High-precision displacement sensor using ultrasonic waves

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Abstract

Measuring displacement or position of an object is often an important topic for engineers, like in positioning tasks, robots, automatic driving cars, safety devices for machines and more. For that reason there are already several well known principles for such measurements, which have individual benefits and drawbacks.

Position can be measured by contact measurements or also contact less. Optical methods enable very precise displacement measurements without any contact to the object. For sure they also have limitations, for example they can be problematic for some surfaces, like transparent ones. Furthermore optical systems are often very sensitive and therefore critical for use in harsh environment. Acoustic displacement measurements, like Time of Flight sensors, are already well established and in use in different areas. The resolution is normally far away from optical sensors, but they are often more robust and easier to handle.

There are applications where precision and robustness is necessary at the same time. For that reason it is of interest to look for an improvement of acoustic measurement principle to reach higher precision. Robust and easy to handle, but also with a high precision.

Zusammenfassung

Messung von Abständen oder Positionen eines oder mehrerer Objekte zu erfassen ist eine grundlegende Anforderungen für Ingenieure, zum Beispiel für Positionierungsaufgaben, Roboter, selbstfahrende Autos, Sicherheitseinrichtungen für Maschinen und vieles mehr. Aus diesem Grund gibt es bereits viele verschiedene Methoden zur Abstandsmessung, mit jeweils individuellen Vor- und Nachteilen.

Es gibt berührungsbehaftete und berührungslose Methoden. Optische Prinzipien bieten eine sehr hohe Präzision trotz berührungsloser Messung. Dafür sind solche Messungen relativ sensibel und nur bedingt in rauem Umfeld einsetzbar. Weiters können abhängig von der Wellenlänge bei manchen Materialen Probleme auftreten, da diese eventuell nur schlecht reflektieren. Akustische Sensoren arbeiten meist mit dem Time of Flight Prinzip, welche in vielen Bereichen bereits verlässlich eingesetzt werden. Die Genauigkeit ist weit von jener mit optischen Messprinzipien entfernt, aber sie bieten Robustheit und sind oft einfach einsetzbar.

Es gibt auch Anwendungen bei denen sowohl eine hohe Präzision, als auch ein raueres Umfeld gegeben sind. Ebenso gibt es Oberflächen mit denen optische Sensoren Probleme haben. Daher soll untersucht werden ob es eine Möglichkeit gibt die akustische Messmethode zu verbessern um eine höhere Präzision zu erreichen. Robust und einfach zu handhaben, aber dennoch eine hohe Genauigkeit der Messgrösse Distanz.

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Acronyms

Lidar	Light detection and ranging
SNR	Signal to Noise Ratio

CHAPTER 1

Introduction

For a lot of technical applications measurement of distance is a basic need. Exact specifications for the measured value are dependent on what should be done using this information. For chip production a very high precision is important, for a robot which vacuums reliability is important and for a security system in production measurement time can be important. So depending on the demand for different applications, different solutions for a distance measurement will be used.

1.1 Motivation

For each available distance measurement principle there are advantages and drawbacks, like in every technical system. There is a field of applications where robustness against environment, acceptable precision and a reasonable measurement time is needed. Such systems should measure contactless. That can be robots in production lines which are welding objects, positioning tools doing mechanical work on objects or accurate positioning of sensors like colour sensors [1].

Optical distance sensors are normally very precise [2], are able to measure very fast and without contact to the object. But they are sensitive against harsh environment because they use sensitive mirrors and optical elements. If we think about laser distance measurements, those systems use a specific area of wavelength of light. This leads to increasing uncertainty if the measurement surface is transparent or at least not well reflecting for this wavelengths.

Acoustic distance sensors are easy to handle and cheap. For that reason such sensors are often used for robots, parking sensors in cars or for positioning objects in production processes. Such sensors are using most likely the Time of Flight principle described in Section 2.2. The Time of Flight method leads to two general drawbacks for measuring the distance. First is the resolution of measured distance. Also using complex signals and Post Process algorithms for precise Time of Flight, measurements have limited resolution at about several 100 μm [3]. Second is the limited measurement time. After each signal sent out from a transmitter it must be waited until the signal travelled to the measurement surface and back to the receiver. In practice often also additional time is waited as additional reflections at other surfaces may occur.

For that reason it is of interest to find a possibility to use acoustic sensors, because of their robustness, easy operability and low price, but to improve their precision and measurement time.

1.2 Challenges & Goals

In order to reduce measurement time and increase measurement precision compared to state of the art acoustic distance measurements, a new method of how the distance is measured should be established. The goal of this thesis is to verify if it is possible to establish a measurement method which

- improves sample time compared to Time of Flight measurements using acoustic sensors,
- improves accuracy of acoustic distance measurement in region of μm,
- keeps the low price of state of the art acoustic Time of Flight sensors and
- is robust against changes of environmental conditions.

1.3 Thesis Outline

Chapter 2 summarizes the actual State of the Art methods to measure distance by using ultrasonic sensors and will lead to Research Questions that should be answered in this thesis. The individual parts of the measurement setup and their functionalities are described in Chapter 3 to be able to describe the details and improvements that will be made in the detailed analysis in Chapter 4. For a valuable comparison different State of the Art methods are implemented using the same setup as also used for the proposed measurement principle of this thesis. This results are shown and discussed in Chapter 5. A conclusion of this thesis and an outlook how it can be used for future works is done in Chapter 6.

CHAPTER 2

State of the Art

This chapter describes how actual systems for distance measurement using acoustic sensors work and where their limits are. It is shown what different methods are available and how the performance varies between those methods. The Time of Flight measurement principle is discussed in detail and will lead to formulation of research questions.

Common used measurement methods for contactless distance or velocity are optical measurements or acoustical measurements. For optical principle classic methods are laser interferometers or Light detection and ranging (Lidar) systems. For acoustic principle it is mainly Time of Flight method.

A very well overview about different approaches for Time of Flight Measurements using ultrasonic waves is given in [4].

2.1 Optical Displacement Measurements

Optical sensors are able to measure displacement in size of nm, for example using laser interferometer [5]. If the optical beam or the object is moved it is possible to scan objects surfaces with a high resolution [6], [7]. The drawback of optical systems is that there are mirrors needed which must be well aligned, so the systems are sensitive against environmental influences like vibration or dust. Furthermore the principle is dependent on reflective properties of objects [8], [9]. For example objects which are transparent for the used wavelength are hard to detect.

2.2 Time of Flight

A basic principle to measure distance is the so called Time of Flight method. In general such a system consists of a transmitter and a receiver, as it can be seen in Figure 2.1. Aim is of course to measure the distance between the sensor pair and an object. A defined, time limited signal is applied to the transmitter and then the reflected signal will be detected again. When the time between output at the transmitter and input at the receiver is measured, it can be directly used to calculate the distance by

$$s = vt, \tag{2.1}$$

where s is the distance, v is the velocity and t is time. The time t is the measured value. The velocity v is dependent on different properties. First it is important what kind of physical quantity is used for transmitter and receiver. This can be typically light or ultrasonic acoustic sensors. Second is the medium where the signal is travelling, which may have minor influence in case of light but definitely in case of ultrasonic acoustic waves. In case the medium is air, the speed of sound is dependent on environmental conditions like temperature, humidity and pressure [10]. For typical conditions in air the velocity for acoustic waves is $v_{air} \approx 340\,\mathrm{m/s}$. This is described more detailed in Section 3.6.

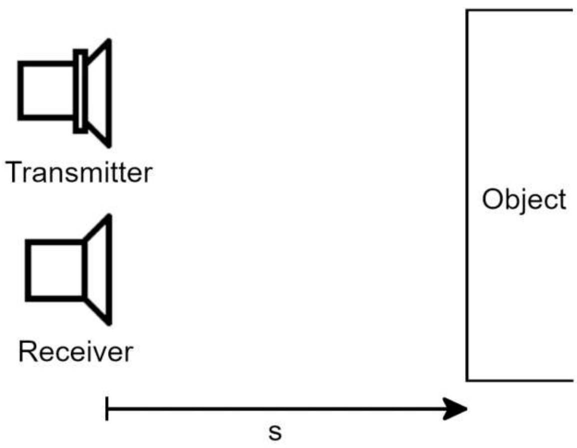


Figure 2.1: Typical setup for Time of Flight measurement

As the signal must be first transmitted and then received, there are also solutions possible where receiver and transmitter are in practice one sensor which can be used as transmitter and receiver one after another.

2.3 Acoustical Distance Measurements

For a lot of systems ultrasonic sensors are used for acoustic distance measurements. The method of acoustic measurements enables robust and easy setups. Theoretical background about acoustic waves in general is described in the following Section.

An easy way to generate and detect such ultrasonic acoustic waves is using piezoelectric materials at a resonance frequency. Electrical voltage is applied to piezo material and this leads to a mechanical movement, which leads to a pressure change in the medium around the piezo. In case of a receiver it is the other way round, that pressure changes at the piezo lead to mechanical movements of the piezo-material, which generates an electrical voltage. Typically resonance frequencies start from about 20 kHz up to several MHz [11]. The used frequency is important for the behaviour of the measurement system. More details about such ultrasonic sensors are described in Section 3.4. Higher frequencies are often used in medicine applications where the sensor is directly connected to the human body. In this case the medium is not air any more, so the speed of sound is most likely much higher then in air. Also the distances of interest are comparable short, which means that higher damping is something that can be handled in such situations. Higher frequency leads to higher damping over distance, but the acoustic beam is more focused and the lateral resolution increases. For this reason sensors in cars for parking are normally in a lower frequency area, as they must not be perfectly focused, but distance is important. On the other hand for measurements in the human body the distances are known to be short, but precision of lateral resolution is more important, therefore here higher frequencies are used.

It can be said that the choice of frequency for an acoustic distance sensor is important and has to fit to the individual measurement situation.

2.3.1 Acoustic Wave Propagation

Before a description of an acoustic distance measurement is possible, some basics about acoustic waves must be discussed.

An acoustic wave is a wave moving in a medium and defined by a change in pressure over time and place. Such a pressure change must be excited by a mechanical movement, which can be a vibrating object or also a short time event like an explosion. A typical example can be a membrane of a speaker which moves periodically forwards and backwards and therefore generates higher and lower pressure areas which move with a specific speed through the medium in front of the membrane. In Figure 2.2 there is shown how molecules in air will change for a typical acoustic wave. There is a constant offset, the atmospheric pressure. This atmospheric pressure is 1013 mbar at sea level and decreases with height above sea level. Additional to the constant pressure there is the acoustic wave which is having areas of higher pressure, where molecules come closer together and areas of lower pressure, where molecules are further away then in standard condition without acoustic wave. For easier understanding we assume a sinusoidal acoustic wave with a constant frequency. In that case there are periodically maximum and minimum pressure areas, where the distance between them is dependent on the speed of sound v and the frequency f of the sinus signal. If the frequency of the signal is between 20 Hz and 20 kHz it is in the hearing range of a healthy, average human ear. Acoustic waves with a frequency higher than 20 kHz are called ultrasonic acoustic waves.

Taking this information into account it is also clear that the environmental conditions of the medium air are having influence on the speed of an acoustic wave travelling in it [10]. Furthermore the damping of an acoustic wave is related to the frequency of the signal. Lower frequencies are changing the pressure not so often, which means less loss during this pressure change progress. Higher frequencies instead have to walk more often through such a pressure change progress in the same time and therefore the loss is higher.

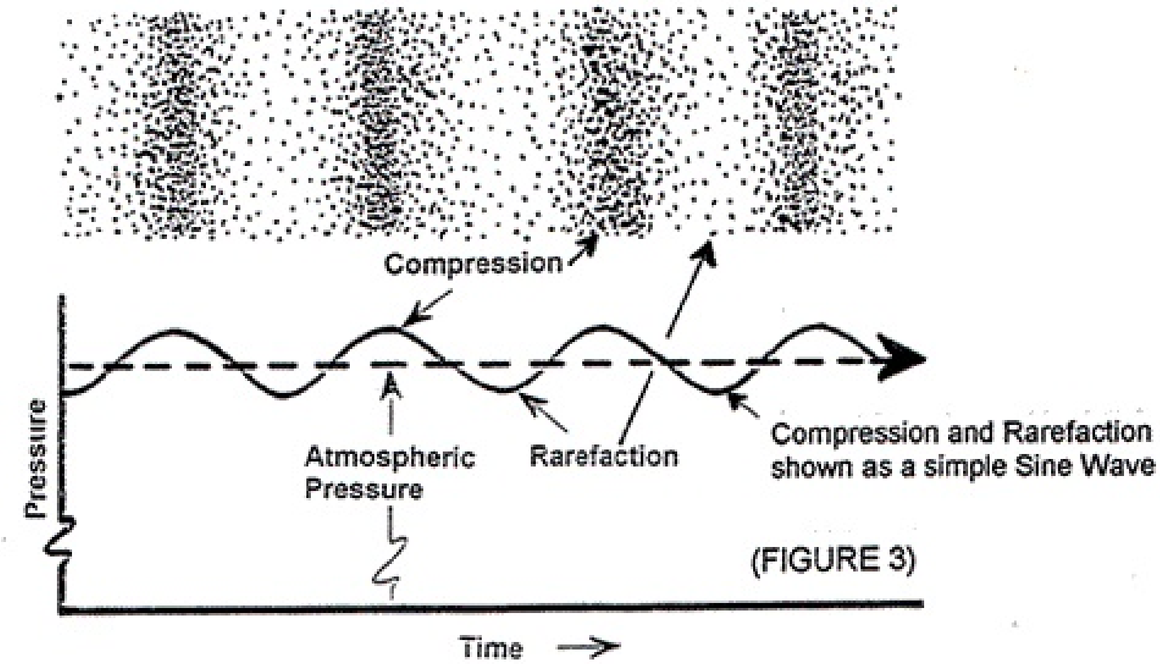


Figure 2.2: Sound Propagation in air

It should also be mentioned that the situation shown in Figure 2.2 is only valid in the so called Acoustic Far Field. Dependent on the dimensions and the frequency of a sound source there is an area called acoustic near field. In this region the acoustic waves have to establish and therefore the behaviour is not comparable to the far field. As a rule of thumb in can be said the acoustic far field starts after about 2 wavelengths λ of the frequency of interest.

