a strong temporal correlation over periods of months, and a significant cross-correlation between stations. The other group's temporal auto-correlations and spatial cross correlation times were much shorter. The sound levels were also correlated with air temperature and ice concentrations. Frequencies above 200 Hz were positively correlated with lower temperature and negatively correlated with ice concentration. Sound levels for frequencies between 50-200 Hz were negatively correlated with ice concentration. Sound levels for frequencies below 50 Hz did not correlate with either environmental variable. Our automated detections of impulses did not correlate with air temperature or ice concentrations. The period of peak bearded seal call counts of May-June correlated with a minimum in the sound levels below 200 Hz and increased the sound levels in the bearded seal calling band of 200-1000+Hz. It appears that the band of 50-200 Hz has the best overall characteristics for long-range communications since ice tends to reduce natural noise and temperature driven variability does not affect the band as much as higher frequencies.

Thursday, 15:00, Lecture Hall **GM4** Knoller, Building BD

**The Impact of Oceanographic Variability on Broadband Acoustic Propagation through the Iceland-Faeroe Front**

Yong-Min Jiang

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More than 25 years ago, in July 1990, NATO – STO – CMRE (then SACLANTCEN) carried out an interdisciplinary experiment in the Iceland-Faeroe frontal region to study the optimal tactical solution of ocean environment for sonar systems. Significant change in the Arctic Ocean environment has been observed in the last 20 years. To understand the impact of the long-term Arctic Ocean environmental change, as well as the oceanographic variability on acoustic propagation, CMRE returns to the Iceland-Faeroe frontal region in 2017 and conducts a joint oceanographic-acoustic experiment. Similar source-receiver geometry and the same propagation paths are adopted. Furthermore, an acoustic payload equipped underwater glider is deployed to monitor the ambient noise level and the oceanographic environment. The comparison between the acoustic transmission losses measured in 2017 and the ones obtained in 1990 is presented in this study (*Work funded by NATO-Allied Command Transformation*).

Thursday, 15:30, Lecture Hall **GM4** Knoller, Building BD

# Observations of Shoaling Internal Solitary Waves and their Properties in the Sand-wave Area on Upper Continental Slope of Northern South China Sea

Yiing Jang Yang[1], Steven R. Ramp[2], Ching-Sang Chiu[3], D. Benjamin Reeder[3], Chen-Hao Hsueh[1]

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In the northern South China Sea, the internal solitary wave (ISW) is extremely active and has the largest amplitude (> 150 m) [1] in the world. The ISWs are generated from tidal forcing on the ridges in the Luzon Strait, propagate northwestward, and traveling across the deep basin to the continental shelf. In addition, a few very large subaqueous sand waves distribute on the upper continental slope and the ISWs could passage these sand waves. The amplitudes and crest-to-crest wavelengths of sand waves were about 10 m and 300 m, respectively. These sand waves could influence the aspects of ISW and underwater acoustic propagation.

Four oceanographic moorings deployed in the sand-wave area and across the upper continental slope of the northern South China Sea on June 3-19, 2014, which contained a spring/neap tide period in order to investigate the properties of ISWs. The transect of the mooring array was almost parallel to the slope and its length was about 13 km from local depth 380 m to 260 m. The observation data included background and wave signatures. Applied the Dubreil-Jacotin-Long (DJL) [2] theory to subtract background signature from temperature and current profiles data and estimate properties of ISWs, such as wave amplitude, instantaneous phase speed and direction, available potential energy (APE), kinetic energy (KE), etc. For the large ISWs, the amplitude and KE decreased sharply upslope between local depths 342 m to 262 m and the APE decreased slightly, causing an increasing ratio of APE to KE as ISWs shoaled. The detailed results will be herein presented.

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Monday, 10:45, Seminar Room BA **02B**, Building BA

# Sound propagation of the continental slope and sand dunes in the northeastern South China Sea

Andrea Y.Y. Chang[1], Linus Y.S. Chiu[2], Chi-Fang Chen[3], Ching-Sang Chiu[4]

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There are sand dunes observed in the upper slope of the northeastern South China Sea. The largest amplitude of these sand dunes was close to 20 m with horizontal length scales between 200 and 400 m. Different aspects of underwater acoustic propagation were studied when simulating the acoustic propagation over the continental slope, with and without the sand dunes. Environmental inputs to the models were measured bathymetry and sound speed profiles, obtained from multi-beam echo sounding surveys and moored oceanographic sensors, respectively. Simulation results pertaining to the 2-D and 3-D propagation effects, modal coupling and uncertainty in relation to the slope, the sand dunes and the water-column variability are presented and discussed. Simulation results are also compared to the measured transmission data. [The research is jointly sponsored by the Republic of China MOST and the US ONR.]

Monday, 11:15, Seminar Room BA **02B**, Building BA

# Measurement of Transmission Loss Using an Inexpensive Mobile Source on the Upper Slope of the South China Sea

Christopher W. Miller[1], Ching-Sang Chiu[1], Chi-Fang Chen[2], Linus Y.S. Chiu[3], Ying-Jang Yang[2]

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[3]National Sun Yat-sen University, Kaohsiung, Taiwan

During the 2014 South China Sea Upper-Slope Sand Dunes Experiment, an inexpensive, expendable mobile sound source was deployed to investigate potential use of such a device to acquire quality transmission loss (TL) data and yield additional spatial information of the complex acoustic environment. The mobile source was programmed to maintain depth, speed, and to transmit a tonal signal followed by a short linear-sweep timing/ranging pulse every minute. A vertical hydrophone array and other receivers recorded the signals. The methodology and related mathematical tools to analyze the received acoustic data for coherence time (optimum integration time) and consequently TL were developed. Coherence times were estimated based on a tolerance of one-dB degradation in the measured SPL of the tone. It is shown that a time segment is coherent when 50% of the segment has phase fluctuations within ± 22.5° about the linear trend of the phase. The optimum integration time was applied to the data to obtain TL estimates versus range using spectral estimation techniques. Measured coherence time and TL were compared to model results to gain insights into the quality, limitations, and attainable future advances of this measurement method.

Monday, 11:45, Seminar Room BA **02B**, Building BA

# Acoustic field horizontal variability and direction of arrival estimation in a canyon with internal tides

Timothy F. Duda[1], Bruce D. Cornuelle[2], Ying-Tsong Lin[1]

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The variable slopes of undersea canyon regions impart complexity to acoustic fields for two reasons: intricate patterns of reflection from the seabed, and effect from water column internal waves generated at the slopes. The seabed interactions may spread the horizontal directional spectrum of sound from 'line of sight'. The directional spectrum is tied to the covariance matrix of the field, a fundamental quantity that can be measured or modeled. Here, sound-field horizontal-lag spatial covariance matrices and other derived quantities are generated from time-stepped 3D parabolic equation acoustic simulations in an underwater canyon filled with long-wavelength tidal internal waves (internal tides) [1]. A relative absence of nonhysdrostatic short internal waves over deep canyons is supported by evidence, theory, and simulations, so the lack of those unresolved waves in the model is acceptable. Other computable quantities are phase structure function, azimuthal beam power content of arriving sound, sound field spatial correlation length, and the eigenmode spectrum. Here the covariance matrices are inserted into the direction of arrival (DOA) estimation problem. Analysis of DOA estimates and error bounds is done for a conventional beamformer and for a Gauss-Markov inverse-based beamformer [2] for a variety of signal-to-noise ratios. The method treats non-line of sight acoustic energy as a form of noise. At low signal-to-noise the Gauss-Markov estimator can perform better than the other. This analysis of field variability and DOA estimation allows performance degradation caused by evolving ocean features to be directly compared to degradation from other detrimental influences such as excess noise and array deformation.

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Monday, 12:15, Seminar Room BA **02B**, Building BA

# Three-Dimensional Sound Propagation and Scattering in an Oceanic Waveguide with Surface and Internal Gravity Waves over Range-Dependent Seafloor

Ying-Tsong Lin[1] and James F. Lynch[1]

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Underwater sound propagation and scattering in an oceanic waveguide can be influenced by environmental fluctuations on the boundaries (the sea surface and the sea floor) and also in the ocean interior. When the horizontal/azimuthal gradients of the environmental fluctuations are significant, three-dimensional acoustic propagation and scattering effects can actually occur. Many studies have only been considering individual environmental factor, but the current work presented in this talk takes into account of the joint effects by surface and internal gravity waves over range-dependent seafloor consisting of sand waves, ripples, and/or scours. This scenario represents better the reality in some dynamic areas at the edge of continental shelf (shelfbreak), continental slopes, submarine canyons, and also riverine and estuarine environments. Two methods are taken in this study: one is theoretical analysis utilizing acoustic mode theory, and the other is numerical modeling with three-dimensional parabolic-equation models. The frequency dependency of the joint effects will be analyzed, as well as the dependencies on the source and receiver positions, acoustic mode numbers, and/or ray angles. Numerical examples of underwater sound propagation and scattering with realistic environmental conditions will be presented with statistical analysis on the temporal and spatial variability. [Work supported by ONR.]

Monday, 12:45, Seminar Room BA **02B**, Building BA

# Salvus: An Open-Source Package for Time-Domain Waveform Modeling and Inversion Across the Scales

Christian Boehm[1], Michael Afanasiev[1], Martin van Driel[1], Lion Krischer[1], Dave A. May[2], Max Rietmann[1], Andreas Fichtner[1]

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Waveform inversion has become a powerful tool for parameter estimation in many exciting domains such as seismic tomography, medical imaging, and non-destructive testing. Despite the vastly different scales, all these applications have in common that they can be stated as a PDE-constrained optimization problem governed by some variant of the time-dependent wave equation that invert for unknown material properties or external forces.

However, each new domain brings with it different geometries, wave propagation physics, spatial and temporal discretizations, and models of variable complexity. Adapting existing software to these novel applications often requires a significant investment of time, and acts as a barrier to progress. To combat these problems we present Salvus, an open-source HPC software package designed to solve large-scale full-waveform inverse problems, with a focus on both flexibility and performance.

Salvus is a collection of packages covering the complete toolchain of waveform inversion, ranging from a module to create unstructured meshes in two and three dimensions to an automated, interactive and graph-based workflow management framework capable of orchestrating all necessary components. The wave equation solver is based on a high-order spectral-element discretization and supports a diverse collection of wave propagation physics, such as viscoelasticity or solid-fluid coupling. Adjoint-based computations of gradients and Hessian-vector products as well as custom-tailored compression methods are built-in, which allows a tight integration with trust-region quasi-Newton methods to solve the inverse problem.

Salvus bridges the gap between research and production codes with a design based on C++ template mixins and Python wrappers that separate the physical equations from the numerical core. We combine state-of-the-art algorithms by following modern software design practices, testing protocols, and by establishing its foundations upon existing high-level scientific libraries, such as PETSc and Eigen. This naturally facilitates solving inverse problems. Additionally, and even more importantly, it enhances reproducibility and reliability of the final results.

Our goal in this presentation is to introduce the software package, its design principles and underlying mathematical framework. Furthermore, we show several numerical examples across the scales.

Monday, 10:45, Lecture Hall **GM2** Radinger, Building BD

# Error Analysis of Non-Conforming FE Methods for Wave-Type Problems and its Application to Heterogeneous Multiscale Methods

David Hipp[1], Marlis Hochbruck[1], Christian Stohrer[1]

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In this talk, we consider first an abstract second-order formulation of wave propagation problems. More precisely, let $H$ and $V$ be two Hilbert spaces forming a Gelfand triple $V \hookrightarrow H \simeq H^* \hookrightarrow V^*$ and $T > 0$. We seek $u : [0,T] \to V$ such that

$$m\big(\partial_{tt} u(t), v\big) + a\big(u(t), v\big) = \big\langle f(t), v \big\rangle, \qquad \forall v \in V, \tag{1}$$

subject to given initial and boundary conditions. Here $m$ is an inner product on $H$, $a$ a symmetric, bounded, and coercive bilinear form on $V$, and $f : [0,T] \to V^*$ a given source term. For the discretization we consider a finite dimensional Hilbert space $V_H$ and approximations $m_H$, $a_H$, and $f_H$ of $m$, $a$, and $f$, respectively. The spatially discrete approximation is given by

$$m_H\big(\partial_{tt} u_H(t), v_H\big) + a_H\big(u_H(t), v_H\big) = m_H\big(f_H(t), v_H\big), \qquad \forall v_H \in V_H. \tag{2}$$

Note that we allow the discretization to be non-conforming, see [2], i.e., we do neither assume that $V_H$ is a subspace of $V$, nor require that $a_H$ and $m_H$ coincide with $a$ and $m$ on $V_H \times V_H$, respectively.

The main result is, that despite the generality of our framework, we still can derive a-priori error bounds. These bounds depend on the differences between the exact and discretized forms (inner products, bilinear forms, source terms) and the approximation properties of $V_H$.

In the second part of this talk we apply these general results to Finite Element Heterogeneous Multiscale Methods (FE-HMM) for the acoustic wave equation or time-dependent second order Maxwell's equations introduced in [1] and [3], respectively. Both FE-HMM schemes allow to approximate the effective behavior of acoustic or electromagnetic waves propagating through a multiscale material without the need of resolving all of its micro scale features. We would like to stress that FE-HMM is only one of many FE methods covered by our general framework.

We gratefully acknowledge financial support by the Deutsche Forschungsgemeinschaft (DFG) through CRC 1173.

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Monday, 11:05, Lecture Hall **GM2** Radinger, Building BD

# Error Analysis of Spectral Element Methods for the Acoustic Wave Equation in Heterogeneous Media

Saulo P. Oliveira[1] and Stela A. Leite[1]

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We present the error analysis of the spectral element solution of the two-dimensional wave equation in acoustic media with a non-constant velocity field. We consider Dirichlet boundary conditions as well as Engquist-Majda first-order absorbing boundary conditions [1].

The spectral element basis is built from Gauss-Lobatto-Legendre (GLL) collocation points for the domain discretization and the time discretization is based on the explicit Newmark's second order scheme. As usual, GLL points are also employed in the numerical quadrature, so that the mass matrix is diagonal and the resulting algebraic scheme is explicit in time.

The analysis provided an a priori estimate which depends on the time step, the element length, and the degree of polynomial used in quadrature rule. The heterogeneity of the velocity field is essentially treatead as in [2], whereas the analysis of time discretization analysis follows the framework proposed in [3], which was also employed in [4, 5]. Numerical examples illustrate the validity of the estimate under certain regularity assumptions. Further testing provides expected error estimates when the velocity field is discontinuous.

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Monday, 11:25, Lecture Hall **GM2** Radinger, Building BD

# Mixed-Dimensional Modeling of Time-Dependent Wave Problems Using the Nitsche Method

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We propose a method for mixed-dimensional modeling of time-dependent wave problems. A two-dimensional (2D) medium is considered, which includes a part that is assumed to behave in a one-dimensional (1D) fashion. The 2D and 1D regions are separately discretized using 2D and 1D finite element formulations. The coupling of the 2D and 1D regions along their interface is performed weakly, by using the Nitsche Method. The advantage of using the Nitsche method to impose boundary and interface conditions has been demonstrated by several authors, including a previous work demonstrating the viability of this method in the context of mixed-dimensional coupling in elliptic problems; here the viability is shown in the context of hyperbolic problems.

The computational aspects of the method are discussed, and it is compared to the slightly simpler Panasenko method numerically. Numerical experiments are presented for two case studies. The performance is investigated for various extents of the 1D region. It is concluded that the Nitsche method is a viable technique for mixed-dimensional coupling of hyperbolic problems of this type.

Monday, 11:45, Lecture Hall **GM2** Radinger, Building BD

# A modal-based partition of unity finite element method for layered wave propagation problems

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Numerical time-domain simulations of wave motion problems in acoustics and structural dynamics usually involve high computational resources due to the required accuracy in the spatial approximation and due to the stability constrains related to the use of explicit time-marching schemes. This high computational cost is even more relevant in those applications where the spectrum of the acoustic sources is located at middle and high frequency regime and if standard piecewise polynomial finite element methods are combined with explicit schemes, which potentially suffer from large phase leak and pollution phenomena [1]. To overcome these computational drawbacks, a classical alternative methodology consists in the use of a spatially modal representation of the solution, which is able to decouple the time-domain problem and so it allows to write explicitly the solution of the time-domain problem by solving a finite number of uncoupled time-dependent ordinary differential equations. The efficiency of this approach is limited to those problems where the modal basis is explicitly known (for instance, for simple geometries involving homogeneous isotropic materials) but it is computationally prohibited if high-frequency eigenfunctions must be approximated by means of a standard finite element method.

The present work is focused on the combination of those two aspects described above and, in this manner, the proposed method takes advantage simultaneously of the accurate representation of a modal basis known in closed-form and its accurate application (at a reduced computational cost) to problems at middle and high-frequency regimes. More precisely, a partition of unity finite element method (PUFEM) will be used for the spatial discretization [2]. However, instead of using planewaves or radial solutions (involving Bessel or Hankel functions), it will be considered a finite set of closed-form eigenfunctions, which are part of the modal basis of a simplified (but related) wave motion problem. In this manner, even with the use of a coarse mesh to define the PUFEM discrete basis, the numerical approximation of those high-frequency contributions to the solution will be accurately represented by the modal behaviour of the discrete basis. To illustrate the numerical capabilities of the proposed method, the wave propagation of interface waves in a layered material [3] will be considered.

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Monday, 12:05, Lecture Hall **GM2** Radinger, Building BD

# A high-order discontinuous Galerkin method for 1D-3C wave propagation in nonlinear heterogeneous media

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During strong earthquakes, nonlinear behaviour of soils is observed when the strain goes beyond the elasticity limit. In particular, this behaviour results in the shift of amplification peaks towards lower frequencies, the generation of high frequency harmonics and the increase of hysteretic attenuation. These phenomena can have serious impacts on engineering structures at the surface. Therefore, it needs to be better understood and this understanding goes, for instance, through numerical simulations.

Recent advances in computing power has led to the development of modern and efficient numerical methods for modelling seismic wave propagation in complex media. Among them, the discontinuous Galerkin finite element method (DG-FEM) constitutes one of the most interesting methodologies as it merges both the flexibility of finite element methods, the accuracy of high-order methods and the computational efficiency of fully local discretization of the wave equation.

In the context of discontinuous elements, nodes at the mesh interfaces are split on each element and joined by a numerical flux. Previous studies [1] in 2D and 3D show that a centered flux is well suited for the linear and heterogeneous case. But, as soon as the nonlinearity is taken into account, a better adapted flux must be proposed. As a matter of fact, taking into account the nonlinearity yields to several numerical difficulties : as the frequency content of the wave changes through the simulation, it modifies the minimal wavelength and the wave propagation velocity : in other words, the medium properties change during the propagation. We first consider a one dimensional medium and one shear component (1D-1C) and derive a numerical upwind flux inspired from the exact Riemann solver [3]. This flux takes into account the heterogeneity of the medium as well as the evolution of its properties. We exhibit an analytical solution of the 1D-1C wave propagation in a nonlinear homogeneous medium and numerically prove that the expected order of convergence is recovered.

Before including the nonlinearity in a 3D solver, the next essential step is to extend the 1D-1C formulation to 1D-3C (one dimensional medium - three components of motion)[2]. That is to say, we solve the equations of motion in a 1D medium but considering shear and compressional terms. On the numerical point of view, this implies to propose another numerical flux able to take into account the complete set of waves (shear and compressional waves). Throughout this work, we will discuss the effect of the nonlinearity and the accuracy of the method through several numerical applications.

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Monday, 12:25, Lecture Hall **GM2** Radinger, Building BD

# Stable Perfectly Matched Layers for a Class of Metamaterials

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For many physical and engineering applications, it is necessary to model the wave propagation in unbounded dispersive media (metamaterials, plasmas). There exist very few stable techniques adapted to such models, see e.g. [1] for istropic dispersive media. We concentrate on a particular case of 2D anisotropic dispersive models, described in the frequency domain by the wave equation with frequency dependent coefficients

$$\varepsilon_y(\omega)^{-1}\partial_x^2 u + \varepsilon_x(\omega)^{-1}\partial_y^2 u + \omega^2\mu(\omega)u = 0.$$

In electromagnetism, $\varepsilon_x(\omega),\ \varepsilon_y(\omega)$ correspond to the permittivity, and $\mu(\omega)$ is the permeability.

In this work we suggest a method to bound the computational domain based on a Perfectly Matched Layer technique [2]. Classical PMLs exhibit instabilities when applied to the above problem [3]. To deal with this problem, we suggest a modification of the change of variables that defines the PML, in the spirit of [1]. The stability of the method is confirmed by theoretical and numerical arguments, see the illustration in Figure 1. All the presented results can be found in [3].

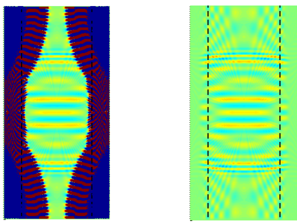

Figure 1: The solution $u$ computed with: left: classical PMLs, right: new, stable PMLs

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Monday, 15:30, Lecture Hall **GM2** Radinger, Building BD

# FEM solution of exterior problems with weakly enforced integral non reflecting boundary conditions

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We consider the scattering of a wave by an obstacle of $\mathbb{R}^2$, having a sufficiently smooth boundary $\Gamma$. In particular, we solve the time-dependent wave equation in the finite computational domain $\Omega$, bounded internally by $\Gamma$ and externally by an artificial boundary $\mathcal{B}$ where we impose an exact Non Reflecting (transparent) Boundary Condition (NRBC) (see [1]).

The NRBC is defined through a space-time Boundary Integral Equation (BIE), which defines a relationship between the solution of the differential problem and its normal derivative on the artificial boundary $\mathcal{B}$. We discretize the BIE on $\mathcal{B}$ by combining a second order (in time) BDF convolution quadrature and a Galerkin (or a collocation) method in space. Such a discretization is then coupled with an unconditionally stable ODE time integrator and a FEM in space.

In previous works, we have tested the robustness of the proposed NRBC discretization, and its higher accuracy with respect to that of the associated FEM. Such properties justify a decoupling of the NRBC grid from that of the FEM. In particular, the discretization of the transparent condition can be constructed on a grid defined on $\mathcal{B}$ which is coarser than the one inherited by the triangulation of $\Omega$. In this context, we propose a non conforming coupling of the FEM-BEM scheme, by using a mortar technique. The method consists in decomposing the FEM-BEM interface into two disjoint sides and in replacing the strong point-wise continuity condition of the traces of the solution on $\mathcal{B}$ by a weak one, by imposing that the jump of the traces is orthogonal to a suitable multiplier space. Such an approach allows to reduce the computational cost of the NRBC and to couple discretizations of different type. We will present numerical results obtained for problems of waves scattered by fixed and rotating obstacles, non trivial data, and sources far away from the computational domain $\Omega$.

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Monday, 15:50, Lecture Hall **GM2** Radinger, Building BD

# Analysis of the cumulant lattice Boltzmann method for acoustics problems

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An alternative way to the classical approachs for simulating fluid dynamics is the lattice Boltzmann method. This method can be used as a compressible Navier-Stokes solve in which the low Mach number is low. Then, sound waves, generally the Mach numbers are very low, even with strong nonlinear effects can be simulated by this method. Recently, the LBM has been significantly improved. The cumulant lattice Boltzmann as the newest method can remove problems related to the previous methods such as BGK and MRT model. This method allow us simulate the flow with high Reynolds number. The lack of studying in the field of acoustic analysis of the lattice Boltzmann method motivate us to research more in this field. The linearization analyses of different collision operators have been carried out in this paper in order to find out the effect of each method on the acoustical results. Energy equation has been coupled with the momentum equation in our analysis in order to understand the effect of heat viscosity in the acoustic analysis. Besides, numerical simulation of lattice Boltzmann method for different collision operators have been done. The fluctuation pressure profile has been shown. This analysis has been implemented in two dimension but the concept can be extended into three dimensions. The analytical solutions have been compared to the numerical results in order to validate our analysis [**?**, **?**].

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Monday, 16:10, Lecture Hall **GM2** Radinger, Building BD

# A Gaussian wave packets approach for transient ultrasonic NDE modeling

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Ultrasonic Non-Destructive Evaluation (NDE) uses high-frequency acoustic and elastic waves to probe components without affecting their integrity. Since the industrial materials and structures are reaching high levels of complexity, the associated ultrasonic NDE technologies and diagnosis methods require up-to-date simulation tools. It means that an end-user solution should encompass a broad range of realistic applications while providing essential results in reasonable time. In the CIVA platform, the propagation of elastic body waves is estimated semi-analytically with a Dynamic Ray Tracing approach (DRT) using paraxial approximation. Although this asymptotic technique greatly reduces the computational cost faced by numerical methods, it may encounter several limitations in reproducing identified highly interferential elastic fields, e.g. caustics, shadows or postcritical incidences. A way to circumvent these so-called singularities inside a ray-based framework consists in the generalization to complex-valued paraxial quantities. We then obtain Gaussian Wave Packets (GWP) in time-domain [1], which are now supposed to be the building blocks of the approximated solution.

In the present work, we introduce a method for modeling transient ultrasonic fields with a limited number of GWP. Inspired by [2], we first obtain a GWP representation of general Cauchy data for the wave equation. The packets are then propagated along the usual rays, and their shape evolution is performed according to the eikonal and the transport equations. We show that a wise choice of the initialization GWP parameter set allow us to control the paraxial error generated over a prescribed propagation time. Simulation results are presented and validated for typical ultrasonic diffracted body wave fields. The presented modeling strategy appears to be well-suited for coupling with existing time-domain numerical methods.

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Monday, 16:30, Lecture Hall **GM2** Radinger, Building BD

# Modeling Longitudinal Wave Propagation in Solids with Slow Dynamics: Application to DAE Experiments

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In dynamic acoustoelasticity (DAE), the speed of sound measured locally decreases in time. This softening occurs over a time scale larger than the period of the dynamic loading, which highlights the phenomenon of *slow dynamics*. Moreover, the evolution of this speed with respect to the strain presents an hysteresis curve. All these phenomena are accentuated when the strain amplitude is increased. An important number of experimental works report such observations, which are characteristic of rocks and concrete [1].

Several models, such as Preisach-Mayergoyz, have been designed to mimic the hysteresis. The soft-ratchet model [2] by Vakhnenko et al. results from a different approach. A variable $g$, interpreted as a concentration of activated defects, is introduced in order to modify the elastic modulus. Also, an evolution equation for $g$ is provided. The soft-ratchet model was developed in one space dimension and does not generalize straightforwardly to higher dimensions.

We propose a new model based on thermodynamics with internal variables. Here too, a variable $g$ is introduced to describe the softening, as well as an evolution equation for $g$. The model satisfies the principles of thermodynamics by construction, which is not the case of the soft-ratchet model. Similarly to [2], viscoelasticity is incorporated to model strong attenuation, which is experimentally observed in geomaterials. The resulting set of equations writes as a hyperbolic system of conservation laws with relaxation terms.