2.3.2 Threshold Measurement

Using the basics about Time of Flight and acoustic waves we analyse in this section a practical measurement example.

The most easy principle to measure Time of Flight is to send a short pulse from a transmitter and then wait until the receiver signal exceeds a defined threshold. It is expected that this increase of receiver signal is the response of a first reflection. Often the transmitter and receiver are at almost the same position, or maybe transmitter and receiver are even one and the same sensor.

In that case the time difference between sending the impulse and the time when received signal exceeds the threshold is the so called 'Time of Flight' t_{flight}. The speed of sound is known in most scenarios and therefore the distance s_{object} from sensor to object can be easily calculated using Equation (2.1). It must be taken into account that the acoustic signal has to pass the way between sensor and object twice, once from transmitter to object and once the reflection from object to receiver. As we are interested in the distance between sensor and object, like in Figure 2.1, we have to adapt Equation (2.1) by a factor of 2 to take this into account.

$$s_{object} = \frac{v_{air} t_{flight}}{2} \tag{2.2}$$

This method is very easy to implement and does not need very complex setup. Also the analysis is quite simple, as it just needs a simple comparator and no complex analysis of the signals. However defining the threshold is a problematic point here. A rectangular pulse will be changed into a longer signal when transmitted from a sensor, when passing the air and also at reflection of the object. The main part of change of signal length is normally due to resonance effects of transmitter and receiver. Furthermore the amplitude of the signal changes over distance, because of damping of the air, geometrical loss and also absorption at the object. So if the threshold is too low, it may reacts on noise, if it is too high it may misses a reflection or evaluates a time that is longer then it should be. A pulse input signal is shown in Figure 2.3. The Pulse at the transmitter is well defined and the time when it is transmitted is known very precise by using the rising edge of the Pulse. The received signal is shown in Figure 2.4. The shape of this signal does not have such a sharp edge and it is more complex to define the exact time of arriving. This leads to a high uncertainty for the measured receiving time. Furthermore there must be a delay between each measurement to wait until all necessary reflections are decayed, which leads to a limited measurement rate.

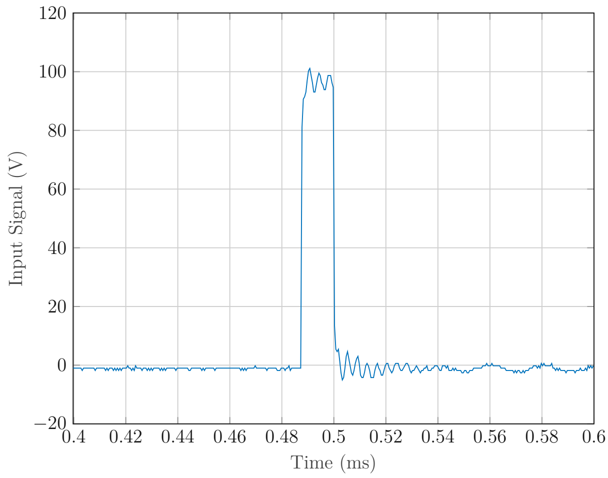


Figure 2.3: Impulse on transmitter

The threshold measurement principle is easy to realize and in combination with a well chosen ultrasonic sensor it can lead to acceptable results for several applications. But in addition to the uncertainty of speed of sound v_{air}, which can be handled with some additional effort, also an additional uncertainty due to imprecise detection of the receiving time is added to the value of t_{flight}.

One drawback of a simple threshold measurement is that the receiver signal has to reach the defined threshold level. In reality that means that the calculated Time of Flight will always be overestimated, because the real arrival time at receiver will be earlier, but can't be detected with a simple threshold because of noise. If the distance changes, also the amplitude of the received signal will change (bigger distance leads to lower receiver amplitude). Also reflectivity of the measured object is having an influence

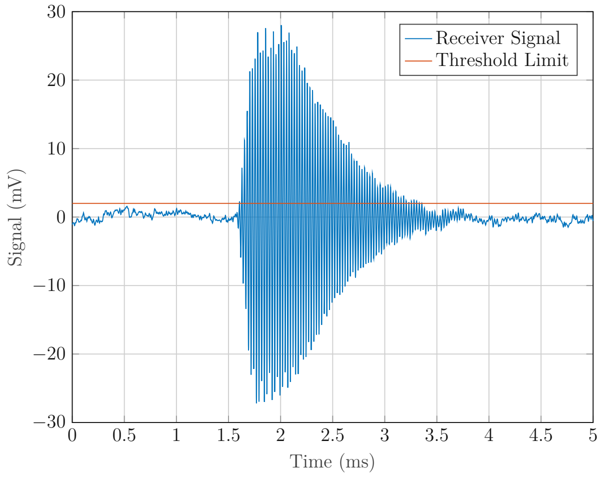


Figure 2.4: Impulse at receiver after reflection

on this receiver signal level. As the threshold level is something that must be defined to a fixed value it means that this uncertainty is something that changes dependent on the distance.

To overcome this issue one solution is to extend the detection of the receiving time by not only using the time when the simple threshold level is reached, but also add a curve fitting in addition to find the expected real point where signal was received at first [4]. In a simple way this curve fitting can be a linearisation of the envelope using two threshold levels which are linearly interpolated like it is seen in Figure 2.5. Here simply two threshold levels are defined and those two points where receiver signal first reaches this level are used to generate a linear interpolation to the x-Axis. This time is now assumed to be the real receiving time. Of course this curve fitting can get more and more complex. Instead of two thresholds the envelope of the receiver signal can be used and higher orders lead to better approximation. An additional advantage of this method is that the absolute value of the first Threshold level is not so important any more on the result, because a higher threshold level simply leads to another curve fitting. As receiving time the moment when the fitted Curve reaches zero is used.

2.3.3 Correlation Measurement

To get a more precise information about the time when reflected signal arrives at receiver then using the threshold measurement from Section 2.3.2, there is a possibility to change the sent signal from a simple rectangular pulse to a defined shape which is more suitable for transmitter and receiver. This opens the opportunity to calculate correlation

$$\rho(t) = \int_{-\infty}^{\infty} x(\tau)\, y(t+\tau)\, d\tau, \tag{2.3}$$

between the sent and received signal. ρ represents here the dimensionless correlation coefficient, $x(t)$ the input signal and $y(t)$ the receiver signal.

It can be imagined that the received signal is shifted in time over the sent signal

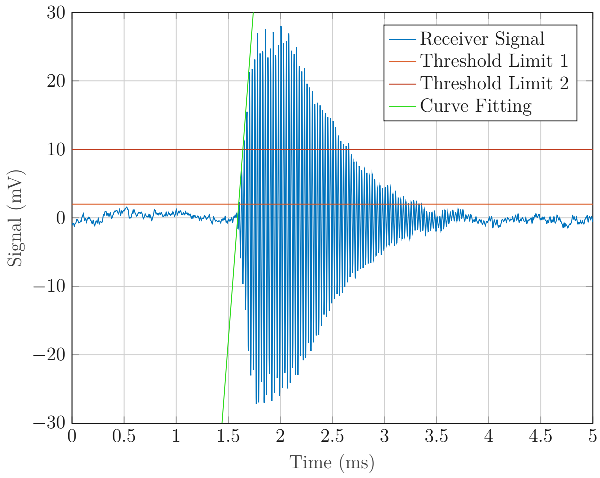


Figure 2.5: Impulse at receiver after reflection including double threshold limits

and it is compared how well they fit together. The correlation coefficient ρ will reach a peak which is estimated to be the best match. This reduces the problem with noise and degree of freedom for defining the threshold. So the estimated time where reflection occurs can be defined much more precise. It must be taken into account that the shape of signal will change during transmission, reflection and receiving the signal. It is important to use a signal which is suitable for the individual system to reduce uncertainty due to this effect. If the correlation method is tried using a pulse signal like in Figure 2.3, the correlation with received signal from Figure 2.4 will not lead to satisfying results. This is mainly because of the transfer function of transmitter and receiver, which will damp most frequencies of a pulse signal. This is described in more detail in Section 4.2.2. For using piezos with resonance it is a good idea to use a signal which is close or at the resonance to have similar signals for sent and received signal. Example for a chirp signal around the resonance frequency can be seen once for the transmitter in Figure 2.6 and once at the receiver after reflection in Figure 2.7. Those two signals will then be evaluated using Equation (2.3), which result can be seen in Figure 2.8.

The advantage of this method compared to threshold measurement method described in the Section before is a higher precision of the measured distance. The drawback is the longer signal length and therefore lower measurement rate. It also must be admitted that there is a more complex post process needed to calculate and evaluate the correlation according Equation (2.3), whereas for a simple threshold method the post process can be a simple comparator.

2.3.4 Phase Measurement

Another principle a bit different then Time of Flight, is to generate a continuous sine wave and measure the phase between the transmitted and received signal. This is possible if the measurement range of the signal is limited to maximum one wavelength of the used frequency, because for higher distance changes it is not possible to distinguish a phase change of $\Delta\varphi$ and $n \cdot 360° + \Delta\varphi$. A detailed description about that follows

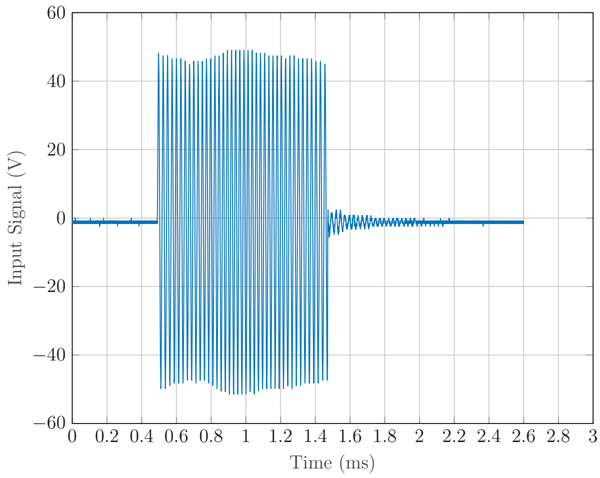


Figure 2.6: Chirp on transmitter

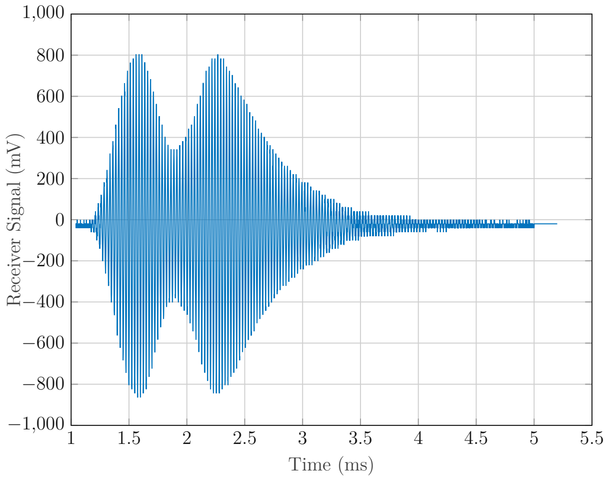


Figure 2.7: Chirp at receiver after reflection

in Section 4.1. Such a principle increases the precision of distance measurement, but reduces the measurement range dependent on the chosen frequency f compared to Time of Flight.

There are several techniques where amplitude and phase modulation are used to increase the measurement range [12], [13]. In practice such systems use one resonant frequency or several frequencies, but very close to this basic resonance. So the used bandwidth of this systems are relatively small.

2.4 Research Questions

As discussed in the Sections before it can be seen that distance measurements based on acoustic waves are based on Time of Flight principle in most cases. One important parameter for the result value distance is here the measured time t, where several uncertainties occur for that value. This uncertainties lead to a limited resolution

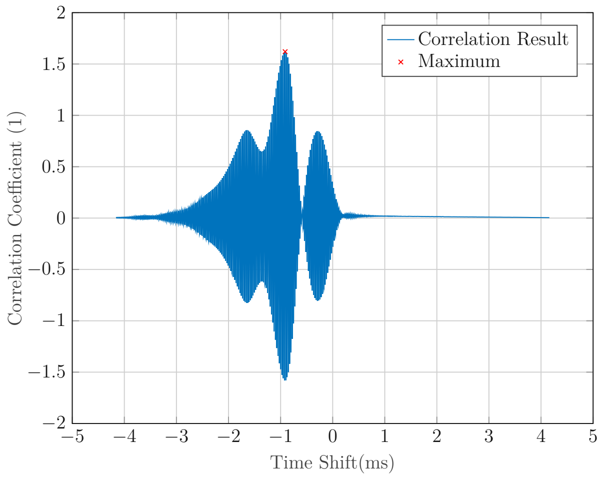


Figure 2.8: Result of correlation between input and output

for the final value distance. According [4] the best possible standard deviation in a measurement is for example at 185 μm. This is by using the correlation method described in Section 2.3.3. When using a continuous frequency signal like in [12] or[13] described in Section 2.3.4, this can be increased to a best measured standard deviation of 35 μm.

This leads to the first Research Question:

Is it possible to increase the resolution of measured distance in the region of several μm, using ultrasonic acoustic sensors?

Another limit for actual state of the art systems is the measurement time. For a useable Time of Flight measurement after each sent signal it must be waited until the signal has passed the distance between sensor and object, once forward and also the way back. In practice it is also realistic that additional objects in sight lead to additional reflections, which can occur also later then the first received signal. This limits the possible measurement time in reality depending on the distance, to at least $2\, t_{flight}$.

This leads to the next Research Question:

Is it possible to increase the measurement time for a distance measurement using ultrasonic acoustic sensors?

The setup should be realised by using standard ultrasonic sensors in a low price area of several Euro. In the following Chapters this is discussed in detail and real measurement results using a new approach are compared to measurements using common Time of Flight principles to prove the performance.

CHAPTER 3

System Description

In this Chapter the individual parts of the measurement setup are described to get the necessary background for the later detailed analysis. First the whole setup is described to see which components are necessary for an ultrasonic distance measurement and how it is realised in this thesis. The most important hardware elements like sensors, amplifier and moving stage are explained in more detail. Not only the combination and properties of the individual parts are relevant, also physical properties of the measurement environment are crucial. Therefore at the end of this Chapter the influence of reflectivity and speed of sound are introduced, as they have major influence on the measurement setup and result.

3.1 Setup Overview

The system is realized with piezo sensors, which convert electrical energy to an acoustic wave and the other way round. Such sensors are available in every electronic part supplier for several Euros. The setup looks generally like shown in Figure 3.1 in a schematic, simplified view. There is one transmitter, one receiver and one unknown object to which the distance s is measured.

The real setup consists of an oscilloscope, a signal generator, an electrical moving stage, a PC, an amplifier and at least two sensors, one transmitter and one receiver, like it is shown in Figure 3.2.

The PC is operating the whole system, which means a connection to the moving stage and the oscilloscope, both via USB. This communication enables the possibility to read and write data to the moving Stage, for a reliable well known positioning. The connection to the oscilloscope enables on one hand the access to measured data, which is most likely signal of transmitter and receiver. On the other hand the external trigger of the oscilloscope is used to activate or deactivate the output of an additional signal generator. For a proper driving signal at the transmitter an amplifier is used between signal generator and transmitter. Due to the high output voltage at the transmitter,

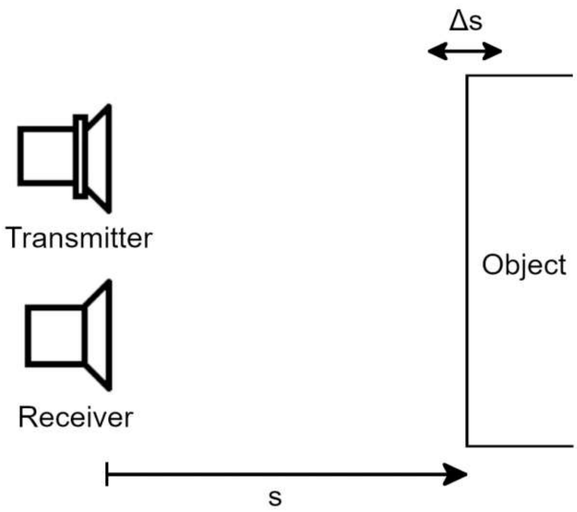


Figure 3.1: Basic Setup for Distance Measurement

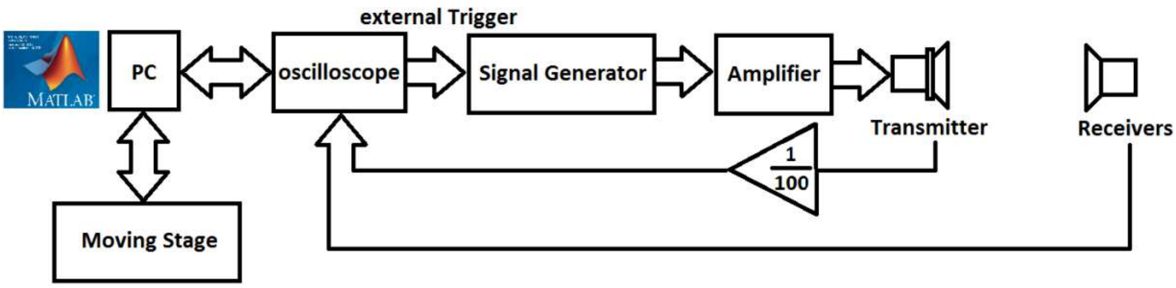


Figure 3.2: Setup Overview

which is up to 150 V_{pp}, the signal of the transmitter is connected with an attenuator to the oscilloscope. As the expected voltage at the receiver is much lower it can be directly connected to the oscilloscope.

This enables the possibility to measure known situations automatically and to evaluate and save the measured data directly on the PC. For communication to hardware and analysis of data the software Matlab (MathWorks, Natick, Massachusetts, USA) is used. Using this setup different measurement methods can be evaluated and compared under same conditions.

A real setup can be seen in Figure 3.3. Here can be seen a transmitter (below No. 1 in Figure 3.3), a receiver (below No. 2 in Figure 3.3), a moving Stage, which is split up in the mechanical moving part (over No. 3a in Figure 3.3) and a controller part (over No. 3b in Figure 3.3), an oscilloscope (No. 4 in Figure 3.3), an amplifier for the transmitter (No. 5 in Figure 3.3), a signal generator (No. 6 in Figure 3.3) and an attenuator (No. 7 in Figure 3.3) between transmitter and oscilloscope.

In Table 3.1 there is an overview about used Equipment.

To simplify the setup for some examples, instead of measuring the reflection from an object, the receiver is placed directly opposite to the transmitter, like shown in

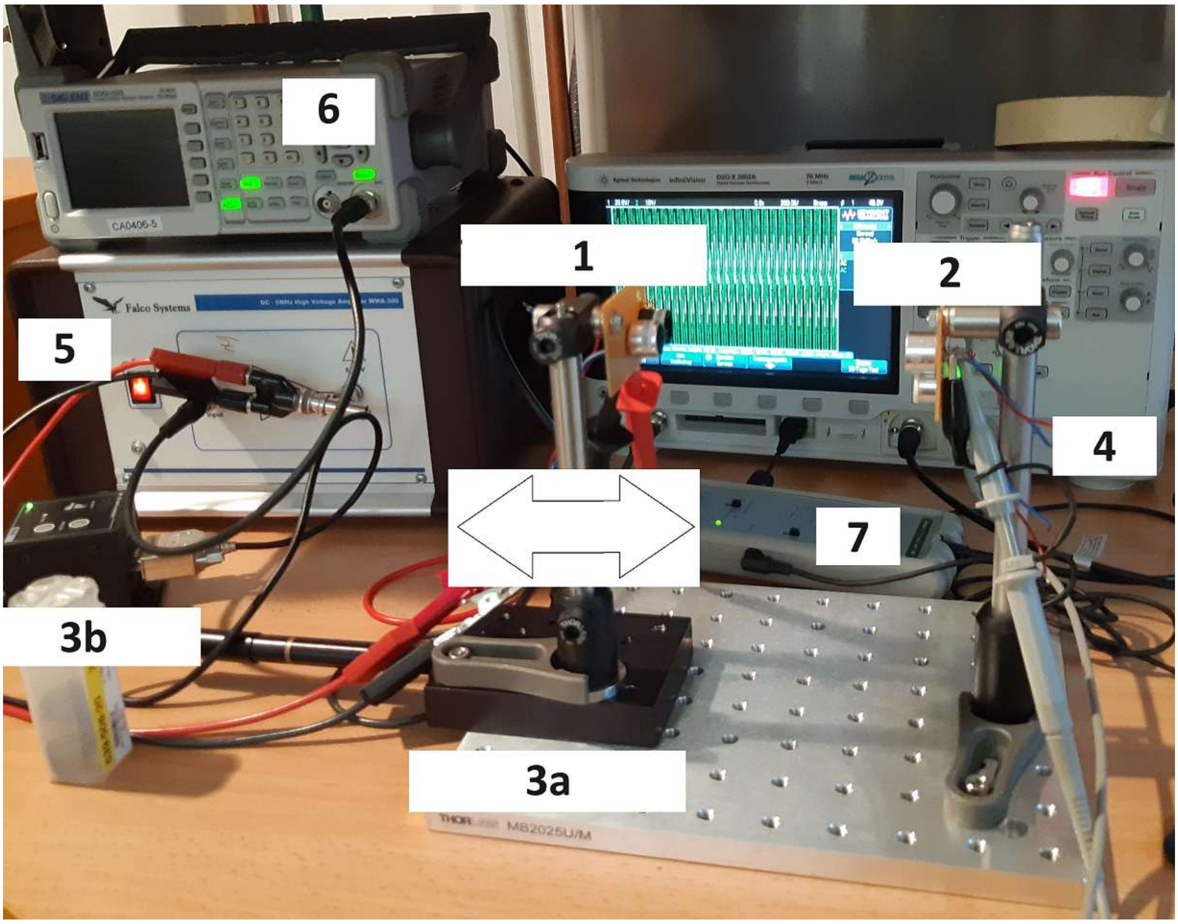


Figure 3.3: Overview about a distance measurement setup, explanation of the Numbers can be seen in Table 3.1

Figure 3.4. This is theoretical almost the same situation like in Figure 2.1 with an object in the middle between transmitter and receiver, having a perfect reflecting surface. The advantage here is that object properties like angle, reflectivity or lateral resolution must not be taken into account and can be seen as ideal.

A setup with an object in front of transmitter and receiver can be seen in Figure 3.5 and 3.6.

3.2 Amplifier

A piezo crystal can be seen from electrical point of view mainly as capacitance [14]. To realise a useable amplitude of motion of the sensor which will result in a higher amplitude of the generated acoustic wave, voltages in order of about 150 V_{pp} are needed. So it can't be simply connected to a typical voltage source, first because of the needed high voltage and second because a capacitance may leads to problems driving the source stable for a signal generator like the used SDG1025 from Siglent (Siglent Technologies Co. Ltd, Shenzen, China). This signal generator is expecting 50 Ω or high impedance [15] at its output and is specified for up to 10 V_{pp} maximum. Therefore a WMA-300 high

Table 3.1: List of Equipment

Number	Item	Name
1	Transmitter	Multicomp MCUSD16P40B12RO
2	Receiver	Multicomp MCUSD16P40B12RO
3a	Moving Stage	Thorlabs ZB625B
3b	Stage Driver	Thorlabs TDC001
4	Oscilloscope	Agilent InfiniiVision 2000 X-Series
5	Amplifier	Falco Systems WMA-300
6	Signal Generator	Siglent SDG1025
7	Isolation Probe	Agilent N2791A

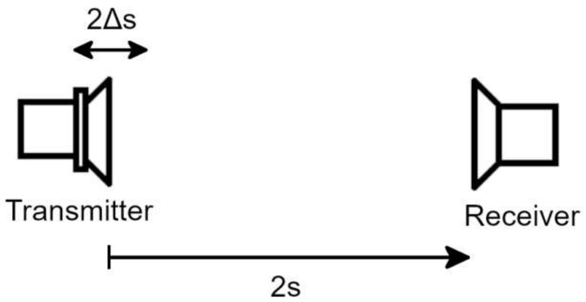


Figure 3.4: Simplified distance measurement

voltage amplifier from Falco Systems (Falco Systems, Katwijk aan Zee, Netherlands) is used. It has a fixed amplification of factor 50 [16] and can drive an output voltage up to $U_{out} = 150\,V_p$. This amplifier is especially made for driving piezo elements.

3.3 Moving Stage

To prove the measurement precision a well defined setup is needed, where of course positioning of the sensors and object is a key factor. The real distance must be known with a precision by at least a factor of 10 higher then the expected resolution of the measurement setup to avoid reasonable influence from position failures on the measurement result. For positioning a ZB625B motorized actuator together with a TDC001 DC server motor driver from Thorlabs (Thorlabs Inc., Newton, New Jersey, United States) is used.