A finite-volume method has been developed to solve numerically this system of equation. Experimental configurations are reproduced by implementing realistic boundary conditions. The numerical model is validated on reference solutions. Then, the DAE experiments are reproduced numerically, and similar observations to real measurements are made. The general 3D case is detailed in a future publication [3], and a 2D numerical code is under development.

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Monday, 16:50, Lecture Hall **GM2** Radinger, Building BD

# Simulation of Sound Radiation based on PIV Measurements

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In some applications of the fluid-structure-acoustic interaction, it is difficult to get the correct solution of the flow field. An example is the correct simulation of the flow through human larynx during human phonation [1]. It still is a challenge to predict the whole coupling process with contact of vocal folds in a hybrid or monolithic simulation approach. Our complementary method allowed to predict the radiated acoustic field from High Speed Particle Image Velocity (HS-PIV) [2] measurements in a synthetic larynx model. The velocity field with a high spatial and temporal resolution was measured in the supraglottal area downstream of aerodynamically driven synthetic vocal folds.

For the acoustic simulation, different formulations of the acoustic source terms based on the HS-PIV measurements were tested and discussed. The acoustic field was predicted using a Finite Element Method (FEM) [3]. Furthermore, the simulated acoustic far field was compared with experimental results and showed a good agreement.

Now, the developed method allows to get a direct connection between the flow induced sound sources and their characteristics in the radiated sound field. Strong aeroacoustic sources were found very close to the glottis area. Considerably smaller contributions were generated from turbulent velocity fluctuation in the random region of the jet flow.

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Monday, 10:45, **GM3** Vortmann Lecture Hall, Building BA

# On The Computaional Performance Of The Hybrid Aeroacoustic Solver Applied To Confined Flows

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Hybrid methods in aeroacoustics are designed to increase the computational performance in solving problems of sound generation and propagation when compared to full Direct Noise Simulations.

In this paper, an in-house hybrid parallel aeroacoustic solver is discussed. The solver consists of two concurrently running programs: a *Noise Generation* part and a *Sound wave propagation* part. The *Noise Generation* part is implemented using a hybrid OpenMP-MPI Stochastic Random Particle Mesh (RPM) method[1, 2] , whereas the *Sound wave propagation* part adopts a parallel MPI Discontinuous Galerkin (DG) method [3]. The programs communicate with each other during runtime to exchange the data.

This paper describes how these two programs interact, and shows the computational performance of the combined RPM and DG solver applied to the sound generation and propagation problem in confined flows.

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Monday, 11:05, **GM3** Vortmann Lecture Hall, Building BA

# Helmholtz-Hodge decomposition of compressible flow data on homologically trivial domains

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An unresolved problem of aeroacoustic, even for direct numerical simulation with a compressible media, is the accurate decomposition of the compressible flow field in a flow associated part and an acoustical part. At low mach numbers the incompressibility condition for the fluid dynamic part holds $\nabla \cdot \mathbf{u}^{\rm ic} = 0$. We assume that the compressible field is an irrotational field $\nabla \times \mathbf{u}^{\rm c} = 0$. These two properties give rise to a Helmholtz-Hodge decompositon of the velocity field. The investigation of homologically trivial domains (domains with holes) is of major importance in fluid dynamics. Realizations of such domains are e.g. components inside a domain, a cylinder or an airfoile in a crossflow.

Based on the compressible flow simulation, we extract a sequence of flow fields $u : \mathbb{R}^n \rightarrow \mathbb{R}^n$. At each realization we apply the Helmholtz-Hodge decomposition. Thus, the compressible flow field is separated in $\mathrm{L}^2$ orthogonal components

$$\mathbf{u} = \mathbf{u}^{\rm ic} + \mathbf{u}^{\rm c} + \mathbf{u}^{\rm h} = \nabla \times \mathbf{A}^{\rm ic} + \nabla \phi^{\rm c} + \mathbf{u}^{\rm h} \ , \qquad (1)$$

where $\mathbf{u}^{\rm ic}$ represents the solenoidal (incompressible) part, $\mathbf{u}^{\rm c}$ the irrotational (compressible) part, and $\mathbf{u}^{\rm h}$ the divergence-free and curl-free part of the velocity field.

In this contribution we investigate the computations of the components and the effect of the calculation procedure on the acoustic wave propagation. Furthermore, a preliminary time filtering method is investigated on the decomposed velocity sequence. Both methods have been implemented in the finite element software CFS++[1] and are applied to a cylinder in a crossflow.

**References**

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Monday, 11:25, **GM3** Vortmann Lecture Hall, Building BA

# Acoustic response of a flat plate due to a turbulent boundary layer excitation

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Flow-induced noise of a flat plate immersed in low Mach number flow is predicted using a hybrid computational fluid dynamics - boundary element method (BEM) technique. Turbulent boundary layer parameters such as convective velocity, boundary layer thickness and wall shear stress are estimated over the surface of the flat plate by solving Reynolds-Averaged Navier-Stokes equations. These parameters are then used along with one of the semi-empirical models in literature to evaluate spectrum of the wall pressure fluctuations. Different realisations of wall pressure field on the surface of the plate are estimated as the result of a combination of uncorrelated wall pressure plane waves. The predicted fluctuating pressure on the surface of the body is directly used as an incident field to a BEM solver to efficiently calculate the scattered acoustic field. The total acoustic response of the plate subject to turbulent boundary layer excitation is obtained from an ensemble average of the responses of the plate due to the realisations of synthesised wall pressure. The computed aeroacoustic results are compared with experimental data from literature.

Monday, 11:45, **GM3** Vortmann Lecture Hall, Building BA

# Noise Sources from Flow over a Forward-Facing Step

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The application of computational aeroacoustic prediction methods has been increasingly used and improved in order to reach the ability for industrial low noise design. Still several numerical and experimental studies show that the complex flow physics and conversion from kinetic energy to acoustic energy even for simply geometries is not fully understood. Of great interest is the identification, quantification of noise sources and the understanding of their physical nature.

This investigation treats the flow over a forward facing step, the derivation of noise sources from unsteady CFD analysis and the description and interpretation of the numerical noise sources through physical source models being in line with the observed flow mechanisms and the directivity patterns of the sources. Wind tunnel data have been collected within the Bavarian funded research project “Flow Noise” for different configurations of a forward facing step [1]. A large eddy simulation is performed with the finite volume code MGLET [2]. The incompressible Navier-Stokes-Equations are solved on a non-equidistant staggered grid and uses second order central approximations.

The acoustic sources are propagated through a high order finite-difference solver in time domain. For the spatial reconstruction a DRP [3] scheme is used together with a fourth order Runge-Kutta scheme. The propagation of acoustic waves is treated by the linearized Euler equations [4] and compared with a Ffowcs-Williams-Hawkings approach based on Lighthill’s acoustic analogy. Comparisons are made between the different numerical CAA methods and the microphone measurements in the far field above the step.

Different noise source mechanisms are considered either intrinsically to the assumptions of the used methods (“surface dipoles”) but also based on the observation of noise directivity patterns which indicate that also coherent noise sources significantly contribute to the overall sound pressure level generated from the flow over the step [5]. The origin of these coherent sources is linked to the characteristics of the flow field.

**References**

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[3] C. Tam, J. Webb. ‘Dispersion-relation-preserving finite difference schemes for computational acoustics’ J. Comput. Phys., 107:pp262–281, 1993.

[4] R. Ewert. ‘A Hybrid Computational Aeroacoustics Method to Simulate Airframe Noise’, PhD thesis 2002

[5] A. Kolb. ‘Noise prediction using hybrid aeroacoustic methods for generic test case’, PhD thesis 2015

Monday, 12:05, **GM3** Vortmann Lecture Hall, Building BA

# Direct aeroacoustic simulation of whistling noise at a side mirror using a high order discontinuous Galerkin method

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## Introduction

Beside the engine and tires, sound generated by the flow around the car is among the most important acoustic noise sources in automotive development. Besides the overall noise reduction, one of the key objectives in aeroacoustic optimization is the prevention of tonal noise, which is perceived as most annoying by the observer. In order to increase the understanding of tonal noise generation processes, we performed high fidelity, large-scale hydrodynamic and acoustic computations of the flow around an early-development-stage, realistic side-view mirror.

## Numerical method

A direct prediction of the flow-induced sound through numerical solution of the compressible Navier-Stokes equations is proposed. Our results indicate that this direct acoustic approach is crucial in this application, since the fundamental acoustic source mechanism is driven by feedback from the acoustic field to hydrodynamic disturbances. Due to the large range of spatial, temporal and energetic scales occurring in the acoustic field as well as in the transitional and turbulent flow, the direct approach demands high numerical accuracy, while maintaining a certain robustness required for large eddy simulations (LES). We employ a high order discontinuous Galerkin spectral element method, which exhibits arbitrary high order accuracy as well as excellent scaling for massively parallel simulations. It is augmented with an extension to non-conforming interfaces on curved elements. We rely on a no-model LES approach, which is suitable for low to medium Reynolds number flows. Cell-local polynomial cut-off filters are employed to avoid aliasing. This treatment intrinsically accounts for the partially laminar and transitional nature of the problem, where typical subgrid-scale modeling approaches may spoil the solution through subgrid-scale viscosity in essentially laminar regions.

## Results

First, we discuss the computational analysis of a side mirror exhibiting tonal noise generation. The computational flow field is shown to agree remarkably well with the corresponding experimental one. Discrete peaks are obtained in the computational acoustic spectrum, originating at the trailing edge of the mirror downstream of laminar separation. Based on a perturbation analysis, the tonal noise is deduced to be caused by an acoustic feedback loop. The feedback loop comprises convective disturbance growth in a separated shear layer, scattering at the trailing edge and reinforcement through receptivity to the emitted sound in the upstream boundary layer. In a second step, this mechanism is studied in more detail based on a specifically designed simplified two-dimensional mirror model.

Monday, 12:25, **GM3** Vortmann Lecture Hall, Building BA

# Finite Element Simulations of Flow Induced Sound from Blowers

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State of the art in the prediction of the flow-induced sound emission of rotating systems is the Ffowcs Williams Hawkings method. The disadvantage of this method in the application to blowers is, however, that only the rotation of the impeller can be included in the calculation, but not reflections of the sound from the housing and the rotor blades. This paper introduces a Finite Element method that correctly maps both the sound sources rotating with the impeller and the reflections of the sound from the rigid surfaces of the components of the blower.

For the prediction of flow-induced sound a hybrid approach is employed using separate CFD and acoustic simulations. The aeroacoustic sound sources are extracted from a CFD simulation. Subsequently, the inhomogeneous wave equation loaded with the pre-computed sound sources is solved using the Finite Element Method. In order to compute the sound propagation in the rotating and stationary reference systems simultaneously, a domain decomposition is performed on the numerical model. The rotation of the impeller is introduced through a moving mesh, where the blades act as rigid surfaces. The mesh motion in the impeller is accounted for by the Arbitrary-Lagrangian-Eulerian method (ALE). For the exchange of sound waves between the non-conforming meshes of the two disjunct regions two different approaches are used, namely the so-called Mortar and Nitsche methods. In contrast to previously known Mortar methods, the method used in this work has been specially adapted to achieve a stable solution despite the mesh motion. The developed method is then applied to a ducted axial fan and a radial blower in order to identify the flow sound sources. The predicted sound pressure level is found to be in good accordance with measurements.

Monday, 15:30, **GM3** Vortmann Lecture Hall, Building BA

# Aeroacoustic Simulation of Complex HVAC Components

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[*]until 2016

The simulation of noise excited by turbulent flows is a challenging task. This applies especially to the field of complex heating, ventilation and air condition (HVAC) components. In this context, we compare two different aeroacoustic analogies with respect to usability, implementation complexity and accuracy in a hybrid simulation environment. At first, a large eddy simulation (LES) is carried out using the finite volume solver Star-CCM+. The assumption of incompressible flow is used in order to reduce the computational cost. Thereby, no acoustic information is contained in the flow solution. In the second step, the aeroacoustic sources are computed on the flow mesh. After their conservative interpolation onto a finite element mesh, the sound propagation is evaluated by solving an inhomogeneous wave equation for the pressure $p'$ or the potential $\psi$ using the solver CFS++. By applying this approach to the HVAC unit of a car, we compare the simplified analogy of Lighthill (1)[1] and the perturbed convective wave equation (PCWE) (2)[2] in relation to experimental results.

$$p'_{tt}/c^2 - \Delta p' = \nabla \cdot \left(\nabla \cdot \rho_0 u^{ic,T} u^{ic}\right); \; p' = p^{ic} + p^a \tag{1}$$

$$D\psi/c^2 - \Delta\psi = -Dp^{ic}; \; p^a = \rho_0 D\psi; \; D\square = \square_{tt} + \overline{u} \cdot \nabla\square \tag{2}$$

In contrast to Lighthill's analogy, the PCWE provides a separation of flow pressure $p^{ic}$ and acoustic pressure $p^a$ even in the acoustic source region. Furthermore, the PCWE incorporates the influence of the mean flow field $\overline{u}$ on the acoustic field. Its drawback is the usage of the incompressible flow pressure $p^{ic}$ of the flow simulation, which suffers from stronger numerical noise than the velocity $u^{ic}$. Due to this, the PCWE is more sensitive to the spatial selection of the source region. The major drawback of Lighthill's analogy is its challenging source computation. The boundary condition $u = 0$ requires a special treatment at complex geometry walls. Nevertheless, we can achieve good agreement between simulation and experiment results for both analogies. This enable us to perform reliable aeroacoustic simulations based on common finite volume flow solutions of complex HVAC components.

**References**

[1] M. Lighthill, *On sound generated aerodynamically. I. General theory*, Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences **211** (1952), 564–587.

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# Determination of Acoustic Scattering Matrices from Linearized Compressible Flow Equations

Max Meindl[1], Malte Merk[1], Fabian Fritz[1], Wolfgang Polifke[1]

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In ducted flows the generation, transmission and reflection of acoustic waves at *duct singularities* – orifices, valves, fans, swirl generators, T-junctions, etc. – is important for the generation and propagation of noise as well as the self-excited aero-acoustic instabilites. The coefficients of the *acoustic scattering matrix* describe transmission and reflection of plane waves and depend in a non-trivial manner on acoustic frequency and mean flow features, in particular the Mach number, such that in general they cannot be determined analytically even for simple geometries. The assessment of scattering matrices by use of nonlinear CFD time-domain simulations is computationally expensive and may require system identification and filtering methods in order to elicit the acoustic signals from the CFD data, in particular for turbulent flows. It has been proposed to determine the acoustic properties of duct singularities by hybrid methods [2, 4, 3] based on mean flow fields computed with Large-Eddy Simulations (LES) and linearized compressible flow equations, e.g. the linearized Euler or Navier-Stokes equations (LEE and LNSE). This is also the objective of the present study, which employs the discontinuous Galerkin method for Finite Elements, which is known to yield high accuracy for the dispersion relation of acoustic waves [1]. By choosing an appropriate, upwind-like flux formulation between elements, stability of the numerical scheme can be achieved. Thereby the influence of mean-flow velocities, i.e. modulation of the acoustic propagation speed and transport of convective waves, can be modeled accurately. The mean-flow effects contribute to – even dominate – acoustic damping and thus influence the acoustic scattering. Interaction between acoustic waves and turbulent fluctuations is modeled by accounting for the increased turbulent viscosity in the LNSE [3]. By Fourier transformation of the linearized equations, the coefficient of the scattering matrix can be computed in a direct manner for a given frequency band by an inexpensive matrix inversion. This yields large savings in computational cost compared to the approach when employing an acoustically forced LES. A comparative study of the scattering behavior of a swirl generator is carried out. We quantify the influence of turbulent and molecular viscosity, mean-flow velocity, wall boundary conditions and resolution of the Stokes boundary layer on the transmission and reflection coefficients. To this end, simplified governing equations, in particular the linearized Euler and the Helmholtz equation are employed. The scattering behavior identified from a forced LES time series by means of system identification serves as a benchmark for the results of the hybrid approach.

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Monday, 16:10, **GM3** Vortmann Lecture Hall, Building BA

# A Prototypical Example for Damping and Dissipation

Adnan Akay

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Damping generally refers to loss of kinetic energy of mechanical oscillations or waves and is often measured as a reduction of amplitude at the observation points. Energy “lost” may be dissipated or it may be transported to other spatial or frequency domains before it is eventually dissipated. Dissipation describes the mechanism by which work on a medium is irreversibly converted to heat by increasing the energy of thermalized motion of the atoms in the medium. During dissipation energy is transferred from few to many degrees of freedom and from larger length and time scales to atomic scales. The relation between damping and dissipation can be illustrated by the damped motion of a massless piston sliding without friction in an adiabatic cylinder [viz., 1]. The results have shown existence of two time scales for the damped motion of the piston. One is associated with the relaxation of piston to mechanical equilibrium. Because the piston is adiabatic, thermal equilibrium is reached over a longer time scale at the end of which the piston still oscillates around its equilibrium position as a Brownian particle in accordance with the fluctuation-dissipation theorem.  In this presentation, the evolution of piston motion will be reviewed and the relationship between damping and dissipation will be illustrated.

**References**

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Monday, 10:45, Lecture Hall **GM4** Knoller, Building BD

# Nonlinear damping in piezoelectric vibrational energy harvesters excited by Brownian and Lévy stable stochastic processes

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Vibration energy harvesting (VEH) seeks to convert the kinetic energy of ambient, random vibration for autonomous electrical power generation. A promising pathway in our quest for novel, sustainable energy sources, VEH is currently a topic of extensive research. Energy conversion is often achieved in VEH using piezoelectric transducers. From an analytical standpoint, a piezoelectric harvester is an electromechanical system, the dynamics of which is represented by a system of coupled stochastic differential equations that account for the time evolution of the mechanical and electrical degrees of freedom as well as the coupling between them.

Despite the significant body of literature available, a fundamental understanding of dissipation in VEH is yet to be developed and this motivates the present effort. The overarching question addressed here is the role of nonlinear damping, represented by a 'van der Pol term', in piezoelectric VEH. In particular, the potential advantages, in terms of harvesting efficiency, of VEH design where the mechanical degree of freedom is a relaxation oscillator with nonlinear stiffness and nonlinear damping is of interest. In this context, several aspects turn out to be important. First, modeling and analysis of VEH is often focused on equilibrium states while it does not appear to be entirely clear what precisely one means by an equilibrium state in VEH. The results reported in this work will provide a better rationale for studying the non-equilibrium regime. Secondly, the interaction between nonlinearity and noise is well known to engender interesting phenomena such as stochastic resonance and the results will elucidate aspects of this interaction. Thirdly, stochastic forcing (representing the ambient vibration) is typically modeled in VEH using Brownian (diffusive) processes. However, due to the characteristics of a large class of ambient vibrations, superdiffusive stochastic processes drawn from Lévy stable distributions are likely to serve as better models. In addition, since Lévy flights are characterized by occasional large deviations from the mean, they are expected to yield higher expectation values of power output. This work will investigate both the aforementioned aspects.

The outline of the paper is as follows. The stochastic differential equations (SDE) that model the VEH system will be first introduced. Results of extensive numerical simulations based on the Euler-Maruyama scheme that seek to resolve the questions raised in the paragraph above will be presented. In addition, the Fokker-Planck equation corresponding to the SDE system will be derived and a comparison of the results between the direct numerical simulation and the Fokker-Planck approach will be discussed. In summary, the results are expected to illuminate broadly the role of nonlinear damping in piezoelectric VEH and, in particular, illustrate the potential advantages of nonlinear damping by design for enhanced harvesting efficiency. In addition, the results are expected to clarify the need to focus on the non-equlibrium dynamics of piezoelectric harvesters as well as the role of stochastic excitations drawn from Lévy stable distributions.

Monday, 11:15, Lecture Hall **GM4** Knoller, Building BD

# Numerical Analysis of a Piezoelectrically Modulated Oscillator Array

Joseph Vignola[1], John Sterling[1], Aldo Glean[2], Teresa Ryan[3], John Judge[1], Diego Turo[1]

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This work describes a numerical study of the capacity of an array of piezoelectric elements individually coupled to a primary system to alter the system response. The piezoelectric elements under consideration are designed to have mechanical resonances that, when considered in isolation from the rest of the system, are closely spaced surrounding a resonance of the primary system. This configuration will allow the rapid exchange of mechanical energy between attached elements and the primary system. Earlier work has shown that small changes in the mechanical stiffness of the subordinate elements can dramatically alter the response of the impulse response of the primary system. Here MATLAB based optimizations are used to select capacitive shunts for the mechanically coupled piezoelectric elements. Examples include an adaptive approach to add prescribed amounts of damping to a lightly damped system simply by changing the distribution of capacitance values used. Additionally, experimental and computational results for an acoustic band-rejection filter will be shown. The concept was tested experimentally on a one-dimensional, open-ended standing wave tube. This filter has been designed to suppress the third acoustic mode without affecting other parts of the system response. We show that system disorder, such as those from small fabrication errors, has a profound effect on predicted performance of such systems. We propose a compensation scheme to mitigate the effect of such disorder.

Monday, 11:45, Lecture Hall **GM4** Knoller, Building BD

# Behavior of Sound Waves at the Vapor-liquid Interface Accompanied with Evaporation and Condensation

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Evaporation and condensation at the vapor-liquid interface are fundamental phenomena that are often observed in nature and in engineering. However, since the evaporation and condensation are induced by the nonequilibrium behavior of vapor molecules adjacent to the interface, one cannot quantify them by fluid dynamics and thermodynamics, which are relying upon the assumption of local equilibrium. These difficulties can be resolved by solving the boundary value problem of the Boltzmann equation with the kinetic boundary condition containing two unknown parameters, called the evaporation coefficient and condensation coefficient [1]. These coefficients are defined by the molecular mass fluxes at the interface and should be equal to each other under equilibrium conditions. In this study, we aim to propose a new method for determining the evaporation coefficient using a sound resonance experiment and linear acoustic theory based on molecular gas dynamics [2]. The use of sound waves enables us to conduct experiments in a weak nonequilibrium state, where one can regard both the unknown parameters as a single parameter, i.e., the evaporation coefficient.

The kinetic boundary condition specifies the functional form of the velocity distribution function for vapor molecules leaving the interface. However, it is difficult to measure the velocities of molecules directly. Thus, instead of the kinetic boundary condition, we use the fluid-dynamic-type boundary conditions obtained from the asymptotic theory of the Boltzmann equation for the case when $\mathrm{Kn} \ll 1$ (Kn is the Knudsen number) [2]. Using the fluid-dynamic-type boundary conditions and conservation law at the interface, the linear theoretical solution including the effect of evaporation and condensation can be derived. From the linear theoretical solution, it is clarified that the effect of the evaporation coefficient can be measured only under sound resonance conditions. We measure the pressure amplitude of a resonant sound wave in a cylindrical space bounded by a sound source and a vapor-liquid interface in a newly devised sound resonance experimental system. As a result, we can formulate the linear theoretical solution, including the effect of the evaporation coefficient on the amplitude variation, thereby driving the relation between the evaporation coefficient and sound pressure.

## Reference

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Monday, 12:15, Lecture Hall **GM4** Knoller, Building BD

# Band Gap and Dispersion Characteristics of Structures with Viscoelastically Damped Resonant Periodic Inserts

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The band gap and dispersion characteristics of viscoelastically damped structures which are provided with periodic locally resonant (*LR*) inserts are determined using the concept of Bloch wave propagation. In this approach, the dispersion curves of damped periodic structures are extracted by employing the Golla-Hughes-McTavish (*GHM*) formulation of the viscoelastic dynamics resulting in real wavenumbers and complex frequencies. In this manner, the obtained characteristics directly relate to wave propagation behavior that admits the computation of the attenuation parameters due to energy dissipation.

Note that using the *GHM* formulation enables readily the integration of the dynamics of the viscoelastic damping with the structural dynamics in such a way which is compatible with the classical finite element approach. Accordingly, the dynamics of the structure with periodic *LR* inserts can be computed both in the time and frequency domains.

The developed methodology is applied to drillstrings which are fitted with viscoelastically damped *LR* inserts in an attempt to mitigate coupled axial and torsional vibrations encountered during stick-slip interaction with the rock formation. Comparisons with the performance of conventional drillstrings with uniform shafts demonstrate the effectiveness of the periodic *LR* inserts in blocking undesirable vibrations [1-2].

**References**

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Monday, 15:30, Lecture Hall **GM4** Knoller, Building BD

# Radiative Decay and Relaxation Processes in Vibrational and Acoustical Energy Dissipation

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The processes by which organized vibrational or acoustical energy are lost during vibration and sound propagation are imperfectly understood. In some cases, the loss can be satisfactorily explained in classical terms with the incorporation of viscosity and thermal conduction in the governing equations. In most lumped parameter formulations of vibrational energy dissipation, one simply postulates dissipative forces that are proportional to the generalized velocities, although this is rarely fully justified in terms of fundamental physics. Present paper considers two non-classical mechanisms for energy loss. The first is that of energy loss by electromagnetic radiation to the outside environment, and the second is that of relaxation processes.

For the first of these mechanisms, a solid of finite size is considered and it is regarded at first as a molecular structure with a very large number of atomic nuclei. When the solid is in a natural mode of vibration, the state is analogous to that of a single harmonic oscillator with discrete quantized energy levels, although the levels are very close to each other. Any given level will decay to a lower level with the emission of a quantum of electromagnetic energy. The process cascades and the energy decays with a characteristic relaxation time. A rudimentary theory is described that leads to an explicit approximate expression for the relaxation time that is proportional to the cube of the speed of light, but (surprisingly) independent of Planck's constant. Procedures for the numerical computation of this relaxation time for realistic examples are described. Because of the strong dependence on the speed of light, this is very weak mechanism for the decay of vibrational and acoustical energy, but one which is nevertheless always present.

The standard prototype of a relaxation process is that where, in local regions, there are two states, each associated with different energies. The probability of the system being in either of these states can depend on pressure (or stress) or temperature. When vibrational fluctuations occur, the population distribution among the states becomes temporarily not in equilibrium, and internal mechanisms cause the distribution to tend toward equilibrium. But when the external causes undergo a (cyclic) change, the tendency is changed. With any given relaxation process, there is associated a relaxation time, which gives the characteristic time for the local system to decay from the higher energy state to the lower energy state, possibly with the aid of external mechanisms. Given the energy difference and the relaxation time, one can work out the vibrational or acoustical energy dissipation rate as a function of frequency.

While relaxation process are believed to be ubiquitous, there are several challenges involved in their explicit incorporation in theoretical and computational formulations of vibrations and acoustics. One is, of course, the identification of the basic physical nature of the dominant relaxation processes, another is the determination of the energy gap between the two characteristic states, and the third is the determination of the relaxation times. The third of these is the most difficult, but not necessarily intractable. The challenges are exacerbated, however, in that there is often a continuous distribution of relaxation processes that can statistically occur in a given medium or structure.