The ZB625B has a precision of 40 nm, which will be reduced in practice dependent on the applied mass [17]. It should be mentioned as well that there is a backlash of

Figure 3.5: Example Setup

up to $8\,\mu m$, which means the positioning error in case of a change of the movement direction. This is more then precise enough for this purpose. The backlash effect can be easily avoided by measuring always when possible by only moving in one direction. The total possible movement is limited by 25 mm. If longer distances are of interest, a manual change of position is made in addition to the movement of the stage.

The Motorized Actuator gets its signal from a TDC001 DC Server Motor Driver [18]. This enables a proper signal for the actuator and in addition opens several possibilities for controlling the moving stage. It can be moved manually directly using the buttons on the device, either with adjustable speed or with controlled steps. The real advantage is that there is connection to a PC possible and from there the Stage can be controlled using an additional software or by an interface. Last one is used here via Matlab and enables a complete automated measurement progress for high precision and repeatability.

3.4 Sensors

To generate and detect an ultrasonic wave, a common technology is the use of direct and indirect piezoelectric effect [19]. The sensors are piezo crystals which are electrical connected. According the piezoelectric effect an external force on such a crystal will lead to an electrical voltage. It is also possible the other way round, to apply an electrical voltage which will lead to a force on the crystal which results in a movement of the

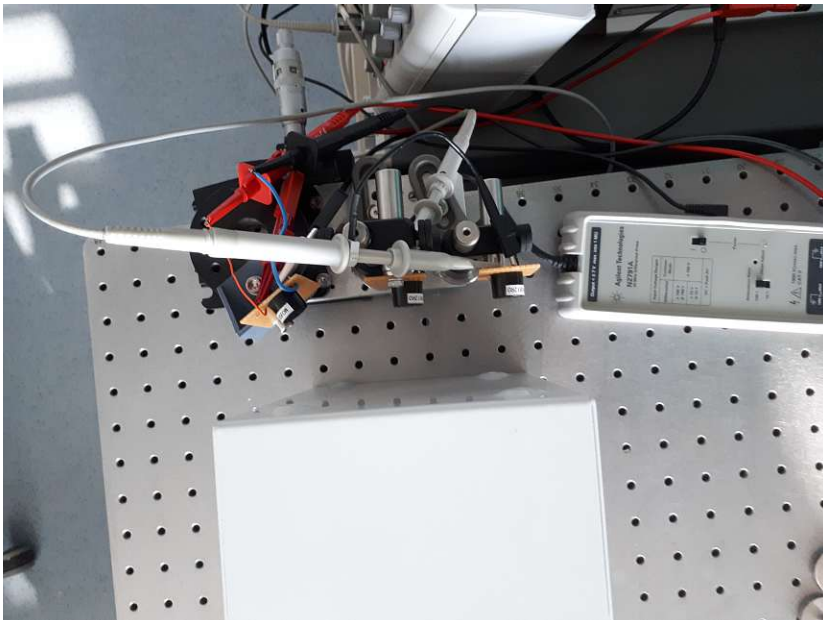


Figure 3.6: Example Setup Top View

piezo. So when an electrical voltage is applied at the transmitter it will result in a movement of the piezo, which generates local air pressure changes, which will move on through the air as acoustic wave. When air pressure changes occur at the piezo crystal of the receiver, it will lead to a mechanical movement of the piezo, which is converted to an electrical signal.

Dependent on the used material, the structure of the setup and how the electric connection to the material is made, such sensors do have resonance frequencies. To transmit and receive signals with best possible Signal to Noise Ratio (SNR) often a resonance of a sensor is used. At frequencies, not close or at the resonances, it is possible to generate signals as well, but amplitude will be significantly lower, which means a loss of SNR at the transition from the electrical signal to the acoustic wave and also at the receiver side when the acoustic wave is converted to an electrical signal again.

For this diploma thesis different sensors were analysed and tested. One sensor is the MCUSD13A300B09RS [20] from Multicomp (Farnell GmbH, Salzburg, Austria), which has a resonance frequency at $f_{res} = 300\,\text{kHz}$. The relatively high frequency of this sensor brings advantages like a precise directivity (see Section 4.2.1) and as explained in Section 4.1.1 also an expected high precision. In practice the drawback of the high frequency is the complex handling for all the electrical signals and the higher damping in this frequency range.

So for most setups a sensor operating at a lower frequency is used. In this thesis this is the Multicomp MCUSD16P40B12RO [21], which has a resonance frequency at $f_{res} = 40\,\text{kHz}$. Both sensors are dual use variants, which means that they can be used for generating ultrasonic waves, but also to detect them. This can be either in the use case that transmitter and receiver are the same sensor or that two sensors of this types are used, where one is used as transmitter and the other one as receiver.

Such a ultrasonic piezo sensor has a structure like shown in Figure 3.7. The piezo-material is located between two plates which are mechanically connected. The lower plate is mounted on the base of the sensor, where the upper plate only has an additional membrane on top. This upper side is less heavy then the whole sensor, especially when the sensor is mounted externally. For that reason in most cases only the upper side will see a mechanical movement when an electrical voltage is applied.

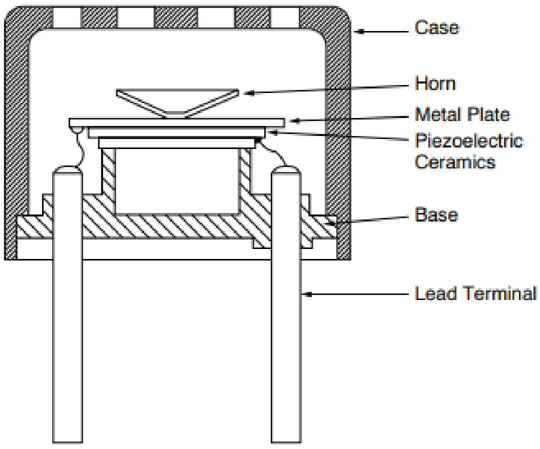


Figure 3.7: Structure of an ultrasonic Piezoceramic sensor

3.5 Reflectivity

As we want to measure distance to an object, we also have to take care about the influence from the object itself. According Section 4.2.1 the directivity is something that is dependent on the used sensor and its frequency. Ultrasonic waves describe a wide frequency range, starting from 20 kHz up to several MHz. How good an object is reflecting an ultrasonic wave, is dependent on the waves frequency and dependent on the acoustic impedances of participating mediums.

If an object is not fully reflecting, the not reflected energy of the acoustic wave must be transmitted or absorbed. Whenever an acoustic wave hits a boundary layer between to different materials, a part of the acoustic waves energy will be reflected, a part will be transmitted and the rest will be absorbed. Absorption is neglected at that point. In Figure 3.8 it is shown that there is one direct reflection (blue line) on the surface of the object and another one which has to be transmitted into the object, where it then will be reflected inside the object, to be again transmitted back to the surrounding medium (red line). The reflection inside the object can be either due to material properties, like changes in density, or because the other end of the object is reached. According Time of Flight principle this would lead to two different time delays and therefore two results within one measurement.

Reflectivity and transmission are dependent on the acoustic impedance Z of the participating materials [22]. Acoustic impedance describes the resistance for an acoustic wave inside a material and is defined as

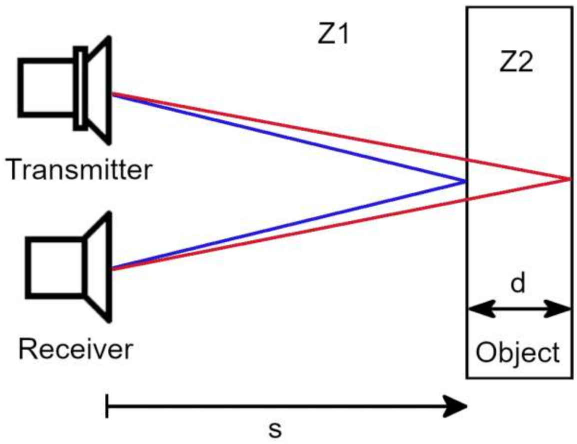


Figure 3.8: Additional signal due to Transmission and Reflection, blue is the direct reflection and red is the additional reflection inside the object

$$Z = \frac{p}{v_{pv}} = \rho v \tag{3.1}$$

where p is the pressure, v_{pv} is the so called sound particle velocity, ρ is the mass density of the material and v is the speed of sound in this material.

The reflectivity index r is

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1}, \tag{3.2}$$

where r is between $-1 \leq r \leq 1$, Z_1 is the acoustic impedance of the first medium and Z_2 of the second medium. So in Figure 3.8 Z_1 is acoustic impedance of air and Z_2 is the acoustic impedance of the objects material.

For a perfect transmission, so a reflectivity $r = 0$, the acoustic impedance of both participating materials must be the same ($Z_1 = Z_2$). The further the acoustic impedances of the participating materials differ, the more will be reflected and less will be transmitted.

So if we take a look at our first participating material air, the acoustic impedance is

$$Z_{air} = \rho_{air} v_{air} = 1.204\,\frac{\text{kg}}{\text{m}^3} 340\,\frac{\text{m}}{\text{s}} = 409.36\,\frac{\text{Ns}}{\text{m}^3} = 40.936\,\text{Rayl}. \tag{3.3}$$

The second material is the object and is generally unknown. If we look at typical materials that the distance could be measured to, for example steel, the acoustic impedance is

$$Z_{steel} = \rho_{steel} v_{steel} = 7,850\,\frac{\text{kg}}{\text{m}^3} 5,100\,\frac{\text{m}}{\text{s}} = 40,035,000\,\frac{\text{Ns}}{\text{m}^3} = 4,003,500\,\text{Rayl}. \tag{3.4}$$

So there is a factor of about 10^5 between Z_{air} and Z_{steel}, which leads to a reflectivity index $r = 0.9999$. Of course other materials have also other acoustic impedances Z, but the factor between air and typical solid materials is big enough to be able to assume a reflectivity index $r = 1$, which means that transmission is 0. We do not consider very soft materials like carpets.

For lot of applications, like in ultrasonic measurements in the human body in medicine or for non destructive analysis of materials [23], this effect is used. Here the acoustic impedances are closer together and the effect seen in Figure 3.8 can be used to find position of different layers inside an object. This reflectivity is also the reason why at ultrasound examination gel is applied on the skin. This gel avoids small air inclusions between the Sensor and the skin, which would lead to high reflections and a bad coupling into the medium of interest, the human body.

3.6 Speed of Sound

Measurement of distance is realised by measuring time and then calculate the distance according Equation (2.1). In the following chapter a principle for displacement measurement will be presented, where the phase φ is measured and the displacement is calculated according (4.2). In both Equations speed of sound is an important factor between the measured value and the calculated result out of it. For that reason the speed of sound v is relevant for the precision of the measurement result. If the value v is not precise, it will lead to a systematic measurement error.

An acoustic wave is physically a pressure change moving forward in a given medium. The molecules in this medium forward this pressure to the next ones, so it is obvious that the propagation of an acoustic wave is highly dependent on the medium properties. How good and fast this wave propagates is dependent on different environmental conditions, such as temperature, humidity, static air pressure [10] and also frequency of the acoustic wave.

There is a general Equation

$$v_0 = \sqrt{\frac{RT\gamma}{M}} \tag{3.5}$$

for the speed of sound in gas [24]. v_0 is the speed of sound, $R = 8.314\,\frac{J}{molK}$ is the universal gas constant, T is the temperature in K, γ the specific heat ratio and M the molar mass. This Equation can be used for a single gas. To get this for normal air, the molar mass of different gases in air must be calculated. Normally air consist of $p = 78.08\,\%$ Nitrogen, 20.95% Oxygen, 0.93% Argon and smaller amount of other gases. This leads to the molar mass of air

$$M_{air} = \sum_{n=1}^{N} M_n p_n \approx M_{Nitrogen} 0.7808 + M_{Oxygen} 0.2095 + M_{Argon} 0.0093 =$$
$$= 28.013\,\frac{\mathrm{g}}{\mathrm{mol}} 0.7808 + 31.999\,\frac{\mathrm{g}}{\mathrm{mol}} 0.2095 + 39.948\,\frac{\mathrm{g}}{\mathrm{mol}} 0.0093 =$$
$$= 28.948\,\frac{\mathrm{g}}{\mathrm{mol}}. \tag{3.6}$$

Now the speed of sound in air at a known temperature of typically $T = 20\,°\mathrm{C}$

$$v_{0_{Air}} = \sqrt{\frac{RT_{Air}\gamma_{Air}}{M_{Air}}} = \sqrt{\frac{8.314\,\frac{\mathrm{J}}{\mathrm{Kmol}}\ 293.15\,\mathrm{K}\ 1.4}{28.948 \cdot 10^3\,\frac{\mathrm{kg}}{\mathrm{mol}}}} = 343.34\,\frac{\mathrm{m}}{\mathrm{s}} \tag{3.7}$$

can be calculated. The influence of air temperature on speed of sound is according Equation (3.7). For the heat ratio a constant value $\gamma = 1.4$ is used. In practice the heat ratio is slightly dependent on temperature and humidity as $\gamma(T, RH)$, but the main influence for Speed of Sound is the temperature [10].

Due to this influence it is necessary to know the speed of sound precisely, to avoid a systematic measurement error. In addition it is also important to track the speed of sound between several measurements, as it may changes during time. When a measurement is repeated and environmental conditions do change between this repetitions, it will lead to different distance results, which is in reality just a change in speed of sound v_{Air}. This effect can also be used to measure the average temperature in air [25]. In this thesis we are measuring indoors where environmental conditions that influence the speed of sound are assumed to be stable.

CHAPTER 4

Continuous Signal Distance Measurement

As the basics of the setup and the available state of the art techniques are known now, the individual influences and real implementation for this thesis will be described in detail in the following Sections. First further investigations on the sensor properties, environmental influences and also expected effects of using a continuous wave are done, which are important for the later described new approach that shall improve measurement performance.

4.1 Displacement using Continuous Signal

Time of Flight measurements do not use continuous signals, they are always somehow limited in time and repeated for each measurement. In this thesis the approach is to change this and use a transmitter and a separate receiver, where the transmitter is continuously sending a signal. The receiver is in that case continuously receiving a signal as well. As for the Time of Flight signal, there will be a damping and also a delay in time. As we assume a continuous signal, for example a sine wave, it is not possible to simply use one of the methods as described in Section 2.3.2 or 2.3.3.

The wave relationship [26] between wavelength λ, the frequency f and the velocity v is given as

$$v = \lambda f. \tag{4.1}$$

The absolute distance is then

$$s = k\lambda = k\frac{v}{f}, \tag{4.2}$$

where $k \in \mathbb{R}$ is a value depending on the distance, representing the number of wavelengths λ which corresponds to the distance s. For an unknown constant distance s it is not possible to get the value of k, by using the sensor signals only. But if the distance s changes by a value Δs, Equation (4.2) can be written as

$$s + \Delta s = (k + \Delta k)\lambda = (k + \Delta k)\frac{v}{f}. \tag{4.3}$$

This can be separated in a fixed distance s and an additional distance change Δs (see Figure 3.1):

$$s = k\lambda = k\frac{v}{f} \tag{4.4a}$$

$$\Delta s = \Delta k\lambda = \Delta k\frac{v}{f} \tag{4.4b}$$

If we assume values of $|\Delta s| < \lambda$, this leads to $-1 < \Delta k < 1$. Such a change Δk is possible to see in the Phase change $\Delta\varphi$ between the sent and the received signal.

So the basic idea is to first measure the distance s to an object by an existing method, for example using the correlation measurement from Section 2.3.3, but then switch to a continuous measurement mode where displacement Δs is measured and added to this absolute distance value s. By doing this an object that moves steadily, without fast movements or jumps, can be followed and the change in position can be measured. This leads to a resolution in sub wave length order, like it is known from optical methods, like interferometers.

4.1.1 Possibilities

According Equation (4.1) a higher frequency f leads to a shorter wavelength λ. By assuming that a specific phase precision is possible to detect, a shorter wavelength directly leads to a higher precision. But of course higher frequencies also lead to higher damping of the signal [27], which will reduce the possible phase resolution. This is directly a basic limitation which must be considered for this kind of measurement. For short distances a higher frequency can be used, because damping does not lead to big problems with received signals. For bigger distances a lower frequency must be used to be able to have a receiver signal with enough SNR and a decrease of resolution must be taken into account.

To get an approximation about precision compared to a classic setup like it is used for methods with Time of Flight as described in Section 2.2, most likely a piezo crystal is used as transmitter and an additional one as receiver. A typical resonance frequency of such a piezo is $f = 40\,\mathrm{kHz}$. According Equation (4.1) this leads for medium air at typical conditions ($T = 20\,°\mathrm{C}$, $RH = 0\,\%$) with $v_{air} = 340\,\mathrm{m/s}$ to a wavelength $\lambda = 8.5\,\mathrm{mm}$. If a precision for the phase φ of $1\,°$ is estimated, this will result in an approximate precision of about $25\,\mu m$. Comparing this to existing Time of Flight methods, like in [3], where a standard deviation of about $130\,\mu m$ is measured, the resolution can be increased by a factor of 5.

By comparing Equation (2.1) and (4.3) it can be seen that in both Equations the speed of sound is a parameter necessary to calculate the value distance. So any uncertainty for speed of sound v directly results in an uncertainty for the distance s. This is the same for Time of Flight method and the here proposed continuous measurement method.

An advantage of this continuous method is the continuously active signal. For Time of Flight principle the timing between two measurements is limited and it must be waited until the signal did travel from transmitter to object and back to receiver, which means according Figure 2.1 a distance of $2s$ or a time delay of $t_{flight} = \frac{2s}{v}$. In case of a continuously active signal any change of distance Δs will directly influence the reflected wave. So the signal only has to overcome the distance $s + \Delta s$ from the object back to the receiver sensor, which leads to a time delay of $t_{flight} = \frac{s+\Delta s}{v}$. This is an improvement for the measurement rate by a factor of 2. In real measurements even more can be expected, because as described in Section 2.3.2 for typical Time of Flight measurements additional time is added to avoid miss interpretation due to additional reflections.

Summarized it can be said that a continuous transmitted signal as extension to an initialised distance measurement has the potential to increase the precision for a distance measurement and also to decrease the time between two measurements. But knowledge about speed of sound is still crucial and also the boundary conditions for such a measurement principle are an object that is moving steadily, because only displacement and not distance is measured.

4.2 Sensor Properties

A fundamental understanding of the used sensors is important for a clear insight on the measurement setup. The basics about the sensor itself can be seen in Section 3.4. In the following a more detailed view on the directivity and the resonance frequency, or more precise on the frequency behaviour of the sensor in general, will be explained.

4.2.1 Directivity

Such sensors are developed to generate an acoustic wave that is directed in a specific direction, most likely in the straight direction of the transmitter. The same is valid for a receiver, where the orientation of the receiver is important for the conversion ratio from acoustic pressure to electrical signal. When a voltage is applied to a transmitter, most likely with a sinus signal at a resonance frequency, the ultrasonic wave that will be generated will have an amplitude for the acoustic pressure $p_\theta(t)$ which is dependent on the angle θ to the normal line of the transmitter, like seen in Figure 4.1. The shape of the directivity is only dependent on the Angle θ, for the angle to the other axis radial symmetry is given.

This is an important property of a sensor, as it has a major influence on the lateral resolution for distance measurement. If an object is located directly opposite to a transmitter, which means $\theta = 0\,°$, the amplitude of the acoustic pressure $p_\theta(t)$ will be higher there, compared to the same distance and at same operating conditions, but the object is located at an angle of $\theta \neq 0\,°$, because of the Directivity from the transmitter. Vice versa a receiver that is placed exactly in the normal direction of an acoustic wave, meaning $\theta = 0\,°$ like in Figure 4.2(a), will generate a higher amplitude in the electrical signal then a receiver that has an angle $\theta \neq 0\,°$, like in Figure 4.2(b), related to the incoming acoustic wave.

In the data sheet of the 40 kHz sensor [21] there is a directivity given when the

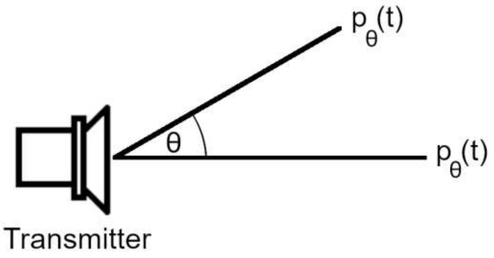


Figure 4.1: Directivity angle θ of a transmitter

sensor is used at resonance frequency as seen in Figure 4.3(a). The same is also available for the 300 kHz sensor [20] in Figure 4.3(b). Higher frequencies are better focused, which can be clearly seen when comparing the 2 sensors directivities. Where the 40 kHz sensor needs an angle θ of about 20 ° for 5 dB, the 300 kHz sensor is already at an angle θ of less then 5 ° at a 5 dB difference. The reference for the dB is here 0 °.

A well alignment of transmitter related to the measurement object and of receiver related to the incoming acoustic wave is therefore important.

For the 40 kHz sensor this directivity at the resonance frequency $f_{res} = 40.29\,\text{kHz}$ at a distance of $s = 20\,\text{cm}$ is measured at the receiver. The transmitter is fixed and is oriented in direction of the receiver. Position of receiver is constant, it is only rotated. The angle θ according Figure 4.2 is changed between -45 ° and 45 °. The results are shown in Figure 4.4.

4.2.2 Resonance Frequency

In general a piezocrystal material has natural resonance frequencies. This natural frequencies depend on several parameters like the material itself, shape and dimension of the probe and also the direction how the probe is cut out of a piezocrystal. This is because piezoelectric materials are anisotropic [28]. For a rectangular probe there are resonance frequencies for the length, the width and the height of the probe and of course also harmonics of them [29]. Typical sensors use probes in circular shape, so dimension of height and diameter will define the resonance.

To excite a piezocrystal, an electrical voltage is applied. A mechanical and electrical connection to the probe is needed. This connection will influence the resonance frequencies, because an additional mass is added to the mechanical structure. If an external mass is applied in addition, it will lead to the same effect and can change resonance dramatically [11]. In the use case of a sensor like in the setup of this thesis,

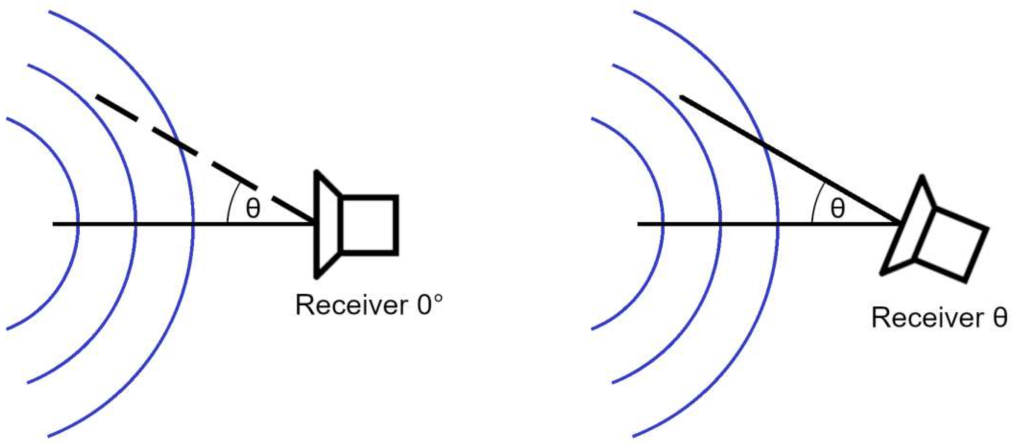


Figure 4.2: Receiver at (a) $\theta = 0°$and (b) angle $\theta°$related to acoustic wave

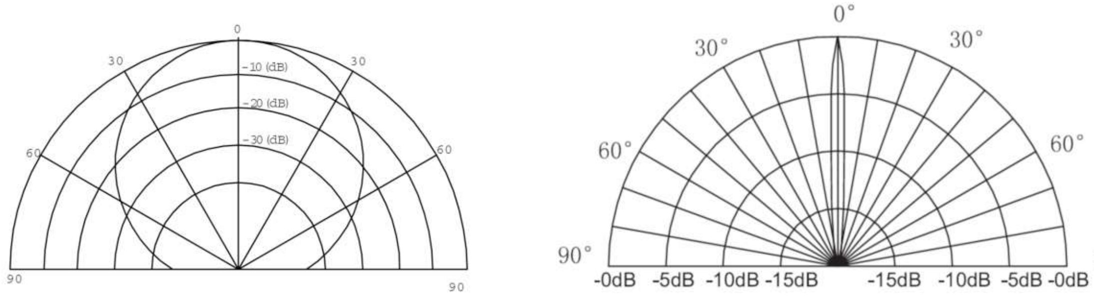


Figure 4.3: Directivity of (a) 40 kHz sensor and (b) 300 kHz sensor

this is not an issue because our transmitter and receiver will not see any additional external mass.

If a sensor like this is made for generating or receiving ultrasonic waves, for higher frequencies also an additional matching layer is often needed to adapt acoustic impedances, otherwise there would be a poor transition from the mechanical movement of the piezo to the medium where ultrasonic wave should be generated. This layer can also influence the resonance frequency.

The temperature will influence the behaviour of the piezoelectric material, including resonance frequency [11].

Furthermore there can be different mode shapes which lead to further resonances. There are different possibilities to visualize such resonances and how the mode shapes look like [30], [31].

So summing up we see that the resonance frequency of an ultrasonic transducer is dependent on:

- used piezoelectric material,

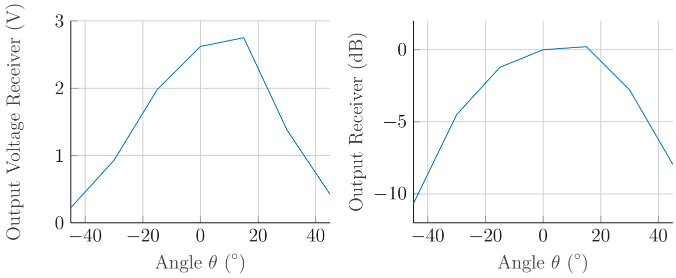


Figure 4.4: Measurement of Sensor Directivity over angle θ with (a) Sensor Voltage and (b) in dB related to main direction

- shape, dimensions and direction of the piezo,
- electric connection to the piezo,
- temperature,
- matching layer and
- mode shapes.