Various examples are discussed and techniques are described for finding the parameters of relaxation processes.

Monday, 16:00, Lecture Hall **GM4** Knoller, Building BD

# Nonlinear dissipation in the classical dynamics of a nanomechanical resonator coupled to a single electron transistor

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Nanoelectromechanical systems (NEMS) may be understood as coupled dynamical systems that operate in the mesoscale wherein the mechanical degrees of freedom - which may be adequately described in terms of classical mechanics - are coupled to the electrical degrees of freedom which follow quantum dynamics. NEMS have attracted much attention over the last couple of decades owing to the paradigm shift they have ushered into sensing technologies via quantum-enabled sensing, their contributions to a better understanding of fundamental physics as well as their promise in areas such as quantum information science and its applications.

A typical realization of NEMS used for displacement detection involves a mechanical resonator with dimensions of the order of 1 $\mu$ m coupled to a charge transport device such as a single-electron transistor (SET). The electromechanical coupling results in interesting dynamics, a key feature of which is the back-action of the SET on the resonator. Essentially, the effect means that the SET acts like a thermal bath for the motion of the resonator thereby providing the mechanism for dissipation of the resonator's energy. The importance of understanding dissipation in the resonator-SET dynamics is underscored by the fact that, under the assumption that the fluctuation-dissipation theorem holds, the state of the SET may be characterized by the bath temperature and driving this temperature down is critical in sensing applications. While studies of the SET- resonator interaction are typically predicated on the key assumptions of linear damping of the resonator motion and Brownian dynamics, certain remarkable experimental results recently reported in the literature indicate the need to revisit those assumptions and hence motivate the present effort.

The outline of the presentation is as follows. The analytical framework for studying nonlinear dissipation in the coupled SET-resonator dynamics will be presented first. Both a Master equation based approach as well as the Fokker-Planck formalism will be discussed in this context. Using a combination of analytical and numerical techniques, the effects of nonlinear damping of the resonator motion will be studied. The implications from the standpoint of the fluctuation-dissipation theorem will be discussed. Finally, the implications of relaxing the assumption of Brownian dynamics will also be discussed.

Monday, 16:30, Lecture Hall **GM4** Knoller, Building BD

# Seismic Modulus Response of Asphalt Pavement in Accelerated Loading Tests with Rayleigh Wave

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Based on the Ultrasonic surface wave (USW) method, the Non-destructive measurement with PSPA (portable seismic property analyzer) can inverse the modulus of structure layers through measuring the propagation velocity of Rayleigh wave and materials' Poisson's ratios [1].

PSPA consists a source and two receivers in this research. Through the process of sending and receiving the Rayleigh wave with a frequency of 5,000-20,000Hz, the average seismic modulus $M$ of asphalt pavement under the receivers can be calculated according to the equation as follows:

$$M = 2\rho(1+\upsilon)\left[(1.13-0.16\upsilon)V_{ph}\right]^2 = 2\rho(1+\upsilon)\left[(1.13-0.16\upsilon)\frac{360^\circ Xf}{\beta}\right]^2 \quad (1)$$

Where $\rho$, $\upsilon$, $V_{ph}$, $X$, $f$ and $\beta$ are the corresponding parameters.

The mechanical properties of asphalt pavement qualitatively regarded as a layered half space system, will change along with the traffic loads and temperature in the actual service process. Asphalt materials possess typical viscoelasticity, of which the modulus is an important indicator for its mechanical characterization.

The authors collected seismic modulus data from three accelerated loading tests with MLS66 (mobile load simulator 66) on new highways and two indoor loading tests with MMLS3 (1/3 model mobile load simulator), and analyzed the seismic modulus along with the loading. Conclusions are drawn as follows: (1) Due to the fast attenuation of Rayleigh wave in the pavement surface, the weakness effect of residual energy from boundary reflected wave and the signal recognizing ability of PSPA, the results are hardly influenced by the materials beyond the far receiver [2]. (2) With the preloading, the seismic modulus showed an increasing trend, and then decreased along the loading because of the mechanical property degradation of asphalt materials. (3) Seismic modulus are influenced greatly by the loading applications and temperature, and the regression relationship along them can be regressed [3]. (4) Further research about the relationship among seismic modulus, temperature, material and structure properties (such as graduation, void ratio and depth) and so on are needed.

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Monday, 17:00, Lecture Hall **GM4** Knoller, Building BD

# Propagation of infrasonic impulsive signals in the Earth's atmosphere

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The direct computation of infrasonic impulsive signals in the Earth's atmosphere is investigated, with the aim of providing a comprehensive view of the physics including sound propagation in a windy heterogeneous atmosphere, nonlinear effects induced by large relative amplitudes in the upper atmosphere, molecular absorption and caustics [1]. The full 3-D compressible Navier-Stokes equations are solved thanks to high fidelity numerical algorithms developed in aeroacoustics over the last two decades, characterized by a high spectral accuracy and a low selective dissipation. The assessment of the numerical accuracy has already been demonstrated in various two-dimensional studies [2, 3]. In particular, the numerical dissipation has been examined by considering the spectral transfer function of the algorithm involving a shock-capturing scheme. In the present work, full 3-D numerical results of the Misty picture experiment are reported [4]. The various phases in terms of waveforms and arrival times propagating through the different atmospheric layers, which are not all well predicted with propagation models, are explained. A direct comparison of quantitative aspects to actual ground-recorded signals remains however tricky for stratospheric phases affected by atmospheric uncertainties.

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Wednesday, 13:45, Seminar Room BD **02A**, Building BD

# Comparison of Different Approaches for Calculation of Sound Radiation from an Open Pipe with a Flow

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In this work, we compare several possible approaches for solving the problem of sound radiation from an open pipe with a hot mean flow. The study is limited to a straight unflanged semi-infinite circular pipe with a thin rigid wall and a straight cut at one end. The mean flow velocity has a low Mach number value and the incident sound wave inside the pipe is plane. Numerical solutions of the following equations are considered: a form of a convective wave equation for non-uniform flows, Acoustic Perturbation Equations APE-4 [1], and linearized Euler equations in the conservative form. Steady mean flow profiles are estimated using Reynolds-averaged Navier-Stokes equations. The results are compared with the analytical solution for a simple uniform mean flow [2], as well as the experimental data.

The comparisons are made according to the estimated far-field radiation patterns. Due to the critical effect of the sound-induced vortices at the trailing edge of the pipe, sufficiently accurate solution of the far acoustic field can be achieved only by using the computationally most involved set of linearized Euler equations. The derived results and conclusions are relevant for many practical problems involving radiation of sound from an open pipe with a sharp trailing edge, such as intake, exhaust, and HVAC systems in vehicles and pass-by noise.

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Wednesday, 14:05, Seminar Room BD **02A**, Building BD

# Dissipation of infrasound and acoustic-gravity waves in inhomogeneous, moving fluids

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Wave energy dissipation through irreversible thermodynamic processes is a major factor influencing atmospheric propagation of infrasound and acoustic-gravity waves. Accurate modeling of the wave dissipation is important in a wide range of problems from understanding the momentum and energy transport by waves into the upper atmosphere to predicting long-range propagation of infrasound to the acoustic remote sensing of mesospheric and thermospheric winds. Variations with height of the wind velocity as well as mass density, kinematic viscosity, and other physical parameters of the atmosphere have a profound effect on the wave dissipation and its frequency dependence. Recently, an asymptotic theory [1] has been developed, which quantifies the dissipation of acoustic-gravity waves in the ray approximation theory without resorting to traditional but unrealistic assumptions regarding spatial variation of the kinematic viscosity and thermal conductivity in the atmosphere. The theory assumes that air temperature and wind velocity vary gradually with position.

Wave amplitude increases significantly in the vicinity of turning points of quasi-plane waves and, more generally, in the vicinity of caustics, where the ray theory does not apply. Dissipation of acoustic-gravity waves in the middle and upper atmosphere is expected to be at maximum in the vicinity of their turning points. Here, we extend the asymptotic theory of the atmospheric wave dissipation to include caustics in moving fluids. Interplay between diffraction effects and dissipation in caustics' vicinity is discussed, and the contribution of this region into the overall dissipation of acoustic-gravity waves and infrasound is quantified. Wind-induced anisotropy of wave dissipation is found to strongly affect infrasound and acoustic-gravity wave propagation.

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Wednesday, 14:25, Seminar Room BD **02A**, Building BD

# Numerical Simulation of the effect of cement defects on flexural wave logging

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Oil and gas industry experiences challenging and there is a particular need for better monitoring for well integrity for increased oil recovery and for avoiding serious environmental consequences. Cementing is an integral part of well construction. Cement provides the seal, protection and support for the casing to maintain the strong barriers that isolate the well. To achieve effective isolation, cement needs to fill the area around the pipe and produce a channel-free section over a length of the cement column suitable to isolate zones and prevent leakage into or out of a hydrocarbon productive zone. Quality of cement seal needs to be monitored and evaluated. To ensure that a proper cement annulus has been placed, ultrasonic logging tools are used to inspect the cement-to-casing bond and to detect channels where fluids can flow within the annulus and defects inside the cement annulus.

The combination of ultrasonic leaky Lamb-wave technique and Pitch-Catch technique is a promising approach for cement bond evaluation [1, 2, 3]. The ultrasonic leaky Lamb-wave is also called flexural wave. The flexural wave attenuation can be calculated from the amplitudes of the first wave packet of two adjacent receivers. Based on the measured flexural wave attenuation and acoustic impedance, the solid, liquid, gas (SLG) state of material behind casing can be estimated. This interpretation method is based on the assumption that the medium behind casing is homogeneous. What happens if the medium behind casing is inhomogeneous, for example, there is a defect filled with water in the cement. This always happens in real situation. In this paper, we establish a 2D Finite Different (FD) model to numerically study the effects of defects (filled with water) in cement annulus on flexural wave attenuation. Different scenarios are simulated and the influence of the defect's size and location inside the cement on the flexural wave attenuation is studied. The simulation results can be helpful for understanding and interpretation of logging data.

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Wednesday, 14:45, Seminar Room BD **02A**, Building BD

# 3D-Soundfield-Simulations for Ultrasonic Flowmeters

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In the development of ultrasonic flowmeters, finite element methods have been successfully used for years, both for the calculation of the running times of sound waves in the fluid as well as in the design of the piezoelectric transducers. Up to now, however, simulations have been restricted mostly to 2D applications. Efficient simulations of the general 3D case have not been available due to the following 2 reasons: firstly, very large models will result due to the large dimensions of the flowmeters compared to the wavelength of the sound waves in the fluid, and, secondly, computer resources were not available with regard to required memory.

Due to the developments of computer hardware in recent years, the computability of such tasks has become possible nowadays. However, as usually several 10 million up to 100 million elements and more are required, it still presents a challenging task for mesh generators, solvers, and postprocessors. Since all simulations are carried out in the time domain and long propagation distances, with respect to the wavelength, have to be considered, a high number of time steps is required in the solution. For practical suitability of these simulations, a minimization of the numerical dispersion must also be considered.

In this talk, the entire process for a 3D-simulation of ultrasonic flowmeters is presented. First, the use of the mesh generator Trelis for the generation of large, conform meshes is presented. For the actual sound field simulation in the flowmeter, the effects of the moving media have to be taken into account. For this type of problems, the FE software NACS, which has been used in the simulations, offers a formulation based on the Pierce equation for the acoustic velocity potential. In view of the large amount of data generated, a reduction in the output data is indispensable for efficient visualization of the sound field propagation; appropriate measures and tools for this purpose are also presented.

Wednesday, 15:05, Seminar Room BD **02A**, Building BD

# Solving Galbrun's Equation with a Discontinuous Galerkin Approach

Marcus Guettler[1] and Steffen Marburg[1]

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In the field of aeroacoustics, Galbrun's equation is still an unknown but attractive formulation. The method utilizes a mixed Eulerian-Lagrangian frame. This way, the number of degrees of freedom can significantly be reduced. Therefore, Galbrun's equation is an alternative to the already established theories such as the linearized Euler equations (LEE), the linearized Navier-Stokes equations (LNSE) and the acoustic perturbation equations (APE). Besides the mentioned advantages, the method suffers from numerical instabilities called spurious modes when solved in the frame of a finite element discretization using a continuous Galerkin approach.

In this work, the authors investigate the solution's behavior when utilizing a discontinuous Galerkin approach in the frame of the finite element method while a mixed displacement-pressure formulation and a pure displacement based formulation are considered.

Wednesday, 15:25, Seminar Room BD **02A**, Building BD

# Investigation of the Acoustic Flame Response in Turbulent Combustion

Konrad Pausch[1], Sohel Herff[1], Stephan Schlimpert[2], Wolfgang Schröder[1]

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Combustion instabilities limit the operating conditions of low-emission lean premixed combustion systems. To predict their onset a description of the unsteady heat release, which drives the thermoacoustic instability, and the acoustic flame response is necessary. This study focuses on the analysis of fully coupled two-way interactions between a turbulent flow field and a premixed flame by solving the conservation equations of a compressible fluid, where the acoustic sound emission is investigated by the acoustic perturbation equations (APE). Results of a turbulent cylindrical jet flame, which is stabilized by a slot flow, will be presented and compared to findings of a turbulent rectangular slot jet flame studied by Schlimpert et al. [1, 2, 3] to investigate the influence of the geometry on the hydrodynamic instability, shear layer effects, and the acoustic flame response. First results with respect to the total heat release response indicate that unlike in the analysis of the rectangular slot jet two typical regimes instead of three can be identified for the round jet flame, which is consistent with the experimental results of Rajaram et al. [4]. This underlines the explanation of previous findings of a rectangular slot jet flame [1], where three typical total heat release regimes were determined due to the additional energy fed into the system induced by the rectangular slot exit. The acoustic flame response determined by the transfer function $F_{pq} = [p'/\bar{p}]^2/[q'/\bar{q}]^2(St)$, however, shows two characteristic regions independently of the burner geometry, i.e., a low frequency trend of $\alpha St^2$ and a plateau region $\beta St^0$. A study on the thermoacoustic source terms of the different configurations is conducted to provide further insight into the sound generation mechanisms of the flames.

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Wednesday, 15:45, Seminar Room BD **02A**, Building BD

# Modern Mathematical Methods for Signal Processing in Audio and Acoustics

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Signal processing is a key technology that forms the backbone of important developments like MP3, digital television, mobile communications, and wireless networking and is thus of exceptional relevance to economy and society in general. The main goal of this talk is to give an overview over modern mathematical methods for signal processing in audio and acoustics. In particular, we will address frame theory, time-frequency analysis, as well as compressive sensing and sparsity, illustrating the benefits of the tools developed in these research areas for acoustic applications.

The mathematical concept of frames [1] establishes a theoretical background for signal processing. Since frames are generalizations of orthonormal bases they can give more freedom for the analysis and modification of information and are thus of utmost importance for accurate models of real-world phenomena (cf. quantum mechanics, acoustics …). Moreover, frame theory has been shown to constitute a mathematical basis for time-frequency analysis.

Compressive sensing has been one of the major developments in applied mathematics in the past 15 years [2–4]. The key to its success is that it allows one to exploit signal structure, such as sparsity, to circumvent the traditional barriers of sampling theory (e.g., the Nyquist rate) [2–5]. In addition, efficient algorithms, based, e.g., on convex optimization techniques allow the practical realization of this theory. Since many real-world signals can be well approximated by an expansion with respect to a suitable basis or frame that has only a small number of non-vanishing terms (sparse representation) it has proven a strong potential for many applications including audio and acoustics.

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Wednesday, 10:15, **GM3** Vortmann Lecture Hall, Building BA

# The Inverse Short-Time Fourier Transform (ISTFT) and its applications

Jont B. Allen[1]

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The Short-time Fourier transform (STFT) was introduced by Gabor, with intended applications to image processing. Between 1970 and 1990 the speech community adopted the method, and refined it in several ways (Rabiner and Schafer, Speech processing). First Gabor's truncated Gaussian window was replace by optimal finite duration windows having better spectral properties, such as the Hamming and Kaiser windows. Second, zero-padding was introduced to increase the resolution in the frequency domain, to any desired value. Of course the Fast Fourier Transform (DFT) was used in these applications. Speech, being a "non-stationary" signal (i.e., time varying) required a moving window approach, to capture the dynamics of the vocal tract (Linear prediction was also used, but it is not robust to additive noise). The third, and very important extension was the inverse transform (ISTFT), allowing one to return to the time domain following modifications to the complex frequency spectrum. The most robust way of doing this is to use the "overlap-add" reconstruction method [Allen, 1977]. With this method several (and array) of signals may be merged, in the frequency domain, in magnitude and phase, and modified to remove uncorrelated noise, dramatically improving the perceptual signal to noise ratio. The method is inherently non-linear, as the modifications depend on the signals themselves, yet the ISTFT reconstruction sound is not distorted. Examples will be played of dereverberated speech and consonants "morphed" from one sound to another (e.g., /ka/ → /ta/ and /ʃa/ → /sa/ → /ça/ → /ða/ → /θa/ ).

**Links:**

https://en.wikipedia.org/wiki/Short-time_Fourier_transform
http://auditorymodels.org/index.php?n=AuditoryModels.HomePage#InterspeechDemos
http://auditorymodels.org/index.php?n=AuditoryModels.HomePage#KunLunPublications

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Wednesday, 10:35, **GM3** Vortmann Lecture Hall, Building BA

# Accelerating Matching Pursuit In Gabor Dictionaries

Zdeněk Průša[1]

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Searching for the best $K$-sparse approximation of a signal $\mathbf{x} \in \mathbb{C}^L$ in an overcomplete dictionary of $P$ atoms $\mathbf{D} = [\mathbf{d}_0|\mathbf{d}_1|\ldots|\mathbf{d}_{P-1}] \in \mathbb{C}^{L\times P}$, $\|\mathbf{d}_p\|_2 = 1$ is a NP-hard problem. Given the budget of $K$ nonzero elements of the coefficient vector $\mathbf{c} \in \mathbb{C}^P$, the problem can be formally written as the minimization of the approximation error energy norm

$$\min \|\mathbf{x} - \mathbf{D}\mathbf{c}\|_2 \ \text{ s.t. } \ \|\mathbf{c}\|_0 = K. \tag{1}$$

The problem is usually solved using suboptimal greedy *matching pursuit* (MP) algorithms. In this contribution, we present a method for accelerating MP-based algorithms acting on overcomplete Gabor dictionaries (frames). The technique is based on pre-computing and thresholding inner products between atoms and on updating the residuum directly in the coefficient domain.

It is known that MP and its derivatives can benefit from precomputing inner products between the atoms in the dictionary $\mathbf{G}(i,j) = \langle \mathbf{d}_i, \mathbf{d}_j \rangle$ i.e. by precomputing the Gram matrix $\mathbf{G} = \mathbf{D}^*\mathbf{D} \in \mathbb{C}^{P\times P}$ (star denotes the conjugate transpose). Starting with $\mathbf{D}^*\mathbf{r}_0 = \mathbf{D}^*\mathbf{f}$ and with the zero solution vector $\widetilde{\mathbf{c}} = \mathbf{0}$, the update of the residual in the coefficient domain is written as [2]

$$\mathbf{D}^*\mathbf{r}_{k+1}(p) = \mathbf{D}^*\mathbf{r}_k(p) - \mathbf{G}(p, p_{\max})c_{\max}, \text{ for } \ p = 0, \ldots, P-1, \tag{2}$$

where $p_{\max} = \arg\max |\mathbf{D}^*\mathbf{r}_k|$, $c_{\max} = \mathbf{D}^*\mathbf{r}_k(p_{\max})$ and the solution is updated as $\widetilde{\mathbf{c}}(p_{\max}) = \widetilde{\mathbf{c}}(p_{\max}) + c_{\max}$. Such approach is usually dismissed as impractical for high-dimensional signals and generic dictionaries. Gabor atoms generated from a window $\mathbf{g} \in \mathbb{C}^L$ are given as $\mathbf{d}_{m+nM}(l) = \mathbf{g}(l-na)\mathrm{e}^{\mathrm{i}2\pi ml/M}$ for $m = 0, \ldots, M-1$ and $n = 0, \ldots, N-1$, $N = L/a$, $P = MN$ and $l = 0, \ldots, L-1$ and $(l-na)$ is assumed to be evaluated modulo $L$. The dictionary of Gabor atoms forms a frame for $\mathbb{C}^L$ iff $\mathbf{D}$ has full row rank and the Gram matrix of a Gabor frame is highly structured. In the two-dimensional time-frequency plane, it takes the form of a *twisted convolution* using a fixed kernel. Moreover, for well behaved windows (Gauss, Hann, etc.) the kernel is essentially supported around the origin and, as it turns out, it can be truncated with only a minor loss of precision and stored efficiently. Therefore, the residual update (2) reduces to substracting the truncated, weighted and modulated kernel from the neighborhood of the selected coefficient in the time-frequency plane. A simple Matlab implementation of MP using the proposed acceleration can perform as many as $10^4$ iterations per second on a signal consisting of $0.36 \cdot 10^6$ samples using four times redundant Gabor system.

The acceleration technique can be applied even to MP algorithms selecting several coefficients in a single iteration (e.g. [1]) and it can also be generalized to dictionaries consisting of multiscale Gabor systems.

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# Applications of the SWAG Penalty to Audio Reconstruction Problems

İlker Bayram[1]

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Energy minimization formulations constitute one of the main approaches for solving audio reconstruction problems. In many formulations, the energy functional consists of the sum of a data fidelity term and a signal prior term. The data fidelity term is determined by the observation model. Therefore, the utility of the energy minimization formulation depends on the penalty function. Specifically, we would like

- the penalty function to reflect our prior knowledge about the signal of interest,
- the resulting minimization problem to be easy to handle numerically.

We consider applications of a penalty function that is conscious of the harmonic structure inherent in audio signals, and that leads to manageable reconstrution algorithms.

In order to motivate and describe the penalty function, consider a slice of a spectrogram taken along the frequency axis (by fixing the time variable). The resulting sequence is expected to be sparse, but due to the harmonics, its non-zeros are also isolated. If we partition this 1D sequence into groups, then in each group, we have a few significant coefficients and the rest of the coefficients are close to zero. As a consequence, along the frequency axis, the coefficients are statistically dependent. In order to address such a dependency, we proposed in [1], a penalty of the form

$$p_{\lambda,\gamma}(x) = \lambda \left( \|x\|_1 + \frac{\gamma}{2} \sum_{i \neq j} |x_i\, x_j| \right),$$

where $x$ denotes the coefficients in a group. We remark that if $|x_i|$ is large, terms of the form $|x_i\, x_j|$ act to penalize $x_j$ strongly, pushing $x_j$ towards zero, thereby isolating the non-zeros in the group. On the other hand, the $\ell_1$ norm serves to promote sparsity of the whole group, so that a zero solution is more attractive than a solution with many small coefficients.

The penalty function $p_{\lambda,\gamma}$ is not convex. Therefore, even if the data fidelity term is convex, the resulting energy function may be non-convex. However, it can be shown that the sum of $p_{\lambda,\gamma}$ with a quadratic becomes convex. This turns out to be a property that is instrumental in deriving numerically stable algorithms.

We consider problems such as dereverberation, denoising, for single-channel as well as multi-channel observations of audio signals, and describe formulations that make use of the introduced penalty. We present algorithms for solving the resulting formulations, discuss how to tune the parameters $\lambda$, $\gamma$ of the penalty function, and compare the performance of the proposed formulations with those of formulations obtained using different penalty functions.

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Wednesday, 11:15, **GM3** Vortmann Lecture Hall, Building BA

# Frame Mask for Robust Representation of Speaker Characteristics

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In this study, we present an application of the so-called frame multiplier and frame masks for speaker characteristics modeling in speech signals. A *frame multiplier* [1] is an operator that converts a signal into another by pointwise multiplication in the transform domain. Applying a frame multiplier $\mathbb{M}_{\boldsymbol{\sigma};g,h}$ to a signal $s$ is expressed as

$$\mathbb{M}_{\boldsymbol{\sigma};g,h}s = \sum_{\lambda} \sigma[\lambda]\langle s, g_\lambda\rangle h_\lambda, \tag{1}$$

where $\boldsymbol{\sigma} = \{\sigma_\lambda, \lambda \in \Lambda\}$ is a sequence of multiplication coefficients. $\boldsymbol{\sigma}$ is also called a *frame mask*, which can be viewed as a transfer function in the considered signal analysis/transform domain. Such masks have been shown to be effective in modeling timbre of different instruments [2].

In this study, we use the frame mask to model speaker characteristics in speech signals. The frame mask between two (pitch-aligned) signals that are of a same phoneme but uttered by two different speakers, is derived from the two signals altogether via a regularized minimization approach. The resulted mask completely characterizes vocal tract difference of the two voices. It is proposed as a relative feature to represent speaker characteristics. We evaluate the validity of the proposed speaker feature via speaker classification tasks. In the evaluation, deep neural network (DNN) was employed as the input feature was of high dimension. DNN-based vowel-dependent speaker classifiers were trained and assessed. For comparison, two linear prediction (LP) based vocal tract features, namely, LP spectrum envelope and LP spectrum mask, were also evaluated. Experimental results show that the frame mask feature is superior to the linear LP-based features in terms of speaker classification accuracy and it is significantly more robust against white noise than the LP-based features. Noise robustness of the frame mask feature roots from the approach of computing the mask from two involved signals altogether. With such approach, deformity caused by noise interference can be effectively canceled out.

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Wednesday, 11:35, **GM3** Vortmann Lecture Hall, Building BA

# Frames in boundary element methods

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Although wavelets and frames are important tools used in signal processing, their potential in other fields of acoustics has not been fully explored yet. They could for example also be used as efficient ansatz functions for BEM and FEM approaches in connection with radiation/scattering problems, i.e. for solving the Helmholtz equation

$$\nabla^2\phi(\mathbf{x}) + k^2\phi(\mathbf{x}) = 0, \quad \mathbf{x} \in \Omega, \tag{1}$$

with appropriate boundary conditions. In these approaches the scatterer (or its surface) is discretized using simple geometric elements, and on each element the unknown solution is currently approximated using basis functions, e.g. B-splines of low order.

For the Helmholtz equation it is known that the solution $\phi(\mathbf{x})$ has oscillating components, that are dependent on the wavenumber $k$, and currently these oscillations are resolved using the general rule of thumb that 4 to 8 elements per wavelength $\lambda = \frac{2\pi}{k}$ need to be used. This implies that for high frequencies/wavenumbers the number of elements becomes very large, which increases the computational effort. Another problem is that the solution becomes discontinuous at geometric singularities, e.g. edges and corners, or at places where the boundary conditions change quickly. To achieve a given numerical accuracy, it is necessary to refine the mesh around these singularities.

Per definition Gabor frames are very well adapted to represent oscillating functions, and therefore have a great potential as ansatz functions for Helmholtz FEM/BEM, that would allow to break the 4-to-8 elements per wavenumber rule. However, if the target function is discontinuous, the representation with Gabor frames becomes very inefficient. In that case, wavelet based methods [1] have their advantages.

To combine both Gabor structure and wavelet properties, we will take a closer look at $\alpha$-modulation frames [2], that depend on the parameter $\alpha \in [0, 1)$, and combine Gabor frame and wavelet properties to a certain degree. For a given window function $g(x)$ the frame can be constructed using a generalization of Gabor Systems:

$$g_{\alpha,x,\nu}(t) = T_x M_\nu D_{1/\beta} g(t) = \sqrt{\beta} g\left(\beta(t-x)\right) e^{2\pi i \nu(t-x)}, \quad \beta = (1+|\nu|)^\alpha.$$

Additionally, we will address issues concerning practical implementation and present first results for (Gabor/$\alpha$-modulation) frames based on B-splines.

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Wednesday, 11:55, **GM3** Vortmann Lecture Hall, Building BA

# Kernel-based Reconstruction of Solutions of the Helmholtz Equation

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A typical problem in acoustics is the reconstruction of a sound field $u$ on some compact domain $\Omega \subset \mathbb{R}^3$ from the measurements of $N$ fixed microphones, see [2] and the references therein. The problem splits into two subproblems. First, where to place the $N$ microphones, and, second, how to numerically approximate the sound field from $N$ noisy measurements, cf. [1]. Starting with the latter, we aim to reconstruct solutions $u$ of the Helmholtz equation

$$\Delta u(x) + k^2 u(x) = 0, \qquad x \in \Omega, \tag{1}$$

with wave number $k \in I \subset \mathbb{R}_+$, from noisy measurements

$$u_i := u(x_i) + \varepsilon_i, \quad i = 1, \dots, N,$$

where $x_1, \dots, x_N \in \Omega$. The sampling points $\{x_i\}_{i=1}^N$ correspond to the fixed positions of the $N$ microphones. We propose the reconstruction of $u$ based on a reproducing kernel $K$, where the approximation is composed as a linear combination of translates, i.e., we determine suitable coefficients $c_1, \dots, c_N \in \mathbb{C}$, such that

$$\tilde{u}(x) = \sum_{i=1}^{N} c_i K(x_i, x)$$

approximates $u$. Such kernel based approximations have been widely and successfully used in scattered data approximations, see e.g. [4, 3]. The sinc-kernel

$$K(x, y) := \operatorname{sinc}(k\|x - y\|) = \frac{\sin(k\|x - y\|)}{k\|x - y\|}, \quad x, y \in \Omega,$$

is a canonical example of a reproducing kernel, whose associated reproducing kernel Hilbert space consists of smooth solutions to the Helmholtz equation (1). In particular, each $x \mapsto K(x_i, x)$ solves (1). Furthermore, the theory of reproducing kernel Hilbert spaces also allows us to determine suitable microphone positions $x_1, \dots, x_N$. Numerical experiments indicate that the computed sample points in conjunction with the kernel based approximation are well-suited for robust and almost perfect reconstruction.

Wednesday, 13:45, **GM3** Vortmann Lecture Hall, Building BA

# Time-frequency analysis and determinantal point processes

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[4]Princeton Materials Institute, Department of Chemistry, Princeton University, New Jersey, USA

We will present a new class of planar determinantal point processes defined using time-frequency representations, known as Weyl-Heisenberg ensembles.

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Wednesday, 14:05, **GM3** Vortmann Lecture Hall, Building BA

# A numerical and asymptotic framework for modelling ultrasonic non-destructive testing

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Modelling and simulation in the field of ultrasonic non-destructive testing are major tools in industrial sectors concerned by advanced inspection methods. Various realization of such tools may be considered, and among them, the use of asymptotic methods based upon high-frequency considerations are very popular due to their efficiency when dealing with large, in terms of wavelength, inspection domains. However, asymptotic-based models may fail at representing phenomena taking place at lower space scale. Additionally, numerical methods are a relevant choice of simulation tool. They provide a precise solution of the complete set of field equations ruling the propagation of waves in the specimen under inspection. Nonetheless, the major drawback for this approach being their associated computational cost in 3D, a significant amount of effort has been directed to building hybrid methods, which try to encompass advantages of both strategies.

The foundation of this coupling method is Auld's reciprocity theorem [1], linking the mechanical quantities at the reception probe with the mechanical quantities in the perturbed area, embedding the defect. The computation of the reciprocity signal requires knowledge of the incident field computed by an asymptotic model, for instance a ray-based method [2], and the local diffracted field at the flaw location. In some cases, the diffracted field can be approximated using asymptotic methods such as Kirchhoff or the General Theory of Diffraction [3]. However, in order to reach a sufficient modeling precision, numerical methods such as Spectral Finite Element methods [4] in time domain or Boundary Element methods [5] in harmonic domain are valuable alternatives.

We propose to give an overview of this general hybrid strategy dedicated to the simulation of non-destructive ultrasonic testing, while emphasizing the use of numerical methods in this context.

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Thursday, 10:15, Seminar Room BD **02A**, Building BD

# Ultrasonic Finite Element Simulations on GPUs with Pogo

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The fast generation of accurate numerical wave propagation data is important for research in the fields of geophysics, medicine and non-destructive testing, allowing predictions to be made prior to lab tests, and is also vital in inversion imaging methods. The majority of numerical wave calculation methods are highly parallelisable, with the same calculation being performed many times with different input values. Graphical Processing Units (GPUs) are widely recognised to possess an architecture well suited to such calculations, by allowing many small, lightweight threads to be run in parallel.

The Finite Element (FE) method is a powerful, flexible method for performing such simulations, having the advantage that arbitrary geometry can be discretised using a free, unstructured mesh. While efficiently allocating a uniform structured mesh to GPU memory is relatively trivial, this key benefit of being able to use free meshes with FE presents a challenge to optimal solution on a GPU.

This presentation introduces Pogo, a finite element solver written to calculate the propagation of elastic waves on a graphics card. Pogo incorporates a technique to enable arbitrary structured meshes to be allocated to GPU memory while maintaining efficient memory access, which will be outlined in this talk. Pogo has been found to allow a speed improvement of approximately two orders of magnitude over typical finite element packages run on the CPU, and its application to several key problems across NDT will be highlighted.

Thursday, 10:35, Seminar Room BD **02A**, Building BD

# Wave propagation in prismatic structures modeled using image-based homogenization

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This work addresses the computation of dynamic stiffness matrices for prismatic structures with an arbitrary cross-section based on homogenized material parameters. The presented approach utilizes two key features of the semi-analytical scaled boundary finite element method (SBFEM). Firstly, a hierarchical quadtree mesh is obtained for an image of the representative volume element. SBFEM allows for a rapid image-based construction of the mesh. The constructed model derives the effective material parameters by means of carefully chosen boundary conditions. Secondly, SBFEM for prismatic structures is able to model homogeneous domains by only discretizing the cross-section of a domain. This results in a particular semi-analytical finite element for bounded and unbounded domains. The proposed approach leads to a frequency-dependent stiffness matrix for homogenized prismatic domains. This stiffness matrix can easily be coupled to other prismatic SBFEM domains or general SBFEM domains. Additionally, pre-existing stiffness matrices from finite element models are coupled to SBFEM domains without additional computational costs.

Thursday, 10:55, Seminar Room BD **02A**, Building BD

# The Scaled Boundary Finite Element Method to Model Contact Acoustic Nonlinearity

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In Non-Destructive Testing, ultrasonic waves are commonly used to identify flaws and cracks. In plates, shells, pipes and other geometries guided waves can be used to test the whole structure at once. In these tests, the input and response signal can have a nonlinear relationship due to cracks. At least for higher deflections, the propagating wave excites each side of the crack in such a way that it hits the other side. This clapping generally leads to a generation of higher harmonic waves [1] and is referred to Contact Acoustic Nonlinearity (CAN). To get a better insight into the salient physics of the effect numerical simulations are necessary.

In the recent years, the Scaled Boundary Finite Element Method (SBFEM) was introduced to efficiently simulate wave propagation [2]. The main advantage of the method is an easy grid generation process because the domain is discretized with arbitrary polygons instead of the triangles and rectangles. Another advantage is the possibility to model crack tips elegantly without additional workload. The SBFEM approach is still related to the Finite Element Method and uses similar techniques. The method is very efficient using high-order-spectral elements.

In this contribution, we present a short introduction into the basics of SBFEM formulation of the dynamic elastic wave equation. The SBFEM is then extended for modeling the non-linear behavior of crack clapping. Different approaches with increasing complexity are presented and assessed with respect to numerical stability.

**References**

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Thursday, 11:15, Seminar Room BD **02A**, Building BD

# Ultrasonic evaluation using FE-based resonance elastic spectroscopy

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Potential applications of resonance elastic spectroscopy (RES) for the purpose of nondestructive evaluation (NDE) are studied in this paper. To investigate the wave propagation characteristics of high frequency modes, Finite Element method is used to simulate the shear wave scattering from an isotropic fiber embedded in an elastic medium. The wave propagation is simulated based on an explicit dynamic formulation, using the commercially available software ABAQUS/Explicit. The numerical investigations are performed using a two-dimensional model assuming plane strain wave propagation. For this purpose, a structured mesh is generated using 4-node plane strain, CPE4R elements. To simulate the piezoelectric excitation, a 5-cycle Hanning windowed tone-burst pressure function is loaded on the side wall of the specimen [1]. The modified short pulse method of isolation and identification of resonances (MIIR) [2] is employed to obtain the far field backscattered frequency spectrum, Form Function, resulting from an aluminum fiber embedded in an epoxy matrix. The numerical results show good consistency with the experimental and mathematical results given in references [3] and [4], respectively. The presented model is used to investigate the resonance modes behavior of the shear wave scattered from the embedded fiber under longitudinal plane wave insonification. The effect of various defect types, positions and sizes on the corresponding resonance modes and frequencies are also investigated based on the converted shear scattered wave.

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Thursday, 11:35, Seminar Room BD **02A**, Building BD

# Effective acoustic modeling of fluid-filled elastic tubes

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Guided acoustic waves can be found in multiple technical and everyday applications as SAW-devices, NDE of pipes, hearing aids, fluid monitoring in tubes or resonance effects in large scale structures. Among those examples the current contribution addresses the modeling and simulation of guided acoustic wave propagation in elastic tubes. Several types of finite element models using pressure acoustics and structural dynamics with varying boundary conditions are explained and their validity investigated. In detail, the characteristics of fluid-filled circular waveguides and the influence of elasticity of the outer boundaries in relation to the compressibility of the filling liquid and the inner boundaries due to an additional fluid phase are discussed [1].

For the sake of numerical and empirical verification, water filled (industrial) "large scale" metallic pipes [2, 3, 4] and "small scale" (medical) flexible elastic tubes are considered. The comparison is made by theoretical assumptions (for low and high frequencies) [5…8], numerical studies with Comsol [4] and alternative common simulation tools [9] and measurements in laboratory scale [2]. With the numerical model the influence of elasticity, diameter and wall thickness in relation to the wavelength is discussed. This includes especially the critical changes of the fluid-dominated wave modes influenced by the elasticity of the tube walls and the arising of additional (multiple) fluid fillings (e.g. combination liquid and gas) with asymmetric boundary conditions.

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Thursday, 11:55, Seminar Room BD **02A**, Building BD

# Shallow Water Geoacoustic Inversion: a Sequential Filtering Approach

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Dispersion analysis in an oceanic waveguide provides critical information on its properties. Particle filtering has been shown to be an effective tool in exploring and identifying dispersion patterns that are then used for environmental inversion [1, 2]. In this work we show how such a pattern can be used for the estimation of sediment sound speed and thickness along with depth of the water column. This is achieved by first computing probability density functions of modal arrival times at distinct frequencies. Initially, inversion is performed in a synthetic shallow-water waveguide at frequencies between 200 and 600 Hz. We show that tracking two modes is adequate for successful sediment sound speed and water depth estimation. The analysis is then carried out with data collected in the Gulf of Mexico using a new sequential filtering model for improved dispersion tracking. Effective inversion using modal dispersion is performed for sediment properties and water depth. [Work supported by ONR.]

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Tuesday, 10:15, Seminar Room BD **02A**, Building BD

# Broadband measurements of the seabed critical angle – inferences for sound speed dispersion in a sandy sediment

Charles W. Holland[1], Samuel Pinson[2], Derek Olson[3]

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The frequency dependence of sound speed, i.e., dispersion, in marine sediments has been a topic of considerable interest and remains a research topic. While laboratory measurements are useful, they are typically limited to somewhat idealized sediments at relatively high frequencies. In-situ measurements of dispersion at lower frequencies offer the advantage of realistic sediment assemblages but the disadvantage of competing frequency-dependent effects. Broadband 1.8-10 kHz seabed reflection measurements conducted in a sandy environment off the coast of Panama City, FL show that the critical angle is nearly independent of frequency across the entire band. Our interpretation of the data accounts for competing frequency-dependent effects of wavefront curvature, sound speed gradients, layering, roughness and shear waves. There is reasonably strong evidence from the observations that the sediment sound speed is nearly independent of frequency over the measurement band. [Research supported by the ONR Ocean Acoustics Program]

Tuesday, 10:45, Seminar Room BD **02A**, Building BD

# Sediment Parameter Inversions in the East China Sea

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Geoacoustic inversions using wide-band acoustic sources (WBS) deployed during the Asian Seas International Acoustic Experiment (ASIAEX) along a circular path of radius 30 km centered on a vertical hydrophone array was used to construct a pseudo 3D model of the seabed sediments [1]. The geometry of the experiment and the details of the data collection effort are described in detail by Dahl et al. [2]. The historic data on the sediments and bottom layering structure obtained from seismic studies are discussed by Miller et al. [3]. Data from the wideband sources deployed during the experiment will be analyzed to produce group velocity dispersion data. The arrival time data corresponding to different modes at various frequencies will be used in the inversion scheme. A normal mode model is used as forward model to calculate theoretical group velocity dispersion. The geoacoustic inversion approach is based on trans-dimensional Bayesian methodology in which the number of sediment layers is included as unknown in addition to the layer parameters. In this study, the inverse problem is recast such that the unknown parameters are sediment parameters such as porosity, permeability, grain size etc. The compressional and shear wave speeds and attenuation are estimated from these parameters using Biot or similar geoacoustic models. This inversion approach enables direct comparison of the inversion results to ground truth measurements for sediment cores. High resolution time-frequency analysis techniques were applied to extract modal arrival times accurately. One-dimensional (depth- dependent) inversions will be applied along the various acoustic propagation paths to construct a pseudo 3D sediment model using interpolation. [Work supported by the Office of Naval research].

**References**

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Tuesday, 11:15, Seminar Room BD **02A**, Building BD

# Implications of vector-scalar reciprocity for acoustic inversion processing

Thomas Deal[1], Kevin B. Smith[2]

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Acoustic vector sensors can reduce uncertainty in acoustic tomography applications by measuring pressure and orthogonal components of particle velocity at a single point. This provides phase information in addition to the amplitude information typically measured by hydrophones. When propagation models are used to estimate unknown environment parameters from recorded vector sensor data, care must be taken to utilize the correct reciprocity relationship. The scalar reciprocity relationship commonly used in underwater acoustics does not apply to individual components of the velocity field. Predicting the velocity components received at a fixed location requires the use of a vector-scalar reciprocity relationship. This is implemented in propagation models by the inclusion of vertical and horizontal dipole sources. An example of this implementation in a parabolic equation propagation model is given, and the capabilities and limitations of this approach in the context of ocean acoustic inversion are discussed.

Tuesday, 11:45, Seminar Room BD **02A**, Building BD

# Similarity Measurements of Acoustic and Seismic signals

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In applications of ocean acoustic tomography and geoacoustic inversions using recorded acoustic signals as input data to the inverse problem, it is of primary importance the definition of a way to distinguish between signals in order that the observed difference is associated with differences of the environmental parameters to be estimated. On the other hand, if the difference is very small the signals can be considered as belonging to the same group. Applications envisaged are referred to monitoring the seismic activity in a certain area, using either acoustic or seismic signals. Thus, the similarity measure obtains a wider range of applications.

Two alternative techniques will be presented here and discussed using seismic signals. Both are based on signal characterization using different methods: The first technique is based on the statistical signal characterization scheme which has been proposed by Taroudakis et.al [1] and has already been applied in various inversion scenarios using both noisy synthetic and experimental data. This technique assigns the wavelet coefficient in $L$ various scales of a signal to a family of symmetric alpha stable distributions each one described by a pair of parameters. These parameters form a vector with $L$ elements which express the features of the signal.

The second technique is based on a probabilistic signal characterization scheme proposed by Smaragdakis and Taroudakis [2] which is still under active research. According to this method, the wavelet coefficients of a signal are assigned to a single Hidden Markov Model, in which the hidden variables take discrete values. Therefore, the wavelet coefficients are modeled via a proper family of conditional emission distributions given the state of the corresponding hidden variables. The transitions among the states are governed by a matrix of transition probabilities. Thus, the transition and emission densities are the corresponding features of the signal.

We consider the similarity measure between two signals for both techniques to be the Kullback--Leibler (KL) divergence of the corresponding features. In the first technique there is a closed form for the KL between two symmetric alpha stable distributions, As there is no a similar closed form between Hidden Markov Models, a numerical estimation based on Monte--Carlo techniques is considered.

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Tuesday, 15:00, Seminar Room BD **02A**, Building BD

# Direct method for solving coefficient inverse problems for hyperbolic equations, based on Gelfand-Levitan approach

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In this talk we consider coefficient inverse problems for hyperbolic equations. Such equations often describes the propagation of a certain wave field in the medium, and the coefficients of the equations correspond to the properties of the medium, like density or acoustic impedance. The inverse problem consists of finding unknown coefficients by using additional information, which is given by measurement of the wave field on the surface of the medium.
We use the approach of I.M. Gelfand and B.M. Levitan to reduce nonlinear inverse problems to a family of linear integral equations of Fredholm type. The main advantage of such approach is that method doesn't involve multiple solution of the direct problem. Another important aspect is that this method does not rely on prior information, which is important due to applied nature of arising inverse problems. The approach can be adjusted for multi-dimensional problems by combining it with projection of the solution on the finite dimensional sub-space.
We consider and investigate the one-dimensional seismic inverse problem and two-dimensional inverse problem for acoustic equation. We present several numerical methods, based on the properties of Gelfand-Levitan equation, like Monte-Carlo method [1], stochastic iterative projection method [2] and method, based on the fast inversion of the Toeplitz matrix [3]. The results of the numerical experiments are presented.
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Tuesday, 15:30, Seminar Room BD **02A**, Building BD

# Gradient-based Model Parameterizations in Bayesian Geoacoustic Inversion

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This paper considers the role of parameterizing the seabed in resolving sediment profile structure in Bayesian geoacoustic inversion. Bayesian inversion is formulated in terms of the posterior probability density over the model parameters, which is sampled numerically using Markov-chain Monte Carlo methods. A key aspect of quantitative geoacoustic inversion is that of parameterizing the seabed model. Recent trans-dimensional (trans-D) inversion methods model the seabed as a sequence of uniform layers and sample probabilistically over the number of layers, which has the advantage that the uncertainty in the parameterization is included in the parameter uncertainty estimates. However, in some cases seabed properties are expected to vary as smooth, continuous gradients which are not well represented by a stack of uniform layers. Most gradient-based inversion schemes assume a fixed functional form for profiles of geoacoustic properties, such as a linear or power-law gradient. A recent alternative is based on representing model profiles in terms of a linear combination of Bernstein-polynomial basis functions. This approach is general as it allows the form of the profile to be determined by the data, rather than by a subjective prior choice. This paper compares trans-D, power-law, and Bernstein-polynomial inversions for the geoacoustic inverse problem of estimating seabed shear-wave speed profiles from the Scholte-wave dispersion data. Simulations and measured data are considered.

Tuesday, 15:50, Seminar Room BD **02A**, Building BD

# Panel Contribution Analysis based on FEM and Numerical Green's Function Approaches

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Principally, the panel acoustic (or noise) contribution analysis (PACA) finds its application in the automotive industry for studying and improving the noise and vibration parameters of vehicles. This technique is used to investigate the contribution of individual panels of a vibrating structure to the acoustic pressure at the points of interest. The acoustic response to the vibration of a certain panel ranks the panel contribution. At the same time, different panels can have both positive and negative contributions, which has an affect on the total acoustic pressure at a point.

The PACA is carried out by establishing a relation between the normal velocity of a vibrating panel and the acoustic pressure at a point of interest. This can be written in the vector-matrix form as follows

$$p\left(\omega\right) = \boldsymbol{g}^T\left(\omega\right)\boldsymbol{v}_n\left(\omega\right), \tag{1}$$

where $p$ is the acoustic pressure at the point, $\boldsymbol{v}_n$ is the vector of the nodal normal velocities, and $\boldsymbol{g}$ is known as the acoustic transfer vector (ATV) [1]. In the case of several points of interest, $\boldsymbol{g}$ transforms to a column matrix $\boldsymbol{G}$.

This work is focused on the application of COMSOL Multiphysics® to PACA. The ATV relation (1) is retrieved from two different approaches. The first approach utilises the FEM engine of COMSOL to solve and invert the system matrix, whereas the right hand side loads (panel contributions) are applied interchangeably using *Load Groups*. On the other hand, (1) is nothing less than a discrete form of the integral expression[1]

$$p\left(\boldsymbol{r}_M\right) = \int_{\partial\Omega}\frac{\partial p}{\partial n}\left(\boldsymbol{r}_Q\right)G\left(\boldsymbol{r}_Q,\boldsymbol{r}_M\right)\,d\Gamma_Q,\ M\in\Omega, \tag{2}$$

taking into account that $\frac{\partial p}{\partial n} = i\omega\rho_0 v_n$ in the frequency domain. The equivalence between (1) and (2) makes up the second approach. The Green's function $G\left(\boldsymbol{r}_Q,\boldsymbol{r}_M\right)$ is a solution to the boundary value problem at each $M\in\Omega$

$$\begin{aligned} \Delta_Q G\left(\boldsymbol{r}_Q,\boldsymbol{r}_M\right) + k^2 G\left(\boldsymbol{r}_Q,\boldsymbol{r}_M\right) &= \delta\left(\boldsymbol{r}_Q,\boldsymbol{r}_M\right),\ Q\in\Omega,\\ \frac{\partial}{\partial n_Q}G\left(\boldsymbol{r}_Q,\boldsymbol{r}_M\right) &= 0,\ Q\in\partial\Omega, \end{aligned}$$

where $k$ is the wave number and $\delta$ is the Dirac delta function. The boundary value problem is solved in COMSOL using the *Coefficient Form PDE* interface. This yields a numerical Green's function and, in the end, leads to (1).

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[1] $\omega$ is omitted.

Monday, 15:50, Seminar Room BA **02B**, Building BA

# Panel Contribution Analysis, One of the Tools to Diagnose the Energy Transfer

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One of the main challenges in CAE is to diagnose how the energy flows through the system. Knowing how the energy flows within the model allows designing and locating efficient countermeasures to reduce the sound pressure level. Panel contribution analysis is one of the tools available to address this question.

A panel contribution analysis can be performed using finite element and statistical simulation methods like: Finite element and Statistical Energy Analysis. This paper will present for each method an overview of the theory implemented to perform the analysis and illustrate it with a practical example.

Monday, 16:10, Seminar Room BA **02B**, Building BA

# Non-Negative Intensity for Structures with Inhomogeneous Damping

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Non-negative intensity is an approach to identify the surface areas of a structure that contribute to sound power. Back-calculated non-negative intensity identifies surface areas of a structure that contribute to sound power at a far-field receiver surface that does not fully circumscribe the structure. In this work, numerical models are developed to analyse the surface contributions from a vibrating structure with inhomogeneous distributions of structural damping. Five different configurations of inhomogeneous damping are applied to a 3D elastic plate. To examine the influence of inhomogeneous damping on sound radiation, the acoustic intensity on the surface of the plate, acoustic intensity on several different far-field receiver surfaces, non-negative intensity and back-calculated non-negative intensity are numerically compared for the different inhomogeneous damping cases and at different frequencies.

Monday, 16:30, Seminar Room BA **02B**, Building BA

# Variable-order Besov Bayesian theory for full waveform inversion of seismic data

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Full waveform inversion (FWI) attracts wide attention for it enables us to acquire high-resolution subsurface images. In Tarantola's treatise [1], FWI has been derived from the Bayesian inverse theory which recasts the inverse problem into a Bayesian inference framework. However, only finite-dimensional Bayesian inverse theory and only Gaussian prior measure have been employed, which makes the deduction in [1] to be imprecise and restrictive. Recently, by means of stochastic analysis theory, Stuart [2] provides a rigorous analysis of the Bayesian inverse theory on infinite-dimensional space which just meets the requirements of seismic imaging. The infinite-dimensional theory provides a new viewpoint and facilitate the convergence analysis of practical algorithms, however, it is also mainly restricted to the Gaussian prior measure.

In this presentation, based on the following wavelet expansion of functions:

$$u(x) = \sum_{j=1}^{\infty} \sum_{k\in\mathbb{Z}} u_{j,k}\phi_{j,k}(x),$$

where $\phi_{j,k}$ stands for wavelet bases and $u_{j,k}$ are random variables sampled from a one-dimensional probability distribution with probability density function defined as follows:

$$C \exp\left(-\frac{1}{2}\int_{\mathbb{T}^n} |x|^{q(y)}\kappa(dy)\right),$$

we provide a new non-Gaussian prior measure named as the variable-order Besov prior measure, which has the ability to characterize the detailed structures of sediment part and salt body of the underground medium simultaneously. Based on this new prior measure, we construct the Bayesian inverse theory and provide a discrete to continuous convergence analysis. The relations of the Bayesian inverse theory and the regularization theory have also been provided, which are important for practical computations. Finally, we apply our new theory to a seismic velocity inversion problem with forward model to be a fractional wave equation proposed in [3]. In order to apply our theory, by using the properties of the fractional Laplace operators, some well-posedness results have been obtained and the Lipschitz continuity of the solution operators have also been obtained. Based on these results, Bayesian theories of the concerned seismic velocity inversion have been established, which provide theoretical foundations for further investigations.