The data sheets of simple Sensors like used in this thesis [21], [20] only give information about one resonance frequency, where they are specified. Therefore a theoretical analysis is hardly possible and for a better understanding the sensor will be further analysed in the following.

To get a better understanding a setup without an object according Figure 3.4 is used, because influence of an object is not of interest for analysis of the sensor. Both, transmitter and receiver, are in a fixed position with a distance of 10 cm opposite to each other. At the transmitter a step with a voltage of $U_{in} = 100\,\mathrm{V}$ is applied and the response at the receiver is measured. Input and output signal can be seen in Figure 4.5, where the receiver signal is scaled by a factor of 400 for visualisation. Despite the input is a sharp step, which means all possible frequencies are stimulated, the response is very limited in bandwidth, which can be seen in time signal as a clear sine signal can be seen and also the frequency analysis of the received signal in Figure 4.6 shows that there are only little frequency ranges with a valuable output. The important information that can be seen here, is that there is in addition to the defined resonance frequency at 40 kHz, obviously also an additional resonance at about 53 kHz.

This additional resonance may can be of interest for improvement of distance measurement. The measurement is repeated with other sensors from the same type and also with a different but familiar sensor MCUSD16A40S12RO from Muilticomp as well. For all of this measurements the result is very similar, the exact value of resonance frequencies, both at 40 kHz and at 53 kHz is fluctuating from sensor to sensor, but the quantitative result that there is a stable second resonance frequency is always visible.

Movement of Sensor Membrane

As already explained earlier in this Section there are different parameters that influence resonance frequency. One explanation for the second resonance frequency is that we

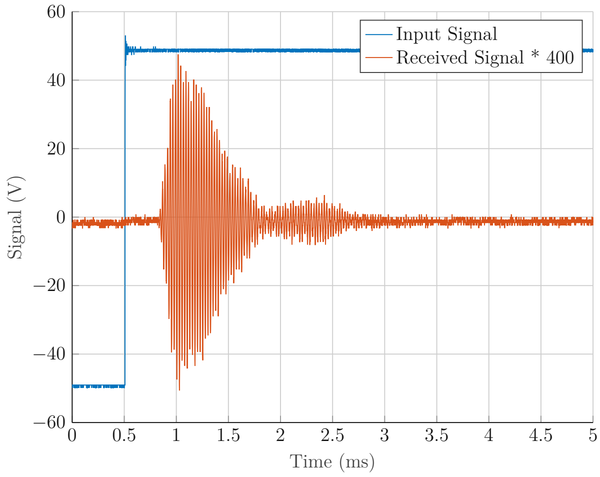


Figure 4.5: Time signal of step response for a transmitter receiver setup

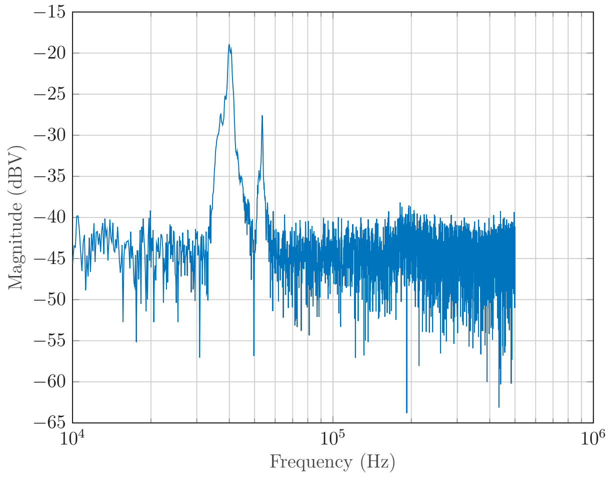


Figure 4.6: FFT result for receiver signal to a step response on transmitter

see a higher order of an Eigenmode, as described in [32]. In case of exciting the sensor electrically and measuring an electric signal at the receiver again, it can't be seen where and how the sensor is really moving.

To be able to do this instead of measuring the electric output of the receiver, movement of the membrane is observed. The movement of the membrane is directly measured using a laser vibrometer from Polytec (Polytec GmbH, Waldbronn, Germany). A combination of OFV-5000 Controller [33] together with OFV-534 Sensor head [34] is used.

The mechanical protective grid of the Ultrasonic Sensor is removed (see Figure 4.8) to get access to the sensor with the laser. In Figure 4.9(b) the inner part of the sensor is shown. At the outer edge there is a mechanical housing of the sensor, inside we see the membrane. A typical structure of a piezoceramic sensor like the one used here is shown in Figure 3.7. The piezoelectric material itself is not directly accessible, so it is not possible to measure directly there.

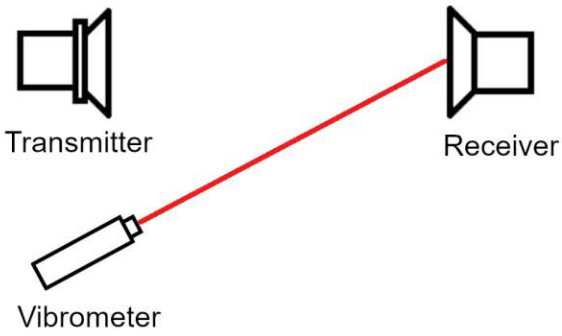


Figure 4.7: Measurement Setup for Membrane Movement

The laser spot is then focused and the movement is measured on different locations of the sensor according Figure 4.9(a). The bode plots for the different positions can be seen in Figure 4.10. This is a typical frequency response for a piezo, like it is described in [32]. It can be seen that all resonances after the first two have already high damping and a useful signal is hardly possible there.

Figure 4.8: Laser spot on receiver Membrane

Important to mention is that the measurement done here is already a combination of three transfer functions. First is the transfer function $G_{transmitter}$ which converts the electrical signal to an ultrasonic wave. Second is the transfer function G_{air} describing the path of the ultrasonic wave in the air. And the third one is $G_{receiver}$ which converts the ultrasonic wave back to an electrical signal.

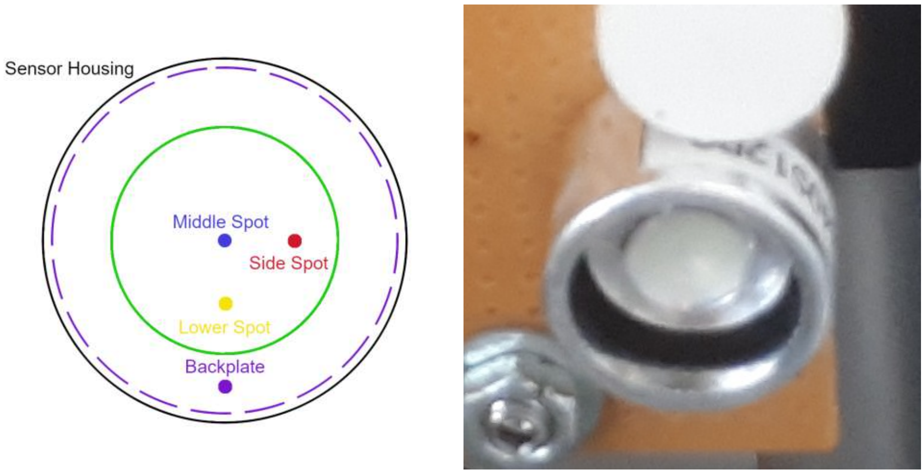


Figure 4.9: Positions for Laser on the open sensor

Transfer Function G_{air} is only damping and a time delay. So there are no resonance effects or big changes in the interesting frequency range. In case of $G_{transmitter}$ and $G_{receiver}$ the general structure is always the same. The exact parameters of mass, stiffness and damping for the piezo vary from sensor to sensor a little bit, which will result in a deviation of real resonance frequencies between different sensors.

This can be clearly seen in Figure 4.11 where the amplitude of resonance at $f_{res1} = 40\,\text{kHz}$ looks smaller then the resonance at $f_{res2} = 53\,\text{kHz}$. The difference to the bode plot from Figure 4.10 is that another Sensor was used as transmitter. When looking at the bode plot more detailed, Figure 4.12 shows that obviously the first resonance is at a lower frequency for one sensor then for the other. Therefore both resonances can be seen in the bode plot, but with a lower amplitude because they are not matching together. It can be concluded that a pairing of sensors is important to get the best possible output, where pairing means that resonances of both sensors, transmitter and receiver, should be as close together as possible.

4.3 Environmental Influence

It is important to know which parameters influence the measurement result and if possible to reduce their influence. There are two major things that will effect the result. First is the fluctuation of speed of sound, which is dependent on different environmental conditions and must be defined for different environments. Second is the influence of the object itself. Size, shape and also the distance between object and receiver may influence the measurement result. Where speed of sound is something that can be handled with manageable effort, the influence of the object is more complex, as object properties are generally unknown.

4.3.1 Calibration

Independent which of the so far described measurement methods is used, an important value for all of them is the speed of sound. As described in Section 3.6 this value

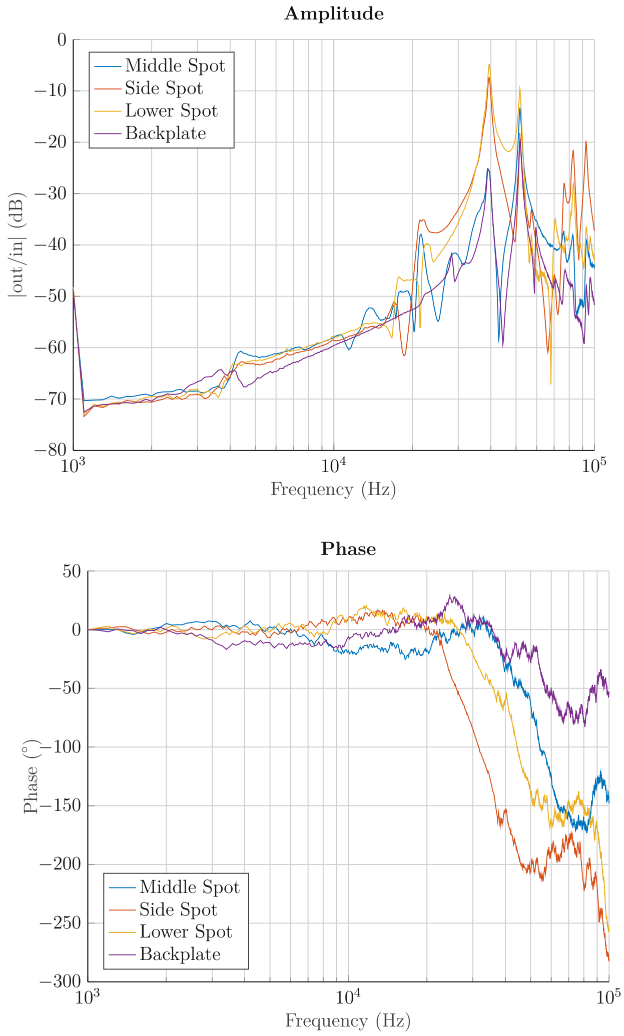


Figure 4.10: Bode Plot of Membrane Movement

is dependent on different environmental conditions. One typical solution is to take formulas from theory like [24] and calculate the speed of sound. To be able to do this the necessary parameters, like temperature T and relative humidity RH are necessary. For a very detailed analysis also values like CO_2 concentration and atmospheric pressure must be taken into account. So they must be either measured with additional sensors or known for a given environment like in a laboratory to do this.

In this thesis we come up with another solution for this issue and instead of calculating speed of sound, it is directly measured. To do so an additional second receiver is added to the measurement setup. This second receiver is positioned in a known distance behind the first receiver.

Using this setup it is possible to calculate speed of sound by

$$v_{air} = \frac{\Delta s_R}{\Delta t_{flight}} = \frac{s_{R2} - s_{R1}}{t_{flight_2} - t_{flight_1}}, \tag{4.5}$$

where s_{R_1} is the path distance between transmitter and receiver 1, s_{R_2} is the path

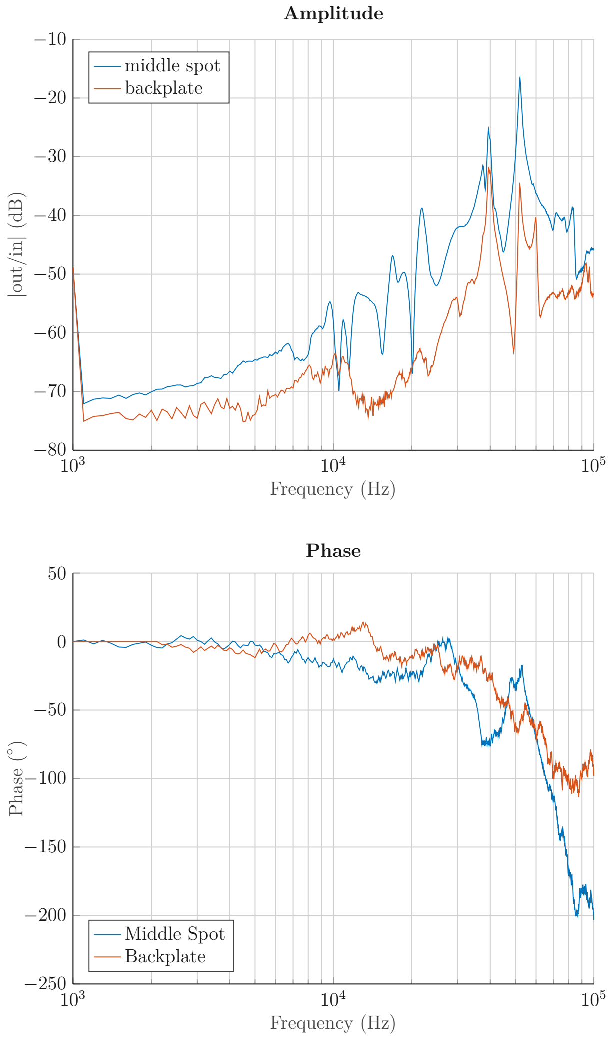


Figure 4.11: Bode Plot of Membrane Movement - Not matching sensors

distance between transmitter and receiver 2, t_{flight_1} is the measured Time of Flight for receiver 1 and t_{flight_2} is the measured Time of Flight for receiver 2. The used setup is shown in Figure 4.13.