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Tuesday, 10:15, Lecture Hall **GM2** Radinger, Building BD

# Analysis of the Viscoelastic Wave Propagation via the Adomian Decomposition Method

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**Abstract**: In this paper, the Adomian Decomposition Method (ADM) is employed to analyze the propagation of viscoelastic wave. Firstly, the recent development of the ADM is reviewed; secondly, some remarks on the newly developed numerical approaches for solving the 2D and 3D viscoelastic wave equations are given; thirdly, the operators appeared in the viscoelastic wave equations are decomposed into two parts: the ideal linear part and the rest part. The ideal linear operators denote the operator of elastic wave equations for the ideal media and the other operators stand for the one of dissipation or imperfection of the media. Finally, being similar to the spectral element method, the true elastic modal functions (their eigenfrequencies are undetermined) are collected as the initial approximation to the viscoelastic wave field. Then, through the ADM, the higher-order approximate solution to the viscoelastic wave equations is obtained. While the method is applied to a practical engineering problem, some kind of numerical approaches is combined with the ADM and the so-called numeric-analytical method is formulated. To illustrate the accuracy and efficiency, the method is compared with the traditional finite difference method, the pseudo-spectral method and the finite element method. The results show that the method presented in the paper is applicable to the analysis of the practical seismic wave propagation.

Tuesday, 10:45, Lecture Hall **GM2** Radinger, Building BD

# Q Correction Based on Seismic Structure Constrained Molecular Decomposition

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We propose a novel Q correction method based on seismic structure constrained molecular decomposition, to address the problems of lateral continuity and complex structure. Since the local peaks of the seismic trace's envelope (LPE) relate to the general structure of the seismic data, we use these peaks as the constraint to construct Molecular Gabor (MG) windows, and use these MG windows to transform the seismic trace into time-frequency (TF) domain, next extract the amplitude spectrum of the time-variant wavelets using the nonlinear contraction mapping method [1] in the TF domain, then calculate the equivalent Q by the frequency shift method [2] and correct the Q-effect in the TF domain.

The LPE relate to the general structure of the seismic data, thus the MG windows constrained by the LPE could help to achieve result with good lateral continuity, and can guarantee at least one wavelet in each MG window, which reduces the number of the windows, improves the computational efficiency significantly as well as degrades the wavelet truncation effect caused by the windows. The nonlinear contraction mapping method is used to estimate the amplitude spectrum of the time-varying wavelet from relatively short MG segments, which lay a basis for getting stable centroid frequency (CF). We apply 2D smooth filtering to the profile of the CF and calculate the absolute difference of the CF before and after smoothing, and remove those CF points with big absolute difference, and then apply 2D smooth filtering again to the new CF profile to achieve the final version of the CF, which could effectively reduce the effect of interference of seismic wavelets and guarantee the lateral continuity of the processed data. In addition, to avoid instability, we construct filters to make it only correct the TF coefficients in effective frequency band. The proposed method does not require to know Q values of the earth in advance, and it also can work for a general earth Q-model variable with travel time.

Both synthetic and real data examples demonstrate that the proposed Q correction method can not only effectively correct the Q-effect caused by stratigraphic absorption, and significantly improve the seismic vertical resolution and the recognition capability of the weak seismic signals from deep lays, but also can achieve good lateral continuity and preserve the complex structure of the seismic data.

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Tuesday, 11:15, Lecture Hall **GM2** Radinger, Building BD

# *Q* Estimation using an improved frequency shift method

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Absorption is a fundamental mechanism when seismic waves propagating in the earth. It attenuates the amplitude and distorts the frequency components of seismic waves and decreases the resolution of seismic data. Attenuation, when quantified, may be a significant seismic parameter in improving the interpretation of seismograms.

Most of the Q estimation techniques begin with a constant Q model, which assumes a linear frequency dependence of attenuation coefficient. Among the various methods for Q estimation, frequency shift methods are commonly used because of their reliability and ease of use. A classic approach is the spectral-ration (LSR) method which measures the log of ratio between the spectral amplitude of reference wavelet and target wavelet. However, this method is easily affected by effective bandwidth and random noise. Subsequently, centroid frequency shift (CFS) [1] method to estimate Q was proposed based on the assumption the source wavelet has Gaussian, boxcar, or triangular shape. Zhang and Ulrych (2002) [2] find that the interval Q can be obtained from the variation of the peak frequency when the seismic wavelet was supposed to be Ricker-like. The CFS and PFS methods were proposed under the assumption of particular source wavelet types, which have poor applicability.

In this work, a novel method for Q estimation is presented. The basic ideal is that the peak frequency can be calculated from mean frequency and its deviation, and the generalized seismic wavelet (GSW) [3] function was designed to fit various asymmetric amplitude spectrum by two parameters: fractional value and reference frequency. Based on this, we have studied the relationship between Q factor of medium and the GSW function, and then we proposed a new method for Q estimation by using the fractional value and reference frequency. Experiments with synthetic data are carried out to testify that the proposed method is less systematic biased and more robust to random noise. Field data test also proves its effectiveness.

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Tuesday, 11:35, Lecture Hall **GM2** Radinger, Building BD

# Modeling Attenuation of Diffusive-viscous Wave Using Reflectivity Method

Haixia Zhao[1, 2], Jinghuai Gao[2] , Jigen Peng[1], Xiaokai Wang[1, 2]

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Seismic waves in earth materials are subject to attenuation and dispersion in a broad range of frequencies and scales from free oscillations of the entire earth to ultrasound in small rock samples. Attenuation and dispersion can be caused by a variety of physical phenomena in which the commonly accepted mechanism is the presence of fluids in the pore space of rocks. Low-frequency seismic anomalies related to hydrocarbon reservoirs are found in both laboratory and field data. The diffusive-viscous model was proposed to explain those anomalies and also used to describe the attenuation property of seismic wave in a fluid-saturated medium. But it does not consider the shear effects of rocks. In this work, we firstly extend the diffusive-viscous model to elastic case based on the mechanisms in a megascopic porous medium. The elastic diffusive-viscous model describes attenuation of compressional wave and shear wave in a fluid-saturated medium and it degenerates to the classic elastic wave equation in a special case. Then, we model the propagation of diffusive-viscous wave in a fluid-saturated medium using reflectivity method. We compare the numerical results of diffusive-viscous wave with those of viscoelastic wave and elastic wave to show the features of attenuation in a fluid-saturated medium. The modeling results show that the diffusive-viscous wave has strong amplitude attenuation and phase shift when it propagates across fluid-saturated layers.

Tuesday, 11:55, Lecture Hall **GM2** Radinger, Building BD

# $Q$ Estimation from the Envelope Peak Instantaneous Frequency based on Generalized Seismic Wavelet

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Seismic waves propagating through the earth experience attenuation and dispersion due to the conversion of elastic energy into heat. This viscoelastic behaviours can decrease amplitude and distort a wavelet, which can be quantified by the quality factor $Q$. Knowledge of $Q$ is desirable for reservoir characterization and resolution enhancement in seismic exploration.

In practice, $Q$ is usually assumed to be frequency-independent over the seismic frequency range. As the wave propagates, the higher-frequency components are attenuated more rapidly than the lower ones. Therefore, seismic attenuation could be estimated by measuring the variations of the frequency contents. The spectral ratio method is easily influenced by the frequency bandwidth chosen to fit the slope. The central frequency shift and peak frequency shift methods are derived under particular assumptions of source wavelet types, thus leading to poor applicability. In fact, the seismic spectrum is usually non-Gaussian and the absorption effects of medium would certainly change the spectrum as seismic wave propagates. Recently, Wang [1] presented a generalization of the Ricker wavelet, which is defined as the fractional derivative of a Gaussian function. With two key parameters, the fractional value and reference frequency, the generalized seismic wavelet can fit the field signal well. Note that the generalized seismic wavelet can be regarded as a constant phase wavelet. Its instantaneous frequency at the envelope peak is equal to the average Fourier spectral frequency weighted by the amplitude spectrum [2]. This envelope peak instantaneous frequency decreases as function of travel-time as the wavelet propagates through an absorptive medium [3]. Therefore, we can establish a novel formula linking the quality factor $Q$ and the variations of the envelope peak instantaneous frequency based on the generalized seismic wavelet.

The procedure for attenuation estimation includes the following steps. First, calculate the the fractional value and reference frequency of the generalized seismic wavelet from the the power spectrum of seismic signal. Then, pick up the arrival times and instantaneous frequencies at the envelope peaks. Finally, calculate the $Q$ factor according to the novel formula. The proposed method is validated by synthetic and field data experiments.

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Tuesday, 15:00, Lecture Hall **GM2** Radinger, Building BD

# Anti-aliasing in Kirchhoff beam migration

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Various beam-based migration methods have shown promising efficiency and imaging fidelity in the last few years[1]. Slant stack Kirchhoff beam migration[2] combined aspects of Kirchhoff migration with preprocessing the seismic data into locally coherent events (beams). It has the flexibility of handling data description for which a slant stack makes physical sense, such as common-shot, common-offset or common-midpoint[1-2]. In general, beam migration can be divided into three steps: beam forming, ray tracing and migration, with of equal importance for the final image quality. All the three steps can contribute to an aliased image if not treated carefully. The aliasing effect manifests itself as uncanceled migration swings that can appear either random or coherent noise in the image. Ignoring the aliasing on migrated stacks and gathers can result in incorrect analysis of migration velocity and migrated amplitudes[3]. However, aggressive anti-aliasing can weaken the amplitudes of the steep dips of the subsurface structures. Basically, the final aliasing effect can be traced back to operator aliasing and data aliasing. It is tedious to find the optimized parameters for anti aliasing in the complicated seismic imaging challenge. In this work, we systematically study the process of anti aliasing in the common offset slant stack Kirchhoff beam migration based on the three dimensional realistic marine seismic dataset. The aliasing energy in slant stack can be raised by the limited aperture, spatially sparse or irregular sampling of the seismic data, which in this cases expands the original traces to an unacceptable size. All kinds of high resolution beam forming is, to some degree, a method of anti aliasing slant stack transform. The migration operator anti aliasing can be achieve by the constraint of the data frequency, traveltime aperture, imaging angle/aperture and ray tracing density/angle et al.[4]. All the parameters or strategy for anti aliasing not only affect the final image, but also the overall migration efficiency.

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Tuesday, 15:20, Lecture Hall **GM2** Radinger, Building BD

# Seismic Instantaneous Attributes Extraction and Applications to Reservoir Characterization

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Seismic instantaneous attributes (IAs) extracted from seismic data are widely applied in abnormal attenuation identification and seismic stratigraphic interpretation [1]. These instantaneous attributes include instantaneous frequency (IF), instantaneous phase (IP), instantaneous bandwidth (IB), instantaneous quality (IQ), et al. IF is successfully applied to thin-bed tuning, quality factor (Q) inversion and boundaries characterization of different fluid saturated rocks [1, 2]. IQ is a powerful tool to characterizing attenuated reservoir.

In general, extracting IAs based on complex-trace analysis is divided into two categories: Hilbert transform (HT) methods and time-frequency transform approaches (such as: continuous wavelet transform). HT based IAs extraction, is introduced by Taner et al. [3], which suffers from noise. Another IAs extraction methods, based on complex-trace analysis, are time-frequency analysis based, which can overcome the noise sensitivity [4].

In this paper, we propose a method to extract IAs, which is based on the synchrosqueezing transform (SST). Using SST [5] to extract IAs can improve the resolution and anti-noise performance. To demonstrate the effectiveness of the proposed method, we apply it to synthetic data examples and filed data examples. The IF extracted by the proposed method has the potential to identify sandstone boundary and fluvial channel features with high resolution. The IQ produced by the proposed method can characterizes the tight gas reservoir accurately and clearly, which is helpful to further oil/gas reservoir identification and well deployment.

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Tuesday, 15:40, Lecture Hall **GM2** Radinger, Building BD

# A robust and precise seismic dip estimation method based on instantaneous phase

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Seismic geometric attribute is one of the most important seismic attribute, also plays an important role in seismic data processing and interpretation. The seismic dip, which reflects the orientations of seismic events in 3D seismic dataset, can be used to reduce seismic interpretation cost and derive other useful seismic attributes. Seismic dip not only can be directly used in characterizing the geological structure, but also can be used as basic data in curvature [1], dip-steered coherence and structure-oriented filter [2].

Several methods have been proposed to estimate seismic dip, such as 3D semblance-based scanning [3], complex trace analysis, gradient structure tensor [4] and plane wave destruction [5]. However, if faults and other discontinuous structures exists, most of the existed methods would result in uncorrected dip, such as confusions of faults, large and meaningless dip values.

In order to achieve a more robust and precise seismic dip, we combine constructing gradient structural tensor and multi-window technology [6]. Firstly, we use complex trace analysis to obtain the instantaneous phase. Secondly, we construct gradient structural tensor on the instantaneous phase to improve the anti-noise ability of dip estimation. Then we adopt multi-window technology to reduce the effects of seismic fault on dip estimation. Finally, we apply our method to several 3D field dataset. The results show our method has better performance in precision and anti-noise ability comparing with commercial software.

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Tuesday, 16:00, Lecture Hall **GM2** Radinger, Building BD

# The DAS coupling noise removal using alternating projection iteration with united sparse transforms

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The distributed acoustic sensing (DAS) system, which uses an optical fiber cable in vertical seismic profiling (VSP) data acquisition, has been launched as a new and fast-growing technology. Compared with common data acquisition, the cost of repeated data acquisition in DAS is much lower [1]. Although the DAS system is an advanced technology for VSP data acquisition, the acquired VSP data suffers from strong coherent noise such as cable slapping and ringing due to the physical placement of the wireline in the well.

From the normalized amplitude spectrum and time-frequency spectrum of single trace data which contains strong coupling noise, we can see that the DAS coupling noise can be treated as the superposition of some single frequency components. According to different morphological characteristics of desired signal and DAS coupling noise, we choose the continuous wavelet transform (CWT) and discrete cosine transform (DCT) as two transform dictionaries to sparsely represent desired signal and DAS coupling noise [2].

We assume that the observed signal $\boldsymbol{s}$ is a superposition of two different components $\boldsymbol{s}_1, \boldsymbol{s}_2$ and random noise $\boldsymbol{n}$:

$$\boldsymbol{s} = \boldsymbol{s}_1 + \boldsymbol{s}_2 + \boldsymbol{n}. \tag{1}$$

Next, we adopt the threshold iterative method to separate the desired signal and coupling noise as follows and finally achieve the purpose of noise suppression.

$$\mathbf{X}_1^k = T_\lambda(\Phi_1^*(\boldsymbol{s} - \Phi_2\mathbf{X}_2^{k\text{-}1})), \mathbf{X}_2^k = T_\lambda(\Phi_2^*(\boldsymbol{s} - \Phi_1\mathbf{X}_1^k)), \tag{2}$$

where $\mathbf{A}_1^*$ and $\mathbf{A}_2^*$ is the forward form of $\mathbf{A}_1$ and $\mathbf{A}_2$, $\mathbf{X}_1$ and $\mathbf{X}_2$ are the sparse coefficient vectors, $k$ represents the iteration step, $T_\lambda$ is the hard or soft threshold function. Once getting the final iteration result $\mathbf{X}_1^*$ and $\mathbf{X}_2^*$, we can reconstruct desired signal $\boldsymbol{s}_1$ and DAS coupling noise $\boldsymbol{s}_2$ as follows:

$$\boldsymbol{s}_1 = \mathbf{A}_1\mathbf{X}_1^*, \boldsymbol{s}_2 = \mathbf{A}_2\mathbf{X}_2^*, \tag{3}$$

From the synthetic data example, we can find that the coupling noise is removed completely and the desired signal is preserved well. The field data experiment demonstrates that the coupling noise is removed and the profile of downgoing and upgoing wavefield is more visible after denoising. The information contained in the useful signal is completely maintained.

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Tuesday, 16:20, Lecture Hall **GM2** Radinger, Building BD

# Random noise attenuation of seismic data using variational mode decomposition and time-frequency peak filtering

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In seismic data acquisition, valid reflection events are always contaminated by various kinds of noise. In this letter, we mainly aim at random noise. The time-frequency peak filtering (TFPF) technique is an effective random noise reduction method , which has been applied to attenuate seismic random noise [1].

There is a pair of contradiction in TFPF. When we select a short window length, it may lead to good preservation for valid signal amplitude but bad random noise reduction, whereas when we select a long window length, it may lead to serious attenuation for signal amplitude but effective random noise reduction. Some researchers have proposed adaptive variable window lengths for time-frequency domain methods,but presents inadequate capability for seismic signal processing. In view of this, an amplitude-preserved time-frequency peak filtering based on empirical mode decomposition (EMD) was proposed [2]. By this measure, it cannot only attenuate the random noise effectively, but also preserve the amplitude of the valid signal.

We extend our studies of seismic denoising with a recently proposed transform called variational mode decomposition(VMD) instead of EMD [3]. The VMD is an adaptive and non-recursive signal decomposition method where each component is almost considered as compact around a corresponding center frequency. Further, VMD has a strong mathematical support and is more robust than the EMD. We test this method on both synthetic signal and field seismic data and find that it really demonstrates better performance in amplitude preservation and random noise reduction.

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Tuesday, 16:40, Lecture Hall **GM2** Radinger, Building BD

# Seismic Source Simulation for Poroelastic Wave Equations

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The choice of the sources is a very important issue in the numerical simulation. Different sources will generate completely different wave fields [1]. The representations of the three common sources: the dilatational source, the shear source and the directional force source are given. We employ the finite difference method [2] to simulate the wave fields of the sources with Gaussian and delta function in space domain, respectively. The numerical results demonstrate that Gaussian function can suppress numerical dispersion compared with delta function. The characteristics of wave fields for three different sources in 3D poroelastic media [3-4] are presented. The numerical results show that these three sources generate different waves and their wave fields are completely different. Then we use these sources to generate the vibration of a geophysical model in a desert area in China. These results will be helpful for the numerical simulation in poroelastic media.

The seismic source can be defined in time and space domain:

$$\Phi\left(x,y,z,t\right)=s\left(x,y,z\right)r\left(t\right) \tag{1}$$

Dilatational source, shear source and directional force ($z$ direction) source can be expressed as

$$\mathbf{S}_{\mathrm{D}}=\nabla F \tag{2}$$

$$\mathbf{S}_{\mathrm{S}}=\nabla\times\mathbf{F} \tag{3}$$

$$\mathbf{S}_{\mathrm{F}}=F\mathbf{k} \tag{4}$$

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Wednesday, 10:15, Lecture Hall **GM2** Radinger, Building BD

# The difference and correlation between the static modulus and dynamic modulus

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Pressure-induced inelastic porosity loss and its associated compaction are commonly observed during the laboratory measurement of unconsolidated sands and weakly cemented sandstones. In addition, Laboratory studies on the unconsolidated sands suggest that the deformation between the pressure points is both time-dependent and permanent while the measured elastic moduli from the converted ultrasonic signals are elastic. Deformation (strain), an essential physical parameter to distinguish the static deformation ( $\varepsilon > 10^{-6}$ ) and dynamic strain ( $\varepsilon < 10^{-6}$ ), could bridge the static properties and dynamic properties of unconsolidated sands. Therefore, based on the measured data of loose sand packs with different percent content of clays and field core samples, the proposed rock physical model not only characterizes both the static and dynamic parameter variations, but also builds the qualitative correlation between them. More importantly, an effort is made to predict the porosity changes as a function of both stress path and strain rate, which has significant potential promotion for reservoir production.

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Wednesday, 10:35, Lecture Hall **GM2** Radinger, Building BD

# The reflection of the inhomogeneous seismic wave in the generalized viscoelastic model

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Amplitude variation with offset/angle of incidence inversion has been playing a key role in hydrocarbon detection and reservoir characterization. Traditionally, it has been limited to elastic even viscoelastic cases. However, subsurface media behave in a much generalized viscoelastic manner. To describe these characteristics, the seismic wave propagation can be written by the generalized viscoelastic wave equation. For obtaining the generalized reflection coefficients and characterizing sophisticated seismic data analysis incorporating wave dissipation, we consider the reflection and scattering of the inhomogeneous seismic wave in generalized viscoelastic models with account taken of attenuation angle. When the viscoelastic controlling parameter $\beta$ is zero, the relative media becomes a pure elastic media and the reflection coefficient is real, our study demonstrated that the polar of the seismic wave is linear. When this viscoelastic controlling parameter is not zero, the relative parameters of the media become complex, analysis show that the polar of the seismic wave will become circle and the attenuation angle of the outgoing waves increase with increase of the viscoelastic controlling parameter. In addition, the linearization of reflection coefficient which is calculated in terms of fractional perturbations shows that it has two parts: the real part is for a low-contrast interface between two isotropic elastic media which is similar as the standard isotropic-elastic Aki and Richards equations; the imaginary part is caused by viscose. It can contribute to analyse the contributions of the jumps in elastic and anelastic properties. The comparison with the case of elastic media shows that the complex part of the reflection coefficients about the generalized viscoelastic media has a significant influence on reflection strengths, particularly when the degree of inhomogeneity was high.

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Wednesday, 10:55, Lecture Hall **GM2** Radinger, Building BD

# Simulation of Elastic Wave Propagation in Media with an Elastic-poroelastic Interface Using COMSOL Multiphysics

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The numerical simulation of wave propagation in media with complex interfaces is essentially crucial to seismic exploration data analysis. In this paper, based on the acoustic wave equation, the conventional elastic wave equations and the Biot equations, the wave propagation in media with poroelastic-poroelastic interface, acoustic-poroelastic interface and elastic-poroelastic interface is simulated by COMSOL Multiphysics. Based upon domain decomposition, as in poroelastic-poroelastic case, the coupling between two media in acoustic-poroelastic case and elastic-poroelastic case is achieved by applying the continuity of displacement and traction across the interface. Different benchmarks have been performed to simulate the wave propagation in the cases above with variable-order accuracy. Research results show that the wave propagation involving all transmitting, reflecting and converting in media with various interfaces can be clearly represented via COMSOL Multiphysics platform. The work indicates the effectiveness of this method in predicting wave propagation across multimedia interfaces, which can be potentially applied to the field of oil and gas exploration.

Wednesday, 11:15, Lecture Hall **GM2** Radinger, Building BD

# Several Problems on Numerical Simulation for Seismic Source Loading

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Seismic source is an important part of gas-oil resources and microseismic monitoring [1]. The corresponding numerical simulation is indispensable for cost savings and efficiency improving [2]. This paper discusses loading ways of physical sources based on finite difference method. Meanwhile, several problems related to the source loading are analyzed in details. After lots of tests, four conclusions are drawn: (1) source loading is the first step should be considered during the solution of wave equation; (2) source excitation should be loaded on the stress items and distributed on only one area; (3) wave propagation is the cumulative effect from the function of seismic source; (4) the wavelet of seismic source has changes not only in the amplitude but also in the shape during wave propagation.

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Wednesday, 13:45, Lecture Hall **GM2** Radinger, Building BD

# The Comparison of Zero Phase Wavelet after 90 Degree Phase Shift and the Trace Integration Method in Seismic Interpretation

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By comparing the zero phase wavelet seismic profiles of 90 degree phase shift and the zero phase profiles through the trace integration, this paper found that after a 90 degree phase shift seismic profiles either to help the interpreters or to maintain the resolution is better than the profiles through the trace integration [1]. Using the correlation method, this paper verified that the cross-correlation value of a 90 degree phase shift wavelet with its wave impedance is higher than cross-correlation value of a zero phase wavelet with its wave impedance [2].

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Wednesday, 14:15, Lecture Hall **GM2** Radinger, Building BD

# Modified Forward of Zero-offset VSP Record with Attenuation based on Ganley's Theory

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The synthetic seismogram with attenuation has better consistency with actual records, since it's more in line with real medium [1]. This paper studies the forward of zero-offset VSP record based on wave equation decomposition and layered structure theory [2]. Take the attenuation factor into account, consider reflection and refraction, then calculate down-going and up-going wavefield independently with source location on the surface and underground [3]. Seismograms of layered models are generated in view of Ganley's theory [4].

Compared with elastic record, the decrease of energy and frequency reveals the viscoelastic property. However, for the source located underground, we find the arrival time of down-going wavefield above the source arises and shifts up, which indicates errors from the original formula. Considering the down-going wave of the *i*th layer above the source is reflected by up-going wave from below, and the corresponding propagation time is repeated, so the term of $\mathrm{e}^{-\mathrm{j}\omega\Delta z_i/c_i}$ should be removed from the transfer matrix. The travelling time in recursion formula is corrected as follows and the asterisk marks the terms which are modified:

$$\mathbf{A}_i' = \frac{1}{\mathbf{T}_i(\omega)}\begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12}^{\;*} \\ \mathbf{A}_{21}^{\;*} & \mathbf{A}_{22} \end{bmatrix} = \frac{1}{\mathbf{T}_i(\omega)}\begin{bmatrix} \mathrm{e}^{\alpha_i\Delta z_i}\mathrm{e}^{\mathrm{j}\omega\Delta z_i/c_i} & \mathbf{R}_i(\omega)\mathrm{e}^{\alpha_i\Delta z_i} \\ \mathbf{R}_i(\omega)\mathrm{e}^{-\alpha_i\Delta z_i} & \mathrm{e}^{-\alpha_i\Delta z_i}\mathrm{e}^{-\mathrm{j}\omega\Delta z_i/c_i} \end{bmatrix} \tag{1}$$

Where, $\alpha_i$ indicates the attenuation factor; $\mathbf{T}_i(\omega)$ and $\mathbf{R}_i(\omega)$ are the Fourier transform of refraction and reflection coefficient for the *i*th layer from surface to the focal depth; $c_i$ and $\Delta z_i$ are the velocity and thickness of the *i*th layer, respectively.

By means of the modification, wavefield is deduced correctly from the first layer to the last one. Applications show that down-going wavefield above the location of source starts to spread only after the direct wave appears. This phenomenon follows the law of propagation, and the rationality of correction applied to transfer coefficient matrix is verified.

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Wednesday, 14:35, Lecture Hall **GM2** Radinger, Building BD

# A Mathematical Morphology Method for Denoising and Fracture Characterization in Seismic Exploration

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Mathematical morphology is a popular and developing science since it was proposed by Mathreon and Serra in 1964 [1]. This approach has been widely taken advantage to a variety of image processing which is based on shape [2], such as computer image analysis, medical image processing, materials science and robot vision, et al [3]. However, the application to geophysics is not very common currently [4-5].

For the seismic exploration, the record is a signal or also can be regarded as an image [6]. Combined the morphological structure and the characteristics of seismic data, we carries out a new filter with an additional amplitude adjustment, and then apply it to denoise and portray fracture edge for processing and interpretation. Concretely, we achieve the calculation to a synthetic seismic data, which is composed of Ricker wavelets with 80Hz dominant frequency as the effective signal and a combination of 20Hz and 50Hz sinusoidal signal as interference. Compared with results from Li [6], our method can suppress noise completely, but also can protect the energy of Ricker wavelets from damage. The S/N is enhanced from 5.27dB to 8dB. After theoretical tests, it's applied to a practical microseismic data. With our method as a low pass filter, the recognition of weak signals in strong noise background is realized. On the other hand, we also utilize this improved operator as an edge detection for fracture characterization in slicing of 3D seismic images. The results of dilatation difference can match with structural diagrams better and be consistent with faults, since the calculation highlights the edges and weakens the internal small details. From the results of our attempts, it's believed that mathematical morphology is suitable in geophysics. It's hoped to be introduced and broaden application fields to achieve unique effect than regular and matured methods.

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Wednesday, 14:55, Lecture Hall **GM2** Radinger, Building BD

# Location of Acoustic Emission Microseismic Events based on Phase-only Correlation and Genetic Algorithm

Yinting Wu[1,2] and Guangming Zhu[1]

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Microseismic is based on acoustic emission and seismology. The accumulated internal energy is released in the form of stress wave when fractures are generated, expanded and rubbed, this results in microseismic events. Theoretically, from the observation and analysis of weak seismic events, the fractures' spatial distribution and development trend can be described. This technique is critical for non-conventional gas-oil exploration. However, the existence of an unknown number of events with the characteristics of weak energy and high frequency, is usually quite large and concentrated in a certain time period. It's difficult to identify, pick up and locate the effective ones.

This paper is focused on depicting locations of microseismic events during hydraulic fracturing based on phase-only correlation algorithm (POC) [1] and Genetic Algorithm (GA) [2]. First, we utilize POC, which is one of the fingerprint identification methods, to pick up the arrival time. Feature extraction and matching is processed [3]. Each channel in every sliding window is treated as a 2D graph. The cross phase spectrum between standard and the rest channels is obtained by 2D Fourier transform, and the influence of amplitude is removed. Then the phase correlation coefficient can be achieved, from which the degree of similarity and the displacement of two signals can be determined. This method can detect weak signals in strong noise background and is superior to the amplitude correlation method and instantaneous frequency method. This is the first step and the acquisition time is used for subsequent inversion, which is that we combine the extracted time difference and GA for the location of fractures [4]. Select the appropriate exchange rule and mutation rate. A 3D synthetic microseismic model is set and solutions are achieved through the establishment of two objective functions. Comparison of the two functions shows that differences exist not only in the accuracy but also in the convolution speed. In this example, the error ratio could run up to 2.7025, and time-cost reaches a difference of triple times. So, it's necessary to consider and choose the reasonable one. In addition, a field data is also processed. From a series of different views and the total solutions, we could evaluate the fracture development.

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Wednesday, 15:15, Lecture Hall **GM2** Radinger, Building BD

# A Data Driven Representation Method for Nonstationary Convolution Seismic Trace Model with Application to Enhancing Resolution of Seismic Data

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The convolution model is the theoretical basis for seismic data processing and enhancing vertical resolution of seismic trace and inversing the reservoir features. This model is most useful when applied to a band limited vertical section of the waves with a limited emergent angle. In particular, if the 3-D prestack seismic data is imaged and corrected properly, or imaged with true amplitude, each seismic trace in the post stack seismic data could be considered approximately to meet the convolution model.

In the convolution model, it is generally assumed that the seismic wavelet is not varying with seismic wave traveling-time. This hypothesis, however, fails under some conditions. As a matter of fact, the seismic trace meets the varying-wavelet model, i.e. non-stationary convolution model [1]. Therefore, we propose a data driven representation method for nonstationary convolution seismic trace [2]. The proposed method contains two steps. Step1: splitting the nonstationary seismic trace into several segments, each of them is stationary. To this end, we propose two approaches, one is deterministic method and another is statistics one. Step 2: Constructing molecular frame transform based on the segments which has an exact inverse transform.

In order to estimate the Q factor from the seismic trace or enhance the resolution of seismic trace, the Fourier amplitude spectrum of “equivalent wavelet” for each molecular is required. Therefore, we construct a constructive operator to obtain the amplitude spectrum [3].

As an application, we propose a method to enhance the resolution of seismic trace. The effectiveness of the proposed method is verified by both synthetic and field data. We compare our method with spectrum-whitening method and the results suggest that the proposed method can produce true reflector coefficients, which is very important for lithology reservoir identification.

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Tuesday, 10:15, Lecture Hall **GM4** Knoller, Building BD

# Discontinuous Galerkin Algorithm for Elastic Wave Scattering by Arbitrary Discrete Fractures

Qiwei Zhan[1], Qingtao Sun[1], Qiang Ren[1], Yiqian Mao[1], Yuan Fang[1], Qing Huo Liu[1]

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Fractures in a medium can induce significant scattering, phase-shifting, and anisotropy, and thus are important to characterize in geophysical exploration, ultrasonic inspection, and hydrocarbon reservoir characterization. Various techniques have been developed to model elastic wave propagation in fractured media. However, directly using an exact volumetric model to simulate a fracture is impractical because its ultra-thin fracture space will lead to an extremely fine mesh in conventional numerical methods. Traditionally, the linear-slip model, where the fracture displacement discontinuities are assumed proportional to the traction on the fracture surface, is used to simulate fractures.

In this work, we focus on explicitly modeling fractures using the 1st-order partial differential equation based discontinuous Galerkin algorithm, where the fractures can be multiple and arbitrarily oriented. We develop a non-conformal mesh discontinuous Galerkin (DG) pseudospectral time domain (PSTD) method for 3D elastic wave scattering problems with arbitrary fracture inclusions. In contrast to directly meshing the exact thin-layer fracture, we use the linear-slip model as one kind of transmission boundary condition for the DG scheme. Through this, we can efficiently impose a jump-boundary condition by defining a new numerical flux for the surface integration in the DG framework. This transmission boundary condition in the DG-PSTD method significantly reduces the computational cost. 3D DG simulations and accurate waveform comparisons validate our results for arbitrary discrete fractures. Numerical results indicate that fractures have significant influence on elastic wave propagation.

Tuesday, 10:45, Lecture Hall **GM4** Knoller, Building BD

# Theoretical and Numerical Simulations of the Indirect Collar Waves in Sonic Logging While Drilling

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Sonic logging while drilling (LWD) is an advanced geophysical exploration technique widely applied nowadays. For such a down-hole acoustic measurement, the suppression of collar waves is the key issue, as those cylindrical guided waves along the rigid tool strongly interfere with the needed P- and S- waves of the penetrated formation. Previous studies on physical insulation for the collar waves designed on the steel collar between the source and the receiver sections did not bring to a satisfying solution. According to our numerical results by the 3D finite difference, it is revealed that, besides the well-known direct collar waves propagating all along the tool, there exists an indirect collar wave in the LWD signals due to the coupling between the drill collar and the borehole. The newly recognized indirect waves cannot be completely blocked even there is a perfect isolator set between the source and the receiver [1]. This is why the collar waves could hardly be eliminated with good effects in many cases by the designs of physical isolators carved on the tool.

To further investigate the propagation mechanism of the indirect collar waves, we analytically evaluate the contributions of the poles of the characteristic function for LWD models in the borehole and in the infinite fluid, respectively. We set an artificial interface located at the collar interior, and let the stress source impulse be loaded on that boundary. The characteristic function can thus be derived by solving the boundary conditions of all radial layers [2]. The influences of the presence of the borehole wall on the collar wave propagation are discussed, based on the comparison of collar waves in infinite fluids and in boreholes with varying sizes. It is confirmed that the indirect collar waves are produced by the reflection echoes from the borehole wall, and they interfere with the direct collar waves during propagation. The indirect collar waves have similar amplitudes as the direct waves in either the time or the frequency domain, and they do not have apparent attenuation at different offsets in the elastic models. Although the formation properties do not have great impacts on the tool-waves, it is still suggested that one should take the borehole and the formation into account during designing or testing the LWD tool (especially, transducers and isolators). The borehole wall can generate extra collar modes, which are rather strong and should not be neglected.

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Tuesday, 11:15, Lecture Hall **GM4** Knoller, Building BD

# Sensitivity of Biot Slow Wave to Fluid Content and Pore Structure of Fractured Porous Rocks

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In recent years, compressional (P) and shear (S) waves have been used extensively to infer rock and fluid properties from seismic data using Gassmann's equation. In addition to these two body waves, Biot in the 1950's developed a poroelastic theory that predicted a second slow P wave in a porous medium. In 1980, Plona reported the observation of a second slow P wave in water-saturated fused-glass-bead samples at ultrasonic frequencies. Using an extended Biot theory, we further demonstrates the possibility of existence of a second slow S wave. Both slow P and S waves are sensitive to variation of fluid content and pore structure of rocks. P-wave velocity of a water-saturated rock is higher than the P-wave velocity of the same rock when gas-saturated. However the slow P-wave velocity of a water-saturated rock is always lower than the slow P-wave velocity of the same rock when it is gas-saturated. Slow waves are more sensitive to pore geometry such as aspect ratio than porosity and crack density. Slow waves are interfacial waves internal to the porous structure of a rock and rock-fluid coupling. Thus more wave energy is converted to interfacial wave energy when the rock is gas-filled than when it is liquid-filled.

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Tuesday, 11:45, Lecture Hall **GM4** Knoller, Building BD

# Overview of Applications of Microwaves in Medicine

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Interactions of EM field with biological systems are utilized in the area of therapy (oncology, physiotherapy, urology, etc.) from late seventieth of last century. Wide utilization of microwave thermotherapy can be observed in the countries of EU, USA, Russia, China, Japan and many others, including the Czech Republic. Important role in development in this area play scientific societies like e.g. ESHO (European Society for Hyperthermia Oncology), which co-operates with STM (Society for Thermal Medicine) and ASHO (Asian Society of Hyperthermia Oncology). Nowadays the electromagnetic (EM) fields are generally used in several well-established medical applications already. Typical examples are e.g. CT and MRI in medical diagnostics as well as e.g. radiofrequency (RF) heating in physiotherapy, microwave (MW) hyperthermia and RF + MW ablation in clinical therapy. Therapeutic applications of MWs, e.g. MW hyperthermia and ablation, are being used for the cancer treatment and treatment of some other diseases. We in this work give a basic overview and divide the medical applications of microwaves in following three basic groups according to the usage: Treatment of patients; Diagnostics of diseases and Part of a treatment or diagnostic system.

Until now, medical applications of microwaves are represented by the treatment methods based on thermal effect, which can be further divided into three different modalities distinguished according to the goal, temperature level or interval: Diathermia - heating up to 41 C(physiotherapy); Hyperthermia - heating to the interval of 41-45 C (oncology), and Thermodestruction/thermoablation: over 45 C (urology, cardilology).

Recent trends in microwave medical applications are to study the possibilities to develop new diagnostics based on EM field resp. on microwave technique - like e.g. diagnostics of cancer, stroke identification and noninvasive temperature monitoring of hyperthermia treatment. In a near future, significantly importance methods are: MRI and CT (widely used in clinics already), Microwave differential tomography, Microwave radiometry, Microwave diagnostic radar.

MRI is working mostly in frequency bands from 64 to 299 MHz (upper part of the so called RF band), CT then is working in hard X-ray band. Frequency bands between these two is the MW frequency band, i.e. frequencies from 300 MHz to 300 GHz. Lower part of this frequency band, approx. from 300 MHz till 6 GHz, is very prospective for Microwave Medical Imaging. Upper part of this frequency band, i.e. frequencies above approx. 100 GHz are very prospective for imaging with terahertz waves.

The use of MWs for medical diagnostics is relatively new but rapidly developing area. The main advantages of MW technology are as follows: MWs belong to a nonionizing radiation and for diagnostics purposes low power levels (1-20 mW) are used only. Furthermore, since the MW technology is being massively used in mobile telecommunication the MW diagnostic systems have potential to be one or even two orders of magnitude less expensive than MRI.

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Tuesday, 15:00, Lecture Hall **GM4** Knoller, Building BD

# Piezoelectric Transducer Modeling in Anisotropic Media

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Piezoelectric transducers (PZTs) are important sensors in many applications, but their simulations require the modeling of complex electromagnetic wave fields coupled with elastic waves in anisotropic media with tentorial elastic constants, electromagnetic constants, and piezoelectric coupling coefficients. Efficient and accurate computation of 3D piezoelectric transducers is key to their design optimization in biomedical, industrial, and geophysical applications.

In such applications, an acoustic transmitter made of a piezoelectric transducer generates an acoustic signal by converting an electrical signals into a mechanical vibration that travels through the medium. On the other hand, receivers made of piezoelectric crystals transform the measured acoustic signals back into electrical signals. Traditionally, a quasi-static approximation is used in the electromagnetic modeling of PZT. In this work, we develop a 3-D spectral element time domain method to model 3-D PZTs in full-wave electromagnetics and elasticity without approximation. The elastic wave propagation in the piezoelectric substrate of a transducer is excited by applying an impulsive voltage signal to the transducer electrodes, and piezoelectric substrates transform acoustic signals back into electrical signals. A fully coupled elasto-electromagnetic model for a piezoelectric medium has been implemented, and a full piezoelectric model of the transducer is used, including anisotropy in the elastic, dielectric, and piezoelectric constants. This spectral element time domain solver is verified by several 3-D numerical examples through their comparison with a finite element method. Significant advantages of this solver over the finite element method will be demonstrated.

Tuesday, 15:45, Lecture Hall **GM4** Knoller, Building BD

# Dielectric Signature of Living Microorganisms in Sediments and Rocks: Theoretical Model and Numerical Results

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Among the fundamental problems of science are the origin, distribution and future of life. Two of the essential steps in addressing these questions are to define various life forms in scientific and quantitative terms and to map the extent of these life forms in their natural habitats on Earth and other planets.

When we limit ourselves to lives in material forms with or without consciousness, electromagnetic force is a common basic cause acting on them from virus and prokaryote to plant and man, to our best knowledge. It seems that all life forms and ordinary non-life matters have definite electromagnetic signature. Furthermore, the cellular structure seems to be common to all basic life forms and celestial bodies, regardless of their content and composition. That such a structure is preferred by Nature is also because of the physical origin of either electromagnetic force or gravitational force, and optimization of geometrical arrangement. The functionality of a cellular life consists of electromagnetic operations at the atomic and molecular level by controlling largely the behaviour of cell membrane. A cell death is usually accompanied by the destruction of the membrane that eliminates the cellular structure. This functionality of cellular life should remain similar for all basic life forms, although the molecules of the cell membrane and nucleus can be entirely different from one life form to another. Thus it should be a valid universal assumption that a basic unit of life has a cellular structure being acted on by electromagnetic force, as a necessity of life. Therefore, studies of the electromagnetic properties of microorganism-bearing porous media, should provide means to distinguish life from non-life, to differentiate life forms, and improve our ability for searching for life by measuring and classifying the dielectric signatures of matter and life.

In this work, we propose a dielectric model of porous media saturated with microbial-bearing fluids to study the dielectric signatures of bio-concentration in sediments and rocks with varying porosity, salinity and frequencies. Theoretical and numerical results could be useful to design bio-probes for laboratory experiments and bio-logging tools for field applications to deep biosphere and astrobiology.

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Tuesday, 16:30, Lecture Hall **GM4** Knoller, Building BD

# Sound intensity fluctuations in the presence of moving nonlinear internal waves in shallow water

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In the paper sound propagation in shallow water waveguide is considered in the presence of nonlinear internal waves (NIW) in the form of train of solitons or individual soliton (IS) moving approximately from the source to receiver (vertical line array – VLA). Angle between wave fronts of NIW and acoustic track is supposed to be not small (> 35-45 o ), that provides mode coupling as main reason for the sound fluctuations [1]. Specific feature of the sound field is the presence of peaks in temporal spectrum of these fluctuations corresponding to predominating frequencies [2]. Remark that spectrum of fluctuations of the sound field at fixed depth (separate hydrophone) differs from the spectrum of total intensity, which is summarized over the depth of the waveguide (or over all hydrophones of VLA) due to different modal attenuation coefficients in a waveguide. In [2] methodology is proposed to estimate bottom parameters on the base of analysis of mentioned spectra. In given paper numerical modeling using PE is carried out for the shallow water waveguide with parameters corresponding to experimental situation in the South China sea (experiment ASIAEX 2001) [3]. Shallow water waveguide of the length about 30 km consists of two parts: about 20km with the depth 250 m, and 10 km with the depth about 120 m, and individual soliton of the amplitude about 100 m moves on the first part during 3 hours. In this case, two sorts of mode coupling take place: (i) due to the presence of moving IS and (ii) due to variation of the depth in some area between two parts of an acoustic track. In the first case, interaction between modes depends on time and can be selected. On the base of PE modeling fluctuations of the sound field at the frequency 224 Hz are analyzed using modal decomposition of time dependent sound field at the VLA. Waveguide modes are constructed numerically on the base of experimental data (sound speed profile and bathymetry measured along acoustic track). Modal amplitudes depend on time and the corresponding spectrum contains predominating frequencies, determined by spatial scales of interference beating of modes and speed of IS. Using comparison of spectra of total intensity and spectrum of the sound intensity at fixed depth, it is possible to estimate bottom attenuation coefficient. Results of modeling are compared with experimental data.

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Monday, 10:45, Seminar Room BD **02A**, Building BD

# Monitoring Internal Wave with Broadband Interference Pattern of Normal Mode Amplitude

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A moving internal wave can cause mode coupling and influence the mode amplitude of sound wave [1]. Previous works mainly focused on the interference pattern among multiple modes[2][3], while this paper is concentrated on the interference pattern in frequency domain for a single coupled normal mode amplitude obtained with warping transform[4]. There are certain interference striation patterns in time-frequency domain for broadband signals which propagate through a moving internal wave. The slope of the interference striation which is proportional to the propagation distance for internal soliton wave is derived according to coupled normal mode theory. The received broadband signals travelling through internal soliton wave in shallow water are simulated with PE method and coupled normal mode amplitudes for these signals are obtained with warping transform. The variation of broadband interference pattern for these normal mode amplitudes is analyzed. It is shown with the simulation results that the interference striation slope estimation can be used to locate internal soliton wave and monitor its propagation procedure.

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Monday, 11:05, Seminar Room BD **02A**, Building BD

# Maximum Entropy Method for Reconstruction of Ocean Current Field

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Ocean acoustic tomography (OAT) [1], proposed by Munk and Wunsch in 1979, aims to infer the state of ocean, such as current velocity, temperature, and so on, from the measured travel time or other acoustic measurements. We use the measured travel time as the observed data to infer the current velocity through solving the integral relationship between the former and the latter by several inverse problem solving methods.

In traditional acoustic tomography experiments, Fourier series is often used to reconstruct the current filed as basis function [2]. However it exists periodic effect of the solutions and edge truncation effect. Tabuchi proposed a neuro-fuzzy approach to reconstruct smooth distribution field using Radial Basis Functions (RBFs) networks [2]. In this paper, we use RBFs as basis function for the reconstruction of current field. To reconstruct current field, we shall solve the coefficient equations of RBFs, which is an inverse problem. The least square (LS) method will achieve good results if we know appropriate constraint information. However, it is hard to choose, and irrelevant constraint information will cause unsatisfactory results. Thus, we adopt the maximum entropy method to reconstruct the current field. Compared to the least square method, the performance of the maximum entropy (ME) method is not dependent on the choice of constraint information, and its solution is most objective, or maximally uncommitted [4]. The comparison of the ME method with the LS method by a series of simulations and the experimental data in Zhitouyang Bay near Zhoushan Island proves that the ME method achieves a lower root-mean-square error (RMSE) and a higher cosine similarity.

Keywords—ocean acoustic tomography; ocean current field; inverse problem; radial basis function; maximum entropy method

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Monday, 11:25, Seminar Room BD **02A**, Building BD

# Tomographic Inverting for Intrinsic Attenuation of Sea-bed Sediment

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It has been known that the inverted geoacoustic (GA) parameters of the bottom sediment via matched field inverting (MFI) under an assumed layered model could only be the so-called "effective" but not the intrinsic parameters whenever the assumed layered sediment model is apart from the true layered structure. Specially, the frequency dependency of the intrinsic attenuation α(f) will be distorted due to the mixed up of the layered waveguide dispersion and the intrinsic GA parameter dispersion caused by model-mismatching. In order to get the true intrinsic GA parameters, especially the attenuation we need to have accurate enough profiles of the GA parameters as the assumed model to do MFI. In other words, instead of making an assumed layered model, we have to do the tomographic inverting to get accurate enough profiles and then we can get accurate enough intrinsic dispersion character. In this paper, we propose a new tomographic inversion approach using the model-free reflective parameters P(f) and Q(f) to synthesize data $\beta_m(f)$ on a broad enough frequency band. Then, the non-linear inversion scheme is used to invert the "combined GA profile" which can give the intrinsic attenuation α(f) without distortion. Some numerical simulations and preliminary experimental results are presented.

Monday, 11:45, Seminar Room BD **02A**, Building BD

# Sequential processing of multiple explosive sources for bottom characterization in shallow waters

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The acquirement of goeacoustic parameters is critical for accurate sound propagation prediction and sonar performance evaluation, and matched field processing (MFP) of measured sound fields have been developed for this purpose [1]. In Bayesian schemes, the inversion solution is provided in terms of posterior probability distributions (PPDs) that combine the information from both prior knowledge and available data. Sampling approach [2] can be adapted for the estimation of PPDs, which may have difficulty in dealing with successive data sets efficiently. This paper adapts a sequential Monte Carlo technique, i.e., particle filtering [3], to incorporate successive data inputs for bottom characterization in shallow waters.

The Yellow Sea data [4] collected on a vertical line array composed of 30 pressure sensors are processed. The source is a 38-g explosive charge that deployed at different ranges (times) from a sailing ship, and detonated at an approximate depth of 7 m [4]. The seabed is treated as a half-space model based on prior knowledge, and associated geoacoustic parameters are estimated by the PF through observing the complex pressure fields across the VLA at discrete frequencies. The results of PF processing are in general accordance with that of time-warping [4], and moreover, the integration of the PF results from different sources can be used to infer the environmental inhomogeneity.

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Monday, 12:05, Seminar Room BD **02A**, Building BD

# The Frequency Dependence of the Effective Seabed Sound Speed Inverted from 2016 Yellow Sea Experimental data

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At low frequencies, the frequency dependence of the seabed sound speed $c_b$ is minor [1] and always ignored in most of the inversions of seabed geoacoustics parameters based on the half-space model [2]. This assumption is always correct in the case of homogeneous seabed, i.e., half-space seabed. In most of the real oceanic environments, the seabed is always layered, and the distortion of the inverted seabed parameters, especially the seabed attenuation will be introduced if ignoring the layered structure [3]. Since the details of the layered structure of the seabed is so critical to the inversion of the seabed attenuation and it is always not available, one compromised method is to consider the frequency dependence of the effective seabed sound speed instead of the details of the layered structure in the inversion scheme. Ref.[3] has testified its effectiveness in eliminating the distortion of inverted seabed attenuation with theoretical analysis and numerical simulations. Hence to obtain the curve of $c_b(f)$might become the first step of the inversion of the seabed parameters for those methods based on the half-space seabed model.

In the winter of 2016, an experiment of seabed inversion was carried out in Yellow sea of China. Two sites with different types of seabed, site A and site B was chosen. The seabed of site A is "hard seabed" with relatively high sound speed and has no obvious layered structure, and the seabed of site B is "soft seabed" with relatively low sound speed and has obvious layered structure. A broad band-width (f=100~1kHz) transducer with high power was used as the source and a vertical array covering the whole water depth as the receiver in the experiment. The curve of $c_b(f)$ was inverted from the field received at the close range with MFP method. The inverted results show that the effective sound speed of the seabed at site B decreasing from 1585m/s to 1520m/s as the frequency varying from 100Hz to 630Hz. The inverted sound speed also has good coincidence with the sound speed measured directly from the coring samples.

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Monday, 12:25, Seminar Room BD **02A**, Building BD

# Analytical and numerical solution for whispering gallery waves near curved isobaths in shallow water

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The horizontal refraction phenomena (or 3D effects) in a shallow-water waveguide with the bottom relief featuring curved isobaths is studied. This situation can be met in areas of a coastal slope that are characterized by curvilinear coastal line, e.g. lagoons and bays, as well as in lakes. Typical curvature radii of isobaths can be estimated from the bathymetry data, and usually they amount to few kilometers.

In our model the bottom relief in cylindrical coordinates $(r, z)$ is described by a function $h(r)$, that is monotonically decreasing with respect to *r* (i.e. we deal with a cylindrically-symmetric lake that is shallower for greater *r*). The waveguide consists of the water column $0 < z < h(r)$ and the penetrable bottom $z > h(r)$. At the surface $z = 0$ the pressure-release boundary condition for the acoustic pressure $P(r, z)$ is imposed.

In the framework of the mode theory, the sound pressure in the water column due to a time-harmonic point source writes in the form of a modal expansion

$$P(r,\theta,z) = \sum_j A_j(r,\theta)\psi_j(r,z)\,, \tag{1}$$

where $\psi_j(r,z)$ are mode functions computed at given range *r*, depending on *r* as on parameter and $A_j(r,\theta)$ are modal amplitudes. The latter are obtained by solving the so-called horizontal refraction equations.

In the work, the condition for the media parameters and the bottom relief surface $z = h(r)$ ensuring the formation of a whispering gallery wave is studied. This condition has the form of a simple relation between the horizontal wavenumbers rate of change with respect to *r* and the waveguide geometry.

The derived relation is validated by the direct computation of the low frequency acoustic field due to a point source in a cylindrically-symmetric lake. The computation is based on a semi-analytical solution of the adiabatic horizontal refraction equations for the modal amplitudes. This solution is obtained via the separation of variables in the polar coordinate system. Results of numerical calculations are compared with solution using ray approximation in horizontal plane (vertical modes and horizontal rays approach). The possibility of excitation and observation of the whispering gallery waves (modes) in realistic shallow-water waveguides is discussed, and the respective simulation results are presented.

A representation of the amplitudes $A_j(r,\theta)$ in terms of the horizontal modes is also discussed. The conditions for efficient excitation of the whispering gallery modes are studied, and the resonance frequencies are determined using the WKB theory.

Monday, 15:30, Seminar Room BD **02A**, Building BD

# Characteristic acoustic impedance for more reliable environmental characterization

Qunyan REN[1,2], Licheng LU[1,2], Li MA[1,2], Shengming GUO[1,2], Tianjun LIAO[3]

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Environmental remote sensing approaches based on acoustical observables, e.g., spatial characteristics, dispersion curve or covariance matrix of sound pressure field have difficulty to resolve the ocean bottom density and attenuation coefficient very well: optimization algorithms may output biased estimates and Bayesian approaches can give flat marginal posterior probability distributions (PPDs) [1]. The capacity of a vector sensor [2] in simultaneously collecting the scalar and vector fields provides more comprehensive information for more accurate environmental measurement. In this paper, the possibility of adapting a combination of scalar and vector fields (characteristic acoustic impedance) to increase the accuracy of geoacoustic inversion is discussed theoretically and numerically.