For smaller distances s it must be taken into account that the path between transmitter and receiver is not only $2s$, but also the side distance s_{TR} must be passed by the wave (see Figure 4.18). To do so an initial measurement for s is done by using an estimated speed of sound $v_0 = 343.34\,\frac{m}{s}$. Using this estimated distance s_e the real path between transmitter and each receiver can be calculated more precise

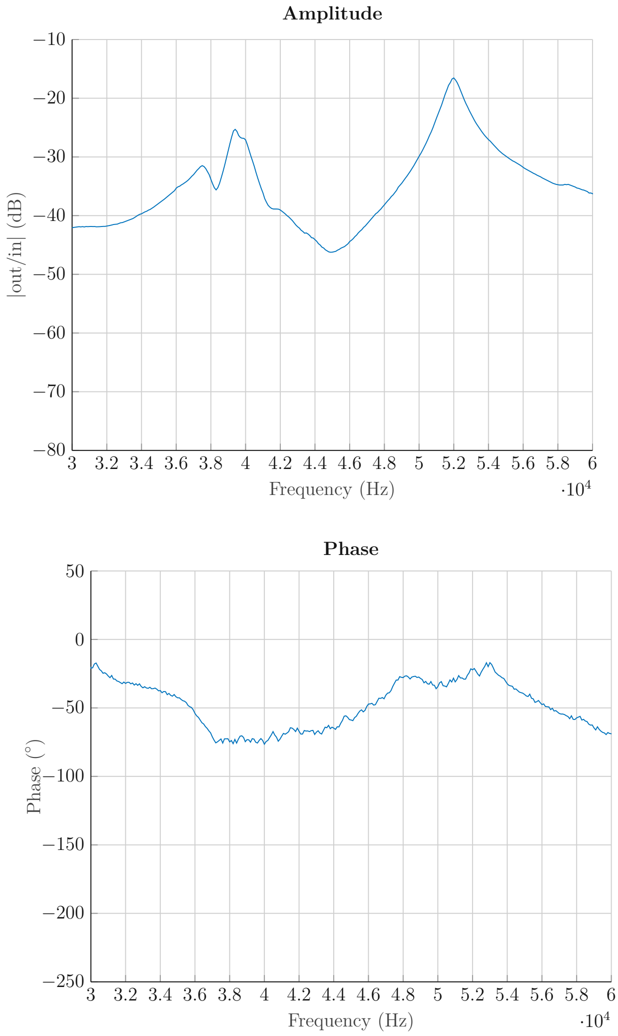


Figure 4.12: Bode Plot of Membrane Movement - Not matching sensors - Detail

$$
\begin{aligned}
s_{R_1} &= 2\sqrt{(\frac{s_{TR}}{2})^2 + s_e^2}, \\
s_{R_2} &= \sqrt{x^2 + s_e^2} + \sqrt{y^2 + (s_e + s_{TR})^2}, \\
y &= s_{TR}\frac{s_e + s_{R_1R_2}}{2s_e + s_{TR}}, \\
x &= s_{TR} - y.
\end{aligned}
\tag{4.6}
$$

s_{R_1} is indicated by the red path and s_{R_2} by the blue path in Figure 4.13. Here the general law, that sound path will be reflected with the same angle as it hits the object, is used. As the receiver 1 is at the same distance s from the object the closest path hits the surface at $\frac{s_{TR}}{2}$. For receiver 2 the position where in e_2 direction the object will reflect for the shortest path is split into x and y, where $s_{TR} = x + y$.

If the distance s is unknown this only gives an approximation for the speed of sound, as it is not possible to get value of s_e precise. Furthermore also the object itself

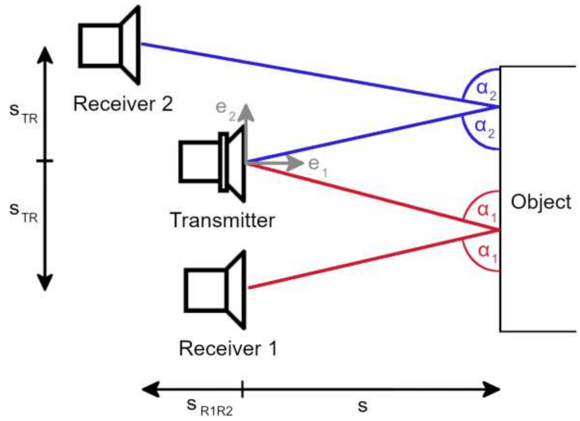


Figure 4.13: Setup with 2 receivers for Speed of Sound Calibration

can influence this precision, because the tilt of the object also has influence on the calculated distance. Dependent on the used measurement method this calibration is more or less precise, but it enables an easy supervision of speed of sound value and only needs one additional ultrasonic receiver.

For the comparison measurements in Chapter 5 a fixed speed of sound is used to be able to compare the different methods independent on speed of sound.

4.3.2 Reflections and Standing Waves

When a measurement using ultrasonic acoustic waves is done, it is assumed that the wave is travelling from transmitter to receiver, fully reflected at the object. So in this approach we assume a path from the transmitter to the object and back to the receiver, exactly like it is done for Time of Flight measurements for example using a pulse as input like in Section 2.3.2. In case of real measurements with a continuous sine signal at $f_{res} = 40\,\text{kHz}$ it can be observed that the amplitude and phase of transmitter signal is changing, dependent on the objects position, despite the input from signal generator keeps the same. This is an important observation as a change of transmitter phase $\varphi_{transmitter}$ is not taken into account in Equation (4.3). This behaviour is not described in state of the art papers like [12] and is further analysed.

One explanation for this effect could be an influence from the reflected ultrasonic wave from the object back to the transmitter. In that case the measured signal at the transmitter would not be only the sine wave from the signal generator, but also in addition the received, reflected signal from the object in addition. To prove this a setup shown in Figure 4.14 is used, where once an object is placed opposite of the transmitter and once there is no object. The transmitter is placed on the moving stage and its position is changed in small steps. In addition a receiver is placed on a fix position 90° tilted and out of sight for the transmitter. The input at the transmitter is a continuously active sine signal at the basic resonance at $f_{res} = 40\,\text{kHz}$. After some seconds of waiting the transmitter and receiver voltage amplitude for the actual, fixed position is measured, then moved to the next distance.

The result is shown in Figure 4.15 and 4.16. Without an object it can be seen that the transmitter voltage is not fluctuating over distance, so the transmitter signal is a

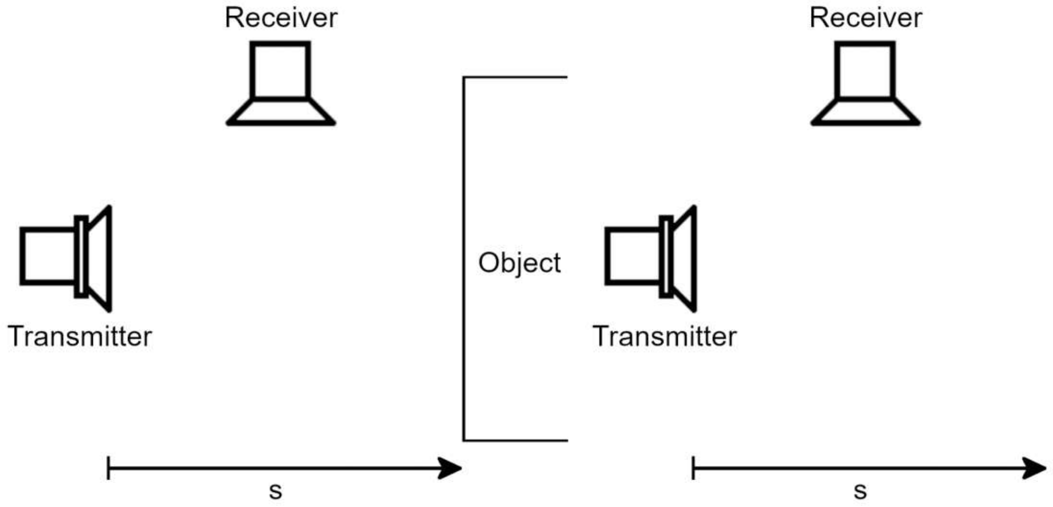


Figure 4.14: Setup to prove Object influence including (a) and excluding (b) an object opposite to the transmitter

steady sine wave, independent on the transmitters position. For the receiver amplitude it can be seen that the signal is relatively low, which is explained by the 90 ° angle between transmitter and receiver. This leads to a damping due to directivity for the signal from transmitter to the receiver and again for the receiver.

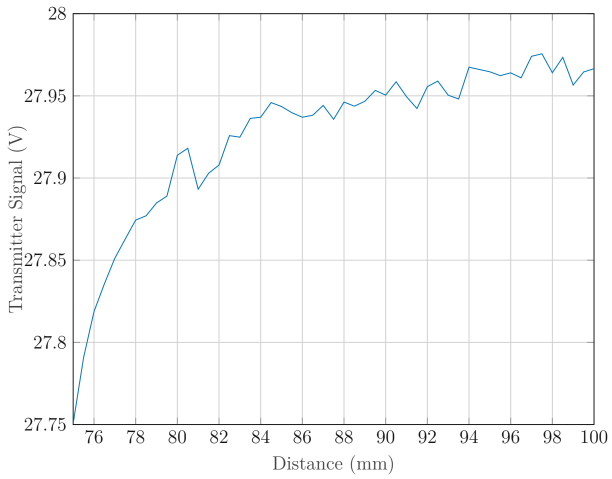
But when the same scenario is repeated, only with an object opposite, the result changes. Figure 4.16 clearly shows that the transmitter amplitude is going up and down dependent on the distance to the object. The same can be seen in the receiver signal. For the transmitter amplitude the fluctuation of the amplitude level is relatively low, at about 0.4 %. For the receiver amplitude the fluctuation compared to the overall amplitude is relatively high, at about 8.5 %.

If the expected explanation that the signal is influenced by the reflected ultrasonic wave from the object is true, the periodic change must be related to the wavelength of the used frequency. We assume dry air at $T = 20\,°\mathrm{C}$, which leads according Equation (3.7) to a Speed of Sound $v_{0_{air}} = 343.34\,\frac{m}{s}$. The sine wave uses a frequency which is adapted to the exact resonance frequency of the receiver, which is at $f_{res_R} = 39.9\,\mathrm{kHz}$. This leads to a wavelength

$$\lambda = \frac{v_{0_{air}}}{f_{res_R}} = \frac{343.34\,\frac{\mathrm{m}}{\mathrm{s}}}{39.9\,\mathrm{kHz}} = 8.6\,\mathrm{mm}. \tag{4.7}$$

A closer look on Figure 4.16 now shows that the distance between two maximums of the amplitude is 4.3 mm, which is exactly half of the wavelength λ. Now we take into account that the ultrasonic wave has to travel from the transmitter to the object and after reflection back to the transmitter. This leads for a distance change Δs of the transmitter to a distance change $2\Delta s$ for the ultrasonic wave. This effect is the same for transmitter and receiver amplitude over distance.

More detailed measurements for this effect can be seen in Section 5.3.



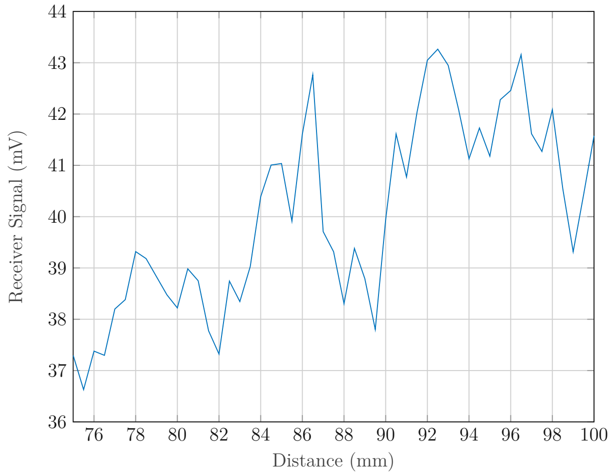


Figure 4.15: Signal amplitude over distance without an object for transmitter (a) and receiver (b)

4.4 Standing Wave Analysis

In the last Section it was described that a continuous sine wave will lead to an unwanted effect where reflections have influence on transmitter and receiver signal. As this influences the measurement result a theoretical model for a more detailed understanding of this effect is done.