Analysis based on normal mode theory proves the change of relative impedance amplitude is stronger than that of pressure or particle velocity component for the same perturbation of environmental property. As a consequence, the impedance is demonstrated more sensitive to bottom geoacoustic parameters in a Bartllet-type objective function that comprises the amplitude and phase consistences between data and replica. Numerical inversion tests were conducted under the seceniro of the representative Yellow Sea environment, China, 2002 [3], the recording system is assumed to be a moored vertical line array composed of 30 vector sensor elements with an interval of 1 m among them. The marginal PPDs of the investigated parameters are estimated by a Metropolis-Hasting sampling algorithm [4] by observing the pressure field, particle velocity component and impedance across the VLA. The results obtained from the impedance demonstrate more rigorous and concreted PPDs, especially for the density and attenuation coefficient. The promising results suggest more reliable environmental information is expected if the impedance is employed in real data processing.

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Monday, 15:50, Seminar Room BD **02A**, Building BD

# Spatial Variability of Ocean Ambient Noise Spectrum in China Offshore

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On the account of ocean ambient noise sources diversity and noise propagation along different propagation waveguide, the ocean ambient noise on different measurement positions lead to the obvious differences in temporal and spatial. This paper analyzes ocean ambient noise sound pressure level spectrum characteristics measured in two different position on China offshore firstly, the result shows that the broadband noise spectrum level variation in different measuring position strongly related to China offshore underwater acoustics environments. Through modeling the noise propagation channel and simulation analysis, compared to the experiment data show that the band of 50Hz ~ 500Hz frequency noise spectrum differential and transmission loss differential with a strong correlation. In addition, in different measuring time vessel density differences caused the noise source spectrum level differ about 20dB. These prove at this frequency band the ambient noise is closely related to ship noise sources, and the noise difference between the two positions results from the transmission loss and the ship noise sources.

Monday, 16:50, Seminar Room BD **02A**, Building BD

# *Reverberation intensity decaying in range-dependent waveguide*

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A shallow water range independent reverberation model based on Perturbation theory has been proposed recently. In this paper, the range independent reverberation model was extended to range dependent waveguide. The bottom composite roughness has been considered. Small scale bottom rough surface provides dominating energy for reverberation. While large scale roughness has the effect of forward and back propagation. Its backscattering energy can be neglected compared to small scale roughness backscattering. For the case of slowly-varing bottom and short signal pulse, Small scale roughness backscattering theory used in range independent reverberation model has been used in range dependent waveguide. And the Green function of range dependent waveguide was calculated using PE program. Modal spectrum of PE field was got through traditional orthogonality property of normal modes. Numerical analysis shows that the reverberation model in range dependent waveguide proposed in this paper can be instead of range independent waverguide reverberation, and works well in range dependent waveguide.

Monday, 17:10, Seminar Room BD **02A**, Building BD

# Wave Attenuation in Metamaterial Beams

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Over decades, periodic structures have been viewed as good candidates for vibration reduction or noise isolation. One typical example is phononic crystals consisting of periodically distributed inclusions in a matrix [1-2]. Those crystals exhibit unique physics properties and can be used for attenuating elastic/acoustic waves at certain frequencies. The wave filtering feature is attributed to the structural periodicity. The resulting attenuation band is called Bragg-type bandgap which is usually occurred in the high frequency regime. Recently, metamaterials offer an additional possibility for eliminating undesired vibration/sound. Liu et al. [3] first proposed a type of composite consisting of an epoxy matrix with periodic coated spheres, which can act as a local resonator. To enrich wave filtering property, many other types of resonators have been developed. Of particular interest is membrane-type acoustic metamaterials comprised of tensioned elastic membranes with loaded masses [4-5]. This type of metamaterial has been viewed as a good tool for insulating low-frequency sound. By adjusting membrane and mass properties, the transmission characteristics can be tuned. With different masses at adjacent cells, multiple sound attenuation peaks can be created and the bandwidth can be conspicuously enlarged. In this study, we attempt to apply the concept of membrane-mass resonator in vibration suppression. The proposed metamaterial beam consists of a host beam containing periodic circular cavities filled with membrane-mass structures. The dispersion relation and bandgap characteristics are emphasized. Two kinds of bandgaps exist in the present structure: locally resonant bandgap (LRBG) and Bragg-type bandgap (BBG). The former originates from the resonant behavior of the resonator while the latter results from the structural periodicity. By altering the properties of the membrane-mass structure, the LRBG can be easily tailored. Multiple cells with different masses can create multiple bandgaps. If the masses are selected to be close enough, the bandgap can be effectively broadened.

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# The noise reduction using meta impact damper for water spray induced vibration

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This study was proposed meta structure with a low vibration by collision damping for water spray induced vibration. An impact damper was generated the energy dissipation by collision between the beam and the damper. The experiment applied by collision damping using an impact damper performed to verify a noise reduction. As a result, the meta impact damper reduce the water spray noise and structural vibration.

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Wednesday, 14:15, Seminar Room BA **02B**, Building BA

# Research on the Finite-amplitude Sound Pressure in the Membrane-sealed Pistonphone

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Aimed at the accurate measurement for the high sound pressure, a primary sound pressure calibration for microphones with the high pressure levels becomes more and more important [1][2], especially at the very-low frequencies. First, a primary very-low frequency finite-amplitude sound pressure calibration device with a pistonphone is proposed, which mainly includes a high precision very-low frequency electromagnetic vibrator and a membrane-sealed coupler. The precision vibrator could output low distortion displacement for the piston, and the membrane-sealed coupler ensures the large time constant for the pistonphone. Secondly, the structure for the membrane-sealed coupler is presented, and the deformation characteristics and dynamic characteristics of the membrane under static load are studied. Thirdly, the nonlinear theories for the finite-amplitude sound pressure in the membrane-sealed pistonphone are studied. The first and second order distributed parameter expressions for the finite-amplitude sound pressure are built under airtight and adiabatic conditions, and nonlinear distortion characteristics of the finite-amplitude sound pressure are studied, and the first and second order intermodulation expressions for the finite-amplitude sound pressure are also built under airtight and adiabatic conditions, and the effects of the intermodulation on the sound pressure distortion are studied. Finally, a very-low frequency finite-amplitude sound pressure calibration device is developed, and the finite-amplitude calibration capacities and distortion characteristics of the device are proved at the very-low frequencies and the high pressure levels.

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# A Uniform Formalism for Acoustic Wave Propagation in a Mixed Liquid-Solid-Porous Viscoelastic Multilayered Structure

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To deepen the understanding of the ultrasonic behaviour of human multi-layered bone tissues, cortical bone for example, the reflection and transmission of ultrasonic wave at such a structure consisting of a combination of liquid-solid-porous layers was studied. A mathematical model for the plane wave propagation in the layered media was developed using the stable stiffness matrix technique, and taking into account the boundary conditions at each type of interface. First, a recursive algorithm was developed to compute the global stiffness matrix of a multi-layered structure whose layers could be of any type of the classical media (liquid, isotropic solid, or isotropic poroelastic medium), based on the assumption that all layer interfaces are perfect which implies the continuity of displacement and stress. The multi-layered structure being merged into a single layer, the reflection and transmission coefficients were calculated considering that the whole structure is bounded by fluids. Then, a back-recursive algorithm was developed to compute the displacement vectors amplitudes in each layer, which allows the calculation of acoustic field in every layer based on the angular spectrum approach. As an application, the reflection and transmission coefficients as a function of incident angle and frequency were obtained for a five layers configuration bounded by fluid.

Thursday, 13:50, Seminar Room BD **02A**, Building BD

# Dispersion of Rayleigh-type wave in an exponentially graded incompressible Crustal layer resting on yielding foundation

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In the present paper, we study the propagation of Rayleigh-type waves in an exponentially graded incompressible layer resting on yielding surface. We have considered a heterogeneous initially stressed isotropic layer of finite thickness $H$ with yielding surface at $y = H$. Let us choose a co-ordinate system in such a way that, $y$ – axis is directed vertically downwards and $x$-axis is assumed in the direction of the propagation of Rayleigh-type wave. The geometry of problem is depicted in FIGURE1.

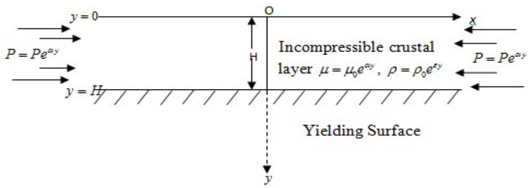


**FIGURE 1:** Geometry of the problem

The equilibrium equation for Rayleigh type waves in Cartesian coordinate system $(x, y, z)$ under initial stress P can be written as follows: [1]

$$\left.\begin{aligned} -\frac{\partial \Pi}{\partial x} + \mu\nabla^2 u + \frac{\partial \mu}{\partial y}\left(\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}\right) - \frac{P}{2}\frac{\partial}{\partial y}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) = \rho\frac{\partial^2 u}{\partial t^2}, \\ -\frac{\partial \Pi}{\partial y} + \mu\nabla^2 v + 2\frac{\partial \mu}{\partial y}\frac{\partial v}{\partial y} - \frac{P}{2}\frac{\partial}{\partial y}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) = \rho\frac{\partial^2 v}{\partial t^2}, \end{aligned}\right\} (1)$$

where $u$ and $v$ are the displacement components along $x$ and $y$ directions respectively, $\Pi$ is the hydrostatic stress, $\lambda$ is Lame's constant and $\Delta$ is dilatation.

Using Boundary Conditions of stress-free surface at $y = 0$ and yielding surface $y = H$ in the above defined relation wehave found the dispersion equation of Rayleigh-type wave in an initially stressed heterogeneous isotropic layer resting on yielding base. The dispersion relation being a function of phase velocity, wave number, initial stress and heterogeneity parameter, reveals that the fact that Rayleigh-type wave propagation is greatly influenced by above stated parameters.

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Thursday, 14:50, Seminar Room BD **02A**, Building BD

# Acoustic Source Localization from Microphone Measurements using an Inverse Scheme based on Finite Element Simulations

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Acoustic source localization from microphone array measurements is a major task arising in many applications. Standard reconstruction schemes such as frequency domain beamforming often perform well but in certain relevant settings suffer from considerable reconstruction errors due to simplifications of the models for the sources as well as the measurement setup. To overcome these limitations, we base our reconstruction on solving the corresponding partial differential equation in the frequency domain (Helmholtz equation) by applying the Finite Element Method (FEM). In doing so, we can consider the actual boundary conditions as given in the measurement setup. To recover the source locations, we apply an inverse scheme based on a sparsity promoting Tikhonov functional to match measured (microphone signals) and simulated pressure. The applicability and the additional benefit of this inverse scheme compared to the frequency domain beamforming will be demonstrated.

Wednesday, 10:15, Seminar Room BA **02B**, Building BA

# Robust Multiple Time-Reversal Focusing

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Time-reversal processing (TRP), also referred to as phase conjugation (in frequency domain), is based on the backpropagation of a time-reversed version of the received signal. Because of the time-reversal invariance (reciprocity) of the wave equation, the signals that are back-propagated from a time-reversal mirror (TRM) are spatio-temporally focused in the locations where they originated.

Kim *et al* [1] suggested an adaptive time-reversal mirror (ATRM) based method, which back-propagates the weight vector obtained as the optimal solution of an objective function with a single imposed constraint. The method is capable of focusing the distortionless response at a single location, while at the smae time forming nulls, by minimizing the total reception power at arbitrary different locations. Additionally, Kim and Shin [2] suggested an extension of the single constraint ATRM to simultaneous multiple focusing, by considering multiple constraints. In their proposed method, the optimization is performed using the linearly constrained minimum variance (LCMV) method, a well known optimization method in the field of adaptive signal processing that allows multiple linear constraints. However, in case that multiple focal locations which are constrained to have unity-magnitude are close to one another, the norm of the weight vector becomes large to satisfy the constraints, and prominent temporal and spatial sidelobes are caused as the weight vector is back-propagated in TRP.

In this study, the weight vector which is the same as the backpropagation vector in TRP is partially reformulated with the optimized multiple constraints such as $\mathrm{e}^{i\theta_1}, \mathrm{e}^{i\theta_2}, .., \mathrm{e}^{i\theta_\mathrm{N}}$.

$$\mathrm{w} = K^{-1}M\left[M^{\dagger}K^{-1}M\right]^{-1}f, \quad f = [1, 1, .., 1]^T \tag{1}$$

$$\mathrm{w} = K^{-1}M\left[M^{\dagger}K^{-1}M\right]^{-1}f, \quad f = [\mathrm{e}^{i\theta_1}, \mathrm{e}^{i\theta_2}, .., \mathrm{e}^{i\theta_\mathrm{N}}]^T \tag{2}$$

Exhaustive search is one straightforward way to find the optimal solution for a small number of focal locations. As focal locations are more needed to broaden the focal spots, it is found that genetic algorithm can be effective way to calculate the new backpropagation vector.

The performance of this method is investigated using experimental recordings based numerical simulations, and it is verified that the new approach has a significantly better sidelobe suppression performance with focusing the distortionless responses than LCMV method in TRP.

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Wednesday, 10:55, Seminar Room BA **02B**, Building BA

# Implementation of a Bandpass Filter and Beamforming Algorithms for Source Direction Finding for an ROV

Sea-Moon Kim[1], Sung-Hoon Byun[1], Kihun Kim[1], Chong-Moo Lee[1]

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A few years ago an underwater sound monitoring system for hearing fishery sound using three hydrophones installed on an ROV has been developed [1]. However, the operation of the system was not successful because of the high level of the self-noise generated by the ROV. Its thrusters had to be turned off to reduce the self-noise and listen to fishery sound clearly. Currently, Korea Research Institute of Ships and Ocean Engineering (KRISO) is developing a light-work class ROV and a similar underwater sound transmission system (USTS) with two largely-spaced hydrophones has been developed for the ROV. Its main purposes are not only to replay underwater sound on the surface vessel for ROV operators but also to identify external source direction. In order to satisfy theses purposes we focus on the minimization of self-noise effect and beamforming algorithm with the largely-spaced hydrophones. To minimize the self-noise effect, a digital bandpass filter with seven filter banks with octave bandwidth was implemented. The conventional delay-and-sum time-domain beamforming technique has been applied to analyze the source direction. To eliminate the spatial aliasing effect induced by the large hydrophone spacing the frequency-difference beamforming algorithms [2] are also considered. The performance of the beamforming algorithms was verified by using a receiver array signal simulator as well as numerical simulations. [This research was supported by a grant from National R&D Project "Development of core technologies for underwater construction robots including a light work-class ROV" funded by Ministry of Oceans and Fisheries, Korea (PMS3700).]

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Wednesday, 11:15, Seminar Room BA **02B**, Building BA

# Modelling and Simulation of Musical Instruments

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The mathematical characterisation of the sound of a musical instrument still follows Schumann's laws, [1]. the idea is that resonances of the instrument body, the formants, filter the oscillations of the sound generator (e.g. string) and produce the characteristic "timbre" of an instrument. This is a strong simplification of the actual situation. It applies to a point source and can be easily performed by a loudspeaker, but in reality an instrument is three dimensional. To describe the effect of geometry and material, we set up a three dimensional model and simulate it using the simulation system UG4, developed by the presenter's team.

UG4 is a fourth generation three-dimensional unstructured grid multi-grid solver package with a multi-physics modelling front end, ideally suited for the simulation of musical instruments in terms of capturing realistic geometry using distributed memory massive parallelism, [2], [3]. Core methods are parallel adaptive multi-grid methods, which allow extremely efficient and accurate simulations, finite volume and finite element methods on hybrid, unstructured grids and a visual programming environment based on VRL, [4].

We set up models of harpsichords and guitars in UG4, simulated these models and finally measured the oscillations of the soundboards by laser vibrometry to compare model and experiment. Results will be presented.

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Wednesday, 11:35, Seminar Room BA **02B**, Building BA

# Automatic Model Reduction and Error Estimation for Vibro-Acoustic Models Using Krylov Subspaces

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The finite element method is the most widely used technique for the numerical modelling of acoustic, structural dynamic and vibro-acoustic problems in industry. Its ability to produce accurate solutions to the underlying partial differential equations for complex geometries has greatly contributed to its popularity. The main drawback of the finite element method is the computational cost associated with solving the resulting algebraic systems of equations, which quickly grows with increasing system size and frequency. The large-scale system of equations to be solved can be written as:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F}, \tag{1}$$

where $\mathbf{M}, \mathbf{C}, \mathbf{K} \in \mathbb{R}^{\mathbf{n}\times\mathbf{n}}$ and $\mathbf{x}, \mathbf{F} \in \mathbb{R}^{\mathbf{n}\times\mathbf{1}}$. Model order reduction techniques attempt to greatly reduce the computational cost by constructing an approximate system of equations of much smaller size in the following way:

$$\mathbf{M_r}\ddot{\xi} + \mathbf{C_r}\dot{\xi} + \mathbf{K_r}\xi = \mathbf{F_r}, \tag{2}$$

with

$$\mathbf{M_r} = \mathbf{W^T}\mathbf{M}\mathbf{V}, \quad \mathbf{C_r} = \mathbf{W^T}\mathbf{C}\mathbf{V}, \quad \mathbf{K_r} = \mathbf{W^T}\mathbf{K}\mathbf{V}, \quad \mathbf{F_r} = \mathbf{W^T}\mathbf{F}, \quad \mathbf{x} = \mathbf{V}\xi. \tag{3}$$

The key challenge in model reduction is generating the projection matrices $\mathbf{V}, \mathbf{W} \in \mathbb{C}^{\mathbf{n}\times\mathbf{r}}$ such that $r \ll n$ (leading to a large reduction in system size) while still providing a good approximation to the response of the original system in (**??**). Multiple methods have been developed with this purpose in mind, but up to now their effective application still requires expert knowledge and experience.

The first part of this work consists in the development of a simple and cheap yet robust error estimator for Krylov subspace type model reduction techniques. A good and cheap estimate of the reduction error is a valuable tool that facilitates the assessment of the accuracy of the reduced-order model.

This error estimator is then combined with a selection strategy for the expansion points and orders of the Krylov subspaces, leading to a fully automatic algorithm for model order reduction of vibro-acoustic finite element models. The algorithm is designed to use a small amount expansion points with high order Krylov subspaces, such that the computational operations scale very well to extremely large model sizes.

Both the automatic model reduction algorithm and the error estimator are validated on large-scale, strongly coupled, interior and exterior vibro-acoustic problems.

Tuesday, 10:15, Seminar Room BA **02B**, Building BA

# Efficient Vibro-acoustic Model Updating of Localized Properties using Low-Rank Parametric Model Order Reduction Schemes

Sjoerd van Ophem[1,2], Axel van de Walle[1,2], Elke Deckers[1,2], Wim Desmet[1,2]

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The growth of computational power in the last decades has made it possible to perform more complicated vibro-acoustic simulations than ever. However, to predict the actual physical behavior of a vibro-acoustic system, an accurate estimation of important physical properties has to be available in order to produce useful simulation results. For localized features, such as bolt connections and welds, this is not always a straightforward task. This is where model updating comes into play: It uses measurement data to update the numerical model through an optimization procedure, so that it conforms more closely the real, physical system.

One of the main drawbacks of the model updating procedure is the time required to perform the optimization, because many frequency response evaluations are required on the full numerical model. For a fully coupled vibro-acoustic analysis, often high-dimensional finite element models are used, for which the calculation of a single frequency line can already consume a significant amount of computational resources. This means that model updating cannot be performed on-line and is usually carried out on only a limited parameter set.

Parametric model order reduction schemes are a promising tool for reducing the calculation time, since they significantly reduce the system size, while maintaining a high accuracy, and still preserve the (explicit) parameter dependency in the reduced order model. These resulting reduced order models can thus be used directly in the optimization procedure. A drawback of most parametric reduction schemes is that the calculation of the reduced basis can be time consuming due to the necessity to sample the parameter space beforehand. This also implies that the range of possible values for the chosen parameters has to be known. However, when the parameters are only acting locally, this is not necessary, because the low-rank character of these parameters can be exploited. Namely, the low-rank character allows the system to be rewritten so that non-parametric model reduction algorithms can be applied.

In this presentation a novel approach for low-rank parametric model order reduction is presented, which significantly speeds up the model updating process. It requires no a-priori sampling of the reduced basis and it can handle many parameters simultaneously, with only a moderate model size. The presented scheme is applied to a fully coupled vibro-acoustic system consisting of a clamped plate with a backing cavity, where the goal is to detect the proper boundary conditions of the plate. Since in practice this clamping is imperfect, the proposed method is used to identify the actual degree of clamping. It is shown that the proposed method successfully identifies the boundary conditions in a short time frame, while the same calculation with the non-reduced model would take several days.

Tuesday, 10:35, Seminar Room BA **02B**, Building BA

# Normal Modes and Modal Reduction in Exterior Acoustics

Lennart Moheit[1] and Steffen Marburg[1]

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By applying the finite element method (FEM) and conjugated Astley-Leis infinite elements (IFEM) to exterior acoustic problems, the Helmholtz equation for the spatial sound pressure field can be solved considering the Sommerfeld radiation condition. Both methods provide frequency-independent system matrices for mass, damping and stiffness in the fluid, forming a discrete, linear system of equations. The homogenous system can be understood as a quadratic eigenvalue problem and solved by the concept of normal modes using a state space formulation [1, 2]. Normal modes can be superimposed in order to obtain the total radiated sound power or entire sound pressure field around an inner obstacle with an arbitrary surface velocity. Due to the frequency-independency, only one eigenvalue problem has to be solved, which is an advantage in comparison to harmonic analysis, where the dynamic stiffness matrix has to be inverted for each frequency of interest separately. Knowledge about the only relevant normal modes, which—when doing modal superposition—still give a sufficiently accurate solution with respect to the full set of modes, might further reduce computational effort. In this work, different criteria for identification of required normal modes in exterior acoustics are presented and discussed.

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Tuesday, 10:55, Seminar Room BA **02B**, Building BA

# Virtual Microphone Sensing for Vibro-Acoustics

Axel van de Walle[1,2] and Wim Desmet[1,2]

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[2]Member of Flanders Make

This work introduces a virtual microphone sensing method which makes it possible to perform full field acoustic measurements.

The classical way of obtaining the actual sound pressure at a specific location is to directly measure it using a microphone. In practice however, only a limited number of locations can be instrumented, and some locations of interest may be difficult to reach or may prove to be impractical for direct measurements. Also, experimental measurements only provide limited insight in the underlying dynamics, and it is practically impossible to characterize or measure the full sound field directly. A numerical simulation can produce this kind of information, but often does not fully match the true system behaviour because of unmodelled effects or modelling errors. This work therefore proposes a virtual sensing approach that combines a small number of readily available microphone measurements with a high-fidelity numerical model. It provides virtual measurements of the sound pressure at uninstrumented locations of interest, and even allows for virtual measurements of the entire sound field. This approach delivers all the physical insight that a numerical simulation typically generates, while maintaining the real-world accuracy one expects from an experimental measurement.

A Kalman filter is used to blend the experimental measurements with a numerical finite element model. However, using a full-sized finite element model may lead to numerical instabilities in the Kalman filter. Additionally the computational effort is far too large for practical applications. Therefore state of the art numerical modelling and model order reduction techniques are used to generate small, accurate, stable and well-conditioned models that are perfectly suited for use in a Kalman filter. The developed method is able to deal with complex and strongly coupled vibro-acoustic systems while still requiring only a moderate amount of computational effort, making it real-time capable. The proposed approach is validated experimentally, demonstrating very accurate virtual sound pressure measurements.

Tuesday, 11:15, Seminar Room BA **02B**, Building BA

# Diffraction Model for Propagation over Realistic Terrain

Subhashini Chitta[1] and John Steinhoff[1]

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A new Finite Difference (FD) method, Wave Confinement, is developed to solve the linear wave equation,

$$\frac{\partial^2 u}{\partial t^2} = c^2 \Delta^2 u \tag{1}$$

When the above equation is solved using conventional finite difference methods, there is an accumulation of diffusive/dispersive error. For problems where the propagating distance is much larger than the wavelength, these errors cannot be prevented even with higher order schemes. In such cases, Lagrangian methods seem reasonable, but these methods use high frequency approximation, which tend to fail since realistic terrain is not flat and diffraction significantly affects propagation.

In this paper, we present a new FD method that uses the idea of solitary waves to counteract the numerical diffusion/dispersion. This involves adding a nonlinear term to the above equation (in 1D) as below.

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} + \partial_t \left[ -\alpha\lambda \partial_x^2 u - \alpha \partial_x^2 \left( \partial_x^2 u - 2\frac{(\partial_x u)^2}{u} \right) \right] \tag{2}$$

Equation 2 produces stable, converged solutions on the grid without changing the conservation of equation 1. We call these solutions, Nonlinear Solitary Waves (NSW's). In addition to conservation of integrals such as phase and amplitude, the essential property of the NSW's is that they do not have the dispersive and diffusive truncation error inherent in conventional Eulerian methods: A confined solitary wave may undergo distortions due to local truncation effects, but due to the shape preservation property, it always returns to its asymptotic shape with no error accumulation in spite of the nonlinear term - as a result the pulse never decays. The pulse can remain concentrated as few as 5-6 grid cells regardless of the number of cells traversed. Because of this property, the grid can be made as coarse as necessary, consistent with overall accuracy (for example, to resolve atmospheric variations). The extension of this method to multidimensions is fairly straightforward. We simply substitute a multidimensional Laplacian in the original wave equation and use a multidimensional nonlinear term. Also, since wave confinement solves the linear wave equation, diffraction is automatically accommodated. This has been proven very useful in long range rotorcraft acoustics and some of the results will be shown in the presentation.

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Tuesday, 11:35, Seminar Room BA **02B**, Building BA

# 3d Modeling and Simulation of a Harpsichord

Lukas Larisch[1], Rossitza Piperkova[2], Martin Rupp[2], Sebastian Reiter[2], Gabriel Wittum[1]

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The mathematical characterization of the sound of a musical instrument still follows Schumann's laws [3]. According to this theory, the resonances of the instrument body, the formants, filter the oscillations of the sound generator (e.g. string) and produce the characteristic "timbre" of an instrument. This is a strong simplification of the actual situation: It applies to a point source and can be easily performed by a loudspeaker, disregarding the three dimensional structure of music instruments. To describe the effect of geometry and material of the instruments, we set up a three dimensional model and simulate it using the simulation system UG4 [4, 2].

In our talk, we present FEM based numerical simulations of a harpsichord. We aim to capture the oscillation behavior of eigenfrequencies of its soundboard. We resolve the complicated geometry by an unstructured 3d grid and take into account the anisotropy of wood. The eigenvalue problem is solved using the PINVIT method [1] with an efficient GMG preconditioner. The latter allows us to resolve the harpsichord with a high resolution grid, which is required to capture fine modes of the simulated eigenfrequencies. For the validation, we compare our results with measurement data obtained from an experimental modal analysis using laser interferometry by a Polytec PSV 400 vibrometer. We finally investigate the impact of various aspects of the geometry on the computed eigenfrequencies.