An acoustic wave in positive s direction can be described as

$$P_f(s,t) = A \cdot 10^{-\frac{ds}{10}} sin(ks - \omega t) \quad \forall s < vt, \tag{4.8}$$

where P_f is the pressure at the place s, at time t. A is the amplitude of the ultrasonic wave, d is the damping, $k = \frac{2\pi}{\lambda}$ is the angular wave number, $\omega = 2\pi f$ is the angular frequency and v is the speed of sound. When a transmitter is turned on, theoretically without any transient oscillation, Equation (4.8) describes the wave moving away from the transmitter. Without any object this acoustic wave would move

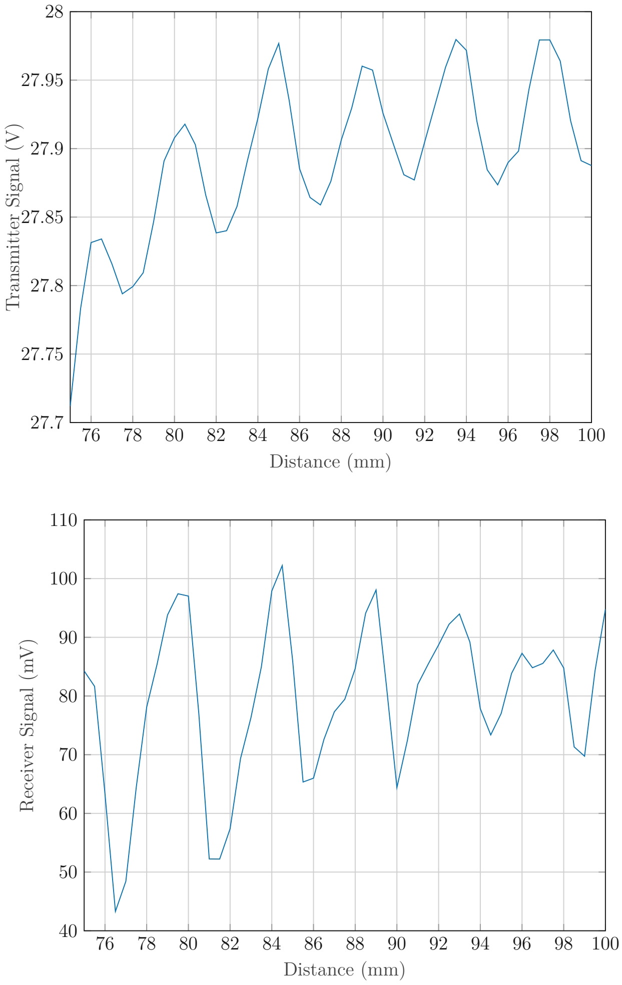


Figure 4.16: Signal amplitude over distance with an object for transmitter (a) and receiver (b)

away from the transmitter towards infinity. As soon as an object appears, the acoustic wave will be reflected and an additional wave with Pressure P_r in the opposite direction

$$P_r(s,t) = A \cdot R_{object} \cdot 10^{-\frac{d(s_{Object}-s)}{10}} sin(k(s_{Object}-s) - \omega(t - \frac{s_{Object}}{v})) \quad \forall s_{Object} - s < v(t - \frac{s}{v}) \tag{4.9}$$

will occur. s_{Object} is here the distance from the transmitter to the object and $0 \leq R_{Object} \leq 1$ is the Reflectivity of the object.

Those two waves will add to a combination

$$\begin{aligned} P_{sum}(s,t) &= P_f(s,t) + P_r(s,t) = \\ &= A \cdot 10^{-\frac{ds}{10}} sin(ks - \omega t) + A \cdot R_{object} \cdot 10^{-\frac{d(s_{Object}-s)}{10}} sin(k(s_{Object} - s) - \omega(t - \frac{s_{Object}}{v})) \end{aligned} \tag{4.10}$$

If we assume very simplified damping $d = 0$ and reflectivity $R = 1$, the reflected wave P_r has the same amplitude like the forward moving wave P_f, which leads to a sum of

$$\begin{aligned} P_{sum_{opt}}(s,t) &= P_f(s,t) + P_r(s,t) = \\ &= Asin(-\omega t + \frac{1}{2}(ks_{Object} + \omega\frac{s_{Object}}{v})) \cdot cos(ks - \frac{1}{2}(ks_{Object} + \omega\frac{s_{Object}}{v})). \end{aligned} \tag{4.11}$$

It can be seen that there is a cosine function only dependent on position s without the time t. So for specific distances s_{Object} there are distances s where forward and reflected wave extinct to 0 for all time, whereas for other distances both waves superimpose exactly and lead to a doubled amplitude $2A$. Cancellation happens at distances s_e

$$\begin{aligned} ks_e - \frac{1}{2}(ks_{Object} + \omega\frac{s_{Object}}{v}) &= \frac{(2n-1)\pi}{2} \quad n \in \mathbb{N} \\ s_e &= \frac{2n-1}{2}\frac{\lambda}{2} + s_{Object} \end{aligned} \tag{4.12}$$

and superposition happens at distances s_s

$$\begin{aligned} ks_s - \frac{1}{2}(ks_{Object} + \omega\frac{s_{Object}}{v}) &= n\pi \quad n \in \mathbb{N} \\ s_s &= n\frac{\lambda}{2} + s_{Object}. \end{aligned} \tag{4.13}$$

So in both cases, cancellation or superposition, the distance between two such events is always $\frac{\lambda}{2}$. The distance between a cancellation distance s_e and a superposition distance s_s is $\frac{\lambda}{4}$. This can be simply explained because the wave has to move to the object and again back, so a distance change of $\frac{\lambda}{2}$ is a distance of λ from the perspective of the wave itself. Figure 4.17 display the wave $P_{sum_{opt}}(s,t)$ after settling for time and distance. It can be seen that there are distances $s = s_e$ where independent on time t the pressure is always 0, and distances $s = s_s$ where a sine wave with doubled amplitude $2A$ is present. Important is here the information that values s_e and s_s are dependent on the object distance s_{Object}. As our sensors are placed most likely at distance $s = 0\,\mathrm{mm}$, we are only able to measure this time signal.

This description without damping is to understand the basic effect, but in real measurement the model is even more complex. First there is damping which will decrease the pressure amplitude over distance for both waves P_f and P_r. This damping is because of absorption of air [27] and also because the sound power from transmitter will be spread over the surface of the acoustic wavefront, which gets bigger with distance s. Furthermore the size and shape of the object is important, as the reflected energy decreases for same object size with increasing distance s. This is because the power density of the acoustic wave is decreasing over distance, so for a constant object size a bigger distance leads to a smaller effective reflected wave P_r. In our calculations we assumed one object distance s_{Object}, which is only a good approximation if the

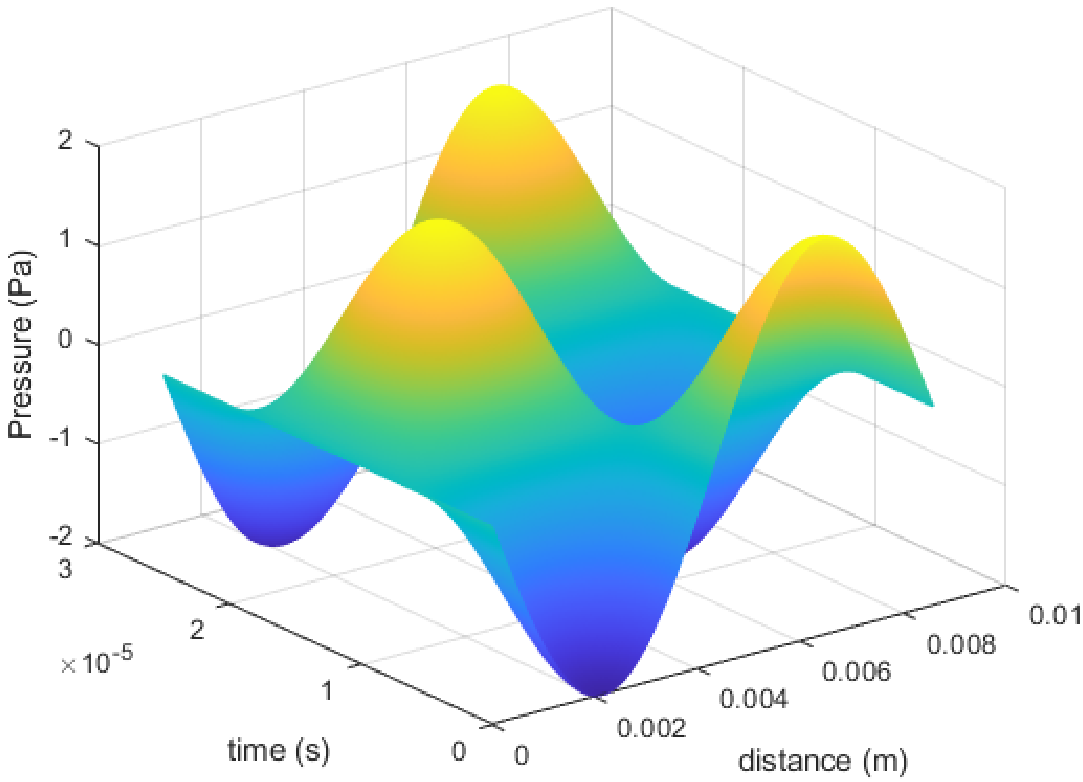


Figure 4.17: Standing Wave over time and distance

distance between transmitter and different points of the objects surface are relatively close. In Figure 4.18 it can be seen that the direct path (red line) has exact distance s, but the path to the edge of the object (blue line) is longer. The path difference is $\Delta s_{edge} = \frac{w}{2sin(\theta(s))} - s$, where w is the width of the object and θ is the angle between the direct path and the path to the edge. In purple there is the Wavefront which reaches the middle point of the object shown. For bigger distances the angle θ will get smaller for the same object width w and therefore the distance difference Δs_{edge} will get smaller. Simplified it can be said that the wavefront is assumed to be parallel to the object for bigger distances.

As soon as this influences are taken into account, there will be no complete cancellation or superposition to a factor of 2 any more. But also a damped reflected wave will overlap with the forward moving wave and lead to changes of amplitude and also phase of the sum wave. As object size and shape can't be known in general it is not possible to determine this effect in general. It demonstrates that for closer distances the measured fluctuation of amplitude and phase can be explained by this effect.

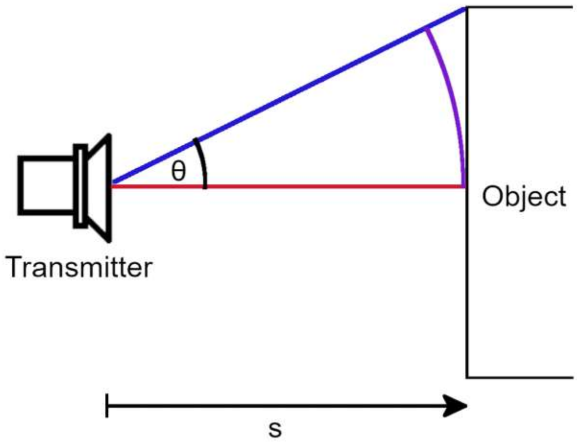


Figure 4.18: Influence of object size related to distance

4.5 Proposed Dual Frequency Method

In Section 4.2.2 it is described that the sensor has two resonance frequencies which can be used with valuable signal. This can be used as advantage by not only using the phase shift of one sine wave, but instead two resonance frequencies are used at the same time. For the here measured sensor pair this can be $f_{res_1} = 40\,\text{kHz}$ and $f_{res_2} = 53.3\,\text{kHz}$. This combines several advantages for the distance measurement. When two measurements are made at the same time the precision can be improved. The described standing wave in Section 4.4 will occur at different distances s for the two different resonance frequencies in most cases. So this hardly predictable effect can be reduced when a combination of the two results is used.

4.5.1 Dual Frequency Signal

To be able to use both resonances, the input signal must be a combined sine wave. So the input is a simple addition of two sine waves

$$U_{Input} = A_1 sin(2\pi f_1 t) + A_2 sin(2\pi f_2 t + \varphi_2), \tag{4.14}$$

where two degrees of freedom A_2 and φ_2 can be defined. The frequency values f_1 and f_2 are defined by the used sensor pair and will be at resonances f_{res_1} and f_{res_2} of receiver to have the best possible SNR. The amplitude A_1 is limited due to sensor properties at maximum $120\,V_{pp}$. For the first approaches the amplitude A_2 where also set close to this maximum like for amplitude A_1. But practice has shown that this input is too much for the sensors and leads to damage at the transmitter. In data sheet of this sensors only the maximum