**Keywords** Eigenvalue problem, finite strain mechanics, FEM, PINVIT, GMG, musical instrument, harpsichord

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Thursday, 10:15, Seminar Room BA **02B**, Building BA

# Piezoelectrically Driven MEMS for Digital Sound Reconstruction

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The present paper deals with a method for sound generation – digital sound reconstruction (DSR). The method provides a possibility to generate an audible signal by the superposition of sound pulses from individual microspeaker cells (speaklets), which are grouped in bits and interconnected in an MEMS array. The following expression shows ratio between number of speaklets and bits

$$N = 2^n - 1,$$

where $N$ is the number of speaklets and $n$ is the number of bits. A speaklet has two extreme positions: the logical "0" (idle position) and the logical "1" (maximal stroke level). When a speaklet moves from "0" to "1" or vice versa, it produces sound, that allows to present an analogue signal as a sequence of "0" and "1" without using a digital-analogue converter (DAC) in a loudspeaker.

For testing the DSR ideas, we have elaborated a Finite-Element (FE) model for a 3-bit and a 4-bit array based on the piezoelectric driving principle, using our in-house research software CFS++ [1]. The FE model considers a speaklet as a bimorph ideal transducer and is able to calculate the overall sound pressure at a distance of 2 cm. Fig.1 illustrates comparison between the maximal obtained sound pressure in the digital mode $p^d$ and in the analogue mode $p^a$.

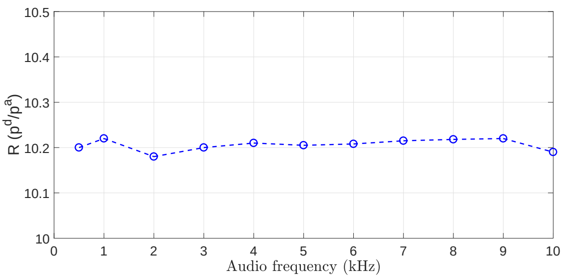


Figure 1: Ratio between maximal producible sound in digital and analogue modes.

Thereby, according to the above presented results, DSR is able to generate overall sound pressure of 10 times higher than the traditional analogue method.

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Thursday, 10:35, Seminar Room BA **02B**, Building BA

# Numerical Analysis of Sound Wave Generated by a Parametric Speaker with Divergence Control of Directivity

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Due to their sharp directivity, parametric speakers using ultrasonic waves modulated by the audio sound signal from the array transmitter have attracted much attention within the sound industry [1]. Conversely, the divergence of directivity is determined by the configuration of the speaker and cannot be controlled. As a result, such sharp directivity sets a limit to the application. In order for the application to become wider, the control of divergence directivity should be controlled. Therefore, in this study, we investigated divergence control in a parametric speaker.

In this paper, numerical analysis of sound waves generated by a parametric speaker with divergence control of directivity is discussed using the Khokhlov–Zabolotskaya–Kuznetsov (KZK) equation [2], which is solved as a transformed beam equation using the Richtmyer method [2]. The parametric speaker conducted amplitude modulation of audible sound with a carrier wave of ultrasonic sound that has a frequency of 40 kHz and self-demodulation in the air. The speaker had a circular configuration with a diameter of 12 cm.

It was considered that there existed a virtual point sound source behind the parametric speaker and that the sound wave passed through the aperture, which had the same diameter as the speaker and was located at the same position. The time delay difference from the source of the point sound to the aperture was calculated as

$$\Delta t = \frac{\sqrt{\left(\frac{a}{\tan\theta}\right)^2 + r^2} - \frac{a}{\tan\theta}}{c}.$$

Here $a$ is the speaker radius, $\theta$ is the divergence of directivity (half angle), $r$ is a position in the radial direction, and $c$ is the sound velocity. The KZK equation is solved using the modulated sound source with time difference.

The results of this study confirmed that divergence can be controlled by controlling the time delay in the parametric speaker. This is achieved by using an array transmitter constructed by ultrasonic transmitting elements.

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Thursday, 10:55, Seminar Room BA **02B**, Building BA

# Study of the resonant interaction between two gas bubbles by using the spherical harmonics expansion

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This work comes within the framework of the scattering of sound waves in concentrated suspensions of gas bubbles. In some cases, it is interesting to study the interactions between two (very) close gas bubbles. In such case, it is well known that the Minnaert frequency splits into two resonance frequencies depending on wether bubbles oscillate in phase or not. This phenomenon is generally described by a model based on the coupled Rayleigh-Plesset equations for which only the radial motion of bubbles is taken into account. The model used here is based on the spherical harmonics expansion of the incident and scattered waves and on the use of the addition theorem. In this case, the two resonance frequencies are calculated numerically and it appears that the number of modes to take into account depends on the distance between the two bubbles. It is shown that a large numbers of harmonics have to be taken into account when bubbles are very close together. The calculations of the scattering cross sections of the pair of bubbles show that the directivity associated to the higher resonance is much more complicated than that of a dipolar resonance due to the out of phase oscillations of the two bubbles.

Thursday, 10:15, Lecture Hall **GM2** Radinger, Building BD

# The Forward and Inverse Scattering Analysis of Love Waves due to A Cavity at the Interface

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The Love wave is a special kind of guided waves that travels along the surface of elastic layer covered on top of an elastic half-space. The scattered Love waves are relied on to investigate underground information in geotechnique engineering, or detecting flaws and cracks at the bounding interface in non-destructive applications [1]. An effective utilization of the Love wave requires a thorough understanding of its scattering phenomenon, both in the forward and inverse aspects.

For the forward analysis of a half-space problem, the boundary element method (BEM) is an effective approach to calculate the scattered wave field, since only the interfaces and flaw boundaries need to be meshed. However, in traditional BEM approaches, due to the inevitable artificial truncation of BEM model, spurious reflected waves are introduced in the final results of scattered wave field, which causes considerable error. Here a modified BEM for calculating scattering of Love waves is introduced. The guided Love-wave displacement patterns are assumed on the far-field infinite boundaries previously omitted, and they are incorporated into BEM equation sets as the modified items. With this improvement, the spurious reflected waves are eliminated. The results are verified by theoretical far-field Green's functions [2].

For the inverse analysis, we try to reconstruct the debonding cavities by the scattering data. A mathematical relation is established between geometric information of the cavities on the interface and the reflection coefficients, by scattering boundary integral equation. By the introduction of Born approximation, the cavity's vertical open-width can be expressed as an inverse Fourier transform of reflection coefficients [3]. By this inversion method we can not only know the location but also the specific geometric information of flaws. The inversion approach is especially suitable for smaller cavities (weak scatterers), and can give an "initial image" for further iterative reconstruction as to larger ones.

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Thursday, 10:35, Lecture Hall **GM2** Radinger, Building BD

# Coupling Coefficient for Flux Density and Density Gradient of Reflected Sound Energy in Quasidiffuse Sound Fields

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Sound pressure levels in premises are determined by the sum of the direct sound energy and the reflected sound energy, arising at sound reflections from the protections. In many sites of premises the reflected sound energy exceeds the energy of the direct sound. For this reason, calculations of density of the reflected sound energy are an important problem. In the majority of premises reflection of a sound from protections has mirror-diffuse character. Thus, one part of the reflected energy, transferred by mirror reflected sound waves, is determined according to the laws of geometrical acoustics, and the second one, dissipated diffusely, is determined under Lambert's law. Calculation of density of the mirror component of the reflected energy is produced by methods of rays tracing, and density of the scattered component is calculated under statistical energy method, developed by the authors for quasidiffuse sound fields in premises. The statistical energy method is based on the connection between the flux density of the reflected sound energy and density gradient of this energy. The accuracy of the method depends on the accuracy of setting the value of coupling coefficient between the indicated quantities. Now there are different views about this value. In the paper the results of the researches of coupling coefficients, depending on space-planning and acoustic characteristics of premises are presented. The studies were performed using the Kuttruf's integral equation. On the basis of the researches recommendations for choosing the coupling coefficient value are provided.

Thursday, 11:35, Lecture Hall **GM2** Radinger, Building BD

# Plane wave kinedynamics in fluid continuum, and at a boundary delimiting two fluids

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The paper deals with the propagation of acoustic disturbances in a homogeneous medium, the reflection from two media boundary, as well as the transmission throughout it, on the basis of local causality analysis of instantaneous conditions, performed with the application of relevant one-dimensional kinedynamic functions. In the analysis of plane wave bifields, the wave front is modeled as a planar layer of infinitesimal thickness in a three-dimensional fluid continuum. Pressure and velocity at the front of a propagating plane wave behave, respectively, as a force and a flow that become two types of Huygens' secondary sources [1]. The first one being a vector source, it directly induces an inert motion in the contiguous fluid continuum with accompanying elastic strain, the second one, of a scalar character, induces directly an elastic strain with accompanying inert motion.

Respective kinedynamic functions related to the mechanical nature of these sources are defined in the paper, describing the physics of elementary phenomena in fluid continuum, forming an acoustic plane wave. These functions are used in a local-causality analysis of mechanisms that assure, first, the forward-only propagation in homogeneous medium on the one hand, and the creation of two new waves at a planar jump of continuum parameters, on the other hand. The latter waves, one of reversed propagation in the original medium (reflected wave) and the other continuing the original propagation course in the second medium (transmitted wave), emerge in the effect of an energy split forced at the delimiting boundary by the requirements of continuity.

A synchronous action of scalar and vector secondary sources results in a total of four pressure (strain) components, and four velocity (motion) components. On each side of the source plane two pressure and two velocity components appear, each originating from one of the sources, either as a direct (primary) component or an accompanying (secondary) one. In the area of medium homogeneity, the elastic and motion phenomena at the wave front layer are balanced in such a way that the above mentioned components originating from both kinds of sources give equal results ahead of them, while backwards they are equal but of the opposite signs. The issue is the foreword-only propagation with null backward effects – intuitively "obvious", yet understood mere vaguely. At the frontier of two continua of different mechanical parameters, the equipartition between the two kinds of secondary sources is being broken, due to the compulsory conditions of continuity. Thus modified proportion between bifield elementary components results in the emergence of two waves starting forwards and backwards from the delimiting boundary, both being farther classic forward-only propagating ones. It is worth noting that the energy being obviously conserved in the phenomenon, the momentum is surprisingly but understandingly not conserved.

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# Layered Structures with Obstacles and Embedded Guides: FEM-Analytic Approach

Evgeny Glushkov[1], Natalia Glushkova[1], Alexander Evdokimov[1]

[1]Institute for Mathematics, Mechanics and Informatics, Kuban State University, Krasnodar, Russia

Numerical simulation of guided wave excitation, propagation and diffraction in structures with local inhomogeneities (obstacles) is of interest for physical acoustics, structural health monitoring (SHM), seismic acoustics, and other applications. The present work is focused on the study of reflection and transmission coefficients for normal modes in elastic layered waveguides with obstacles of arbitrary shape and material properties, complex natural scattering frequencies, and trapping modes associated with the nearly-real resonance poles. Moreover, guided leaky waves in waveguides of arbitrary cross-section embedded in or bonded to a plate-like structure are also under consideration.

Nowadays, the mesh-based approach, primarily the finite element method (FEM) implemented in commercial packages, is recognized as a universal tool for scientific and engineering applications. However, with extended domains, the FEM becomes too time-consuming or even completely inapplicable beyond certain threshold amounts of mesh cells needed to correctly simulate the wave propagation over long distances between the source and scatterers as well as for scattered waves going to infinity. An effective way to overcome this difficulty is a hybrid approach based on the correct coupling of a FEM solution obtained in a local vicinity of the source and/or scatterers with explicit guided wave (GW) representations in the outer semi-infinite parts of the guide. Unfortunately, standard FEM packages, being a "black box" for users, cannot usually provide such a coupling, because it requires adding the joining equalities into the package manually.

To make it possible the use of standard FEM packages in selected local areas, a hybrid FEM-Analytic method has been developed [1]. A set of FEM solutions for specified boundary conditions induced by traveling and evanescent modes is used as a basis in the local areas while the solution in the exterior is sought for in terms of those normal modes. The unknown expansion coefficients are obtained from a low-sized linear algebraic system derived from the docking conditions. The scattering resonance frequencies, or the wavenumbers of leaky GWs in the case of embedded guides, are obtained via the zeros of the determinant of that system. This way avoids a huge number of superfluous unphysical roots appearing when the infinite domain is reduced to a finite but long area of FEM application by means of absorbing boundary conditions.

The FEM-Analytic scheme has been validated against the integral equation based solutions for thin horizontal obstacles in an elastic strip (cracks, flexural patches) and independent numerical results obtained by other methods. The results illustrating the influence of the scatterer's shape, size and material parameters on the diffraction effects are discussed.

The work is partly supported by the RFBR grant No 16-41-230744.

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Thursday, 13:30, Lecture Hall **GM2** Radinger, Building BD

# Wave Generation and Source Energy Distribution in Acoustic Fluid with an Immersed Plate

Evgeny Glushkov[1], Natalia Glushkova[1], Olga Miakisheva[1]

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The generation of acoustic waves by a specified source (e.g., ultrasound transducer) and their interaction with a metallic or composite plate immersed in acoustic fluid (water or air) is a classical problem of computational acoustics. It relates to numerous technical applications ranging from the vibration isolation and noise control to the contactless non-destructive inspection. This classical problem is well studied theoretically, but it is still a hard task to simulate wave processes with a strict accounting for the wave source. Finite-element packages are ample for such a simulation but their use is often too expensive.

In the present work, the simulation of wave energy transfer from the source to the plate and further to infinity is fulfilled on the basis of semi-analytical computer models based on the explicit integral representations for the generated and scattered wave fields and far-field asymptotics derived from those integrals [1]. The source energy partition among the generated waves (incident, transmitted, reflected and guided) is evaluated using closed-form representations for time-averaged wave energy transfer through arbitrary plane-horizontal, spherical and cylindrical surfaces. To visualize the trajectories of energy fluxes, energy streamlines specified by the power density vector field are traced from the source into the environment including the lines passing through the immersed plate. The latter can be in general an arbitrary anisotropic laminate governed by the equations of 3D linear elasticity.

The research is focused on the backward leaky mode phenomenon [2] and the effect of increasing energy transmission through the plate at those frequencies [3]. Due to the fluid environment, the real wavenumbers of classical free-plate Lamb modes shift into the complex plane and traveling waves become guided leaky waves. The backward mode range is featured by inverse energy fluxes coming from infinity. In the near field, they are turned away by the more powerful energy flux radiated from the source. Energy streamlines and plots of energy density show specific ways of increased energy transfer through the plate at the resonance frequencies. The numerical results for the wave transmission through the plate obtained within the low-cost semi-analytical model developed coincide with those calculated by FEM and experimentally measured [3].

The work is partly supported by the RFBR grant No 16-41-230769.

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Thursday, 13:50, Lecture Hall **GM2** Radinger, Building BD

# Guided wave based damage localization in isotropic thin-walled structures with time-reversal approach and linear resonance scattering

Artem Eremin[1,2], Evgeny Glushkov[1], Natalia Glushkova[1], Rolf Lammering[2]

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Resonance scattering is among the features that accompany interaction of elastic guided waves (GWs) with localized obstacles, such as cracks/delaminations or abrupt thickness changes [1, 2]. This phenomenon, being conditioned mathematically by the presence of (nearly)-real eigenfrequencies of the corresponding boundary value problem, is characterized by a strong motion localization in the obstacle vicinity. If a transient GW packet with a resonance central frequency interacts with the defect, it manifests itself through the GW energy capturing and accumulation in the course of wave packet arrival. These stored oscillations are further re-emitted from the damaged area in the form of long-term pulses at the resonance frequency. Being measured by a distributed sensor network, these signals may allow for the damage characterization and serve as an input for the corresponding imaging algorithms, e.g., computational time-reversal method. The latter has become a recognized approach for defect localization due to its natural capability to refocus measured scattered GW signals on the initial obstacle location [3].

In this contribution, a possibility of joint use of GW resonance diffraction phenomenon and time reversal approach for the refined localization and characterization of elongated and circular flat-bottom holes simulating pit-like corrosion is discussed. Analytically-based numerical analysis of the considered problem relying on the first-order plate theories or general equations of three-dimensional linear elastodynamics reveals the existence of nearly real resonance diffraction frequencies and shows their strong dependence on the damage severity. Experimental investigations, carried out for metallic specimens with artificial obstacles by means of non-contact laser Doppler vibrometry, verify the predicted values of the resonance frequencies. The prolonged GW radiation from the damaged area on these frequencies is confirmed as well. Since the corresponding wave packets are clearly distinguishable from the incident ones in the signals measured at the remote locations, they are further utilized as an input for the developed time-reversal procedure based on semi-analytical asymptotic representations for GWs, providing a promising opportunity for baseline-free damage localization.

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Thursday, 14:10, Lecture Hall **GM2** Radinger, Building BD

# Analysis the Size Effect on the Vibration of Flexible Core Micro Sandwich Beams based on High Order Nonlocal Theory

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A new high order nonlocal theory for the analysis of the free vibration of a soft-core micro sandwich beam is presented in this paper. The model uses the nonlocal Euler theory [1, 2] for the face sheets and a nonlocal elasticity solution for the core and includes derivation of the governing equations. The proposed theory consists of a systematic approach for the analysis of micro sandwich beams with a flexible core, having high-order effects caused by the nonlinearity of the in-plane and the vertical displacements of the core [3, 4]. Using the nonlocal theory, the small-scale effect is employed to obtain equation of motions. The micro sandwich beam consists of thin skins, which are attached to each other with an elastic core. In this paper, the small-scale effect, the Young's modulus of core and the effect of the thickness of micro sandwich beam on natural frequencies are discussed. The accuracy of the solution is examined by comparing the results obtained with the analytical and numerical results published in the literatures.

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Thursday, 14:30, Lecture Hall **GM2** Radinger, Building BD

# Causal-feedback phenomena as the essence of bi-field relations describing linear acoustics

Henryk Lasota

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When defining two symmetric pairs of acoustic variables, namely pressure/strain and velocity/momentum, in the way the two "intensity/density" pairs, namely electric and magnetic fields intensity/induction, were defined in electromagnetics by Maxwell [1], it is possible to develop symmetric representation of acoustic linear phenomena, making it possible to put the three equations usually made use of in the derivation of acoustic wave equations, in a concise form of two relations analogous to Maxwell's ones. One of them is the well known Euler's relation of dynamics, concerning inert motion of fluid matter, the second one being a condensed form compiled from the standard stream continuity and the adiabatic state relations. Such a symmetric approach is the author's proposal to elicit the fundamental role of fluid's elastic volume strain as being dual to its inert motion (momentum density). The symmetry of description thus obtained reveals a N. Ph. equivalence of local causality of the two phenomena, meaning their implicit simultaneity. Such a simultaneity can be, and is being, reached in a kind of local circular action of either of two possible causal sequences. In reality, these sequences are somehow hidden in the very derivation procedures of two kinds of the second order partial differential relations concerning either pressure or velocity, known as "wave equations". Either of these two separate forms are valid anywhere in a homogeneous fluid space.

As both the first order relations, worth being called Euler's ones, are implicitly causal, the above double result reveals the existence of two autonomous mechanisms of local circular action, meaning two kinds of causal feedback sequence that can take place in any time, at any location. Both the relations being fully autonomous, their application in given conditions depends on the kind of primitive cause of the disturbance, namely the (mechanical) nature of its source. The overall propagation dynamics of the disturbance emerges next from the compulsory condition of local energy conservation.

The paper proposes introduction of two physics based kinedynamic functions for characterizing acoustic disturbance as pressure-velocity or velocity-pressure bi-fields related each to the nature of its source. These functions are physical, dynamic counterparts of the traditional Green's function that is the mathematical representation of mere wave kinematics.

So obvious an interpretation has nowhere been given to linear dynamic disturbance phenomena, their view having been hidden from the very start by the beauty of time-domain solutions to the wave equations, next somehow shaded by the practical usefulness of their harmonic forms. In the author's opinion, the model of two cause-effect feedback sequences induced by primary sources of disturbance that continue to act throughout all the homogeneous medium, is the one having been missing in the development of the foundation of linear acoustics. It complements the traditional mathematics focused description of wave phenomena with a clear physical image of primary effects.

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Thursday, 14:50, Lecture Hall **GM2** Radinger, Building BD

# Prediction of the vibration response of the seat back with variable stiffness

Hyukju Ham[1], Deokman Kim[1], Chunkyu Park[2] and Junhong Park[1]

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[2]Hyundai Motors Company, Seoul, Republic of Korea

The seat back vibration with nonlinear dynamic characteristics was analyzed in this study. The vibration was transmitted from road surface to the driver through the seat and caused the whole-body vibration. It is necessary to study the vibration response of the seat back to improve the ride comfort. The seat back was modeled as a beam supported with the gear. The gear could be considered as rotational stiffness and damper changed with the angle. The dynamic characteristics of the gear were determined along the contact points of the gear pair and affected the transmissibility of the seat vibration. The computational simulation was performed to analyze the vibration response of the seat back with the gear conditions using finite element method (FEM). The human body was modeled as the several beams with different mass. The driver posture significantly influenced the vibration response of the seat back. These results can be utilized to design the seat back for enhancing the ride comfort.

Wednesday, 10:35, Seminar Room BD **02A**, Building BD

# Effects of the rotational stiffness affecting on the dynamic characteristics of the vehicle seat back

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The whole-body vibration in the vehicle is the source of passenger discomfort and health risk. The seat back vibration in the resonance frequency and non-periodic impact input from various road conditions affects dynamic comfort cognized by a passenger. The seat back is composed of frames and gears linked with seat cushion frame. The gears are an important part to transmit the vibration induced by the vehicle body excitation from by the road condition to the seat back. The seat back is represented as a vibrating beam having boundary conditions supported by rotational springs and hinge. The gear connecting seat back to the cushion is modeled as the rotational complex stiffness. The transfer function method is used to analyze the effect of the rotational complex stiffness of the gear on dynamic characteristic of the seat back. An experimental method to determine the dynamic properties of gear is proposed. The properties are calculated comparing the measured transfer function with the predicted one.

Wednesday, 10:55, Seminar Room BD **02A**, Building BD

# FEM modeling and analysis on the mechanism of vibration reduction of railway with impact absorber

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**Abstract**

This paper is presented a method which can suppress railway vibration using impact absorber. While the traditional dynamic absorber attenuate the vibration mainly at the pre-tuned frequency mode of the rail, impact absorber generates greater damping to reduce all resonant frequency modes of the railway. For analysis and predict the damping effect of impact absorber on the railway, finite element method (FEM) is applied to model. Assuming the rail as Euler-Bernoulli beam which the element mass and stiffness matrices are given. The global matrices can be constituted by element matrices so that the global equation of the system can be expressed. Runge-Kutta method is employed to simulate inelasticity collision between rail and impact absorber. In this way, it's not only able to calculate time and frequency response but also can analyze its sensitivity to variations of the clearance, mass ratio and restitution coefficient. To test the performance, impact absorbers are installed on a 'freely' supported rail and verify the mechanism experimentally. The result can be utilized to reduce the rolling noise from high-speed trains.

**References**

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Wednesday, 11:15, Seminar Room BD **02A**, Building BD

# Application of an equivalent fluid model for the simulation of sound absorption properties of microperforated panels in 3D environments

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The acoustical pre-evaluation of new designs in the fields of HVAC-systems, automobiles and aircrafts becomes more important as the regulations to reduce noise pollution become more strict. Beside the standard sound absorbing fibrous materials and foams, the popularity of microperforated panels (MPP) increases due to their special characteristics, like tunable broadband high sound absorption, robustness in harsh environments and durability.
The behaviour of such panels can be modelled via an equivalent fluid, where physical viscous and thermal effects are accounted for with a modified density ($\tilde{\rho}_{eq}$) and bulk modulus ($\tilde{K}_{eq}$). Within the finite element software CFS++[1] a modified Helmholtz equation

$$\frac{\omega^2}{\tilde{K}_{eq}}\tilde{p}' + \triangledown \cdot \frac{1}{\tilde{\rho}_{eq}} \triangledown \tilde{p}' = 0 \tag{1}$$

is solved for the sound pressure field in the porous absorber. The MPP is modelled with the parameters porosity, radius of the perforations and thickness of the plate in accordance with the Johnson-Champoux-Allard formulation [2].
In this contribution we investigate and compare the numerical simulation of the transmission loss of a simple expansion chamber with physical 4-microphone-measurements. The measurement design allows for the analysis and assessment of different MPP arrangements within a frequency range up to 8 kHz as well as the quality of the porous absorber model both in the case of a plane wave grazing sound field and for the propagation of higher order modes.

## References

[1] M. Kaltenbacher. Numerical Simulation of Mechatronic Sensors and Actuators: Finite Elements for Computational Multiphysics, 3rd Edition. Springer (2015)

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Wednesday, 11:35, Seminar Room BD **02A**, Building BD

# Extended analytical Model for the Transmission Loss of a Plate Silencer in a Flow Duct

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In principle, a plate silencer is used to attenuate airborne duct noise. It consists of a duct segment which has plates flush-mounted to its walls. These plates cover enclosed air volumes, resulting in a coupled resonating system. The incoming grazing sound waves excite the plate to vibrate, leading to energy dissipation and sound reflection. The resulting transmission loss depends on various geometrical and structural parameters of the plate and cavity. Current models, which attempt to model their acoustic behavior, are limited to certain physical assumptions, geometrical boundary conditions and high computational effort.

An extended analytical model of a plate silencer is developed in this paper which is capable of performing an accurate and fast computation of transmission loss in a flow duct. In addition to current existing models, it consists of arbitrarily positioned, multiple wall-mounted, impermeable plate resonators. The upgraded design derived here allows for multiple adjacently placed plates in close proximity to each other. This enables a more precise individual configuration of a desired frequency spectrum of the transmission loss. Moreover, a wider bandwidth of the acoustic attenuation can be achieved.

The model presented here is derived by assuming fully grazing sound incidence. Therefore, it is capable of resolving sound reflexion back to the inlet as well as absorption by calculating the excited plate bending waves and their radiated sound. In addition, the radiated sound fields of adjacently aligned plates are fully coupled. As a result, an accurate analytical modeling of arbitrarily arranged plate segments in a single duct becomes possible. Furthermore, optimization of physical and geometrical properties is easily applicable due to the model's analytical formulation and the resulting low computation time. As a consequence, this extended model can be used to accurately maximize acoustic attenuation of duct noise. These additional properties give the possibility to design optimized broadband silencers, even with little available space.

In order to determine its accuracy, a validation of the implemented extended model is performed by comparing the calculated transmission loss of generic configurations with Finite-Element-Method simulations and measurements. Subsequently, parametric studies are conducted by varying geometrical and structural properties of the silencer, showing promising results in terms of broadband, low-frequency sound attenuation.

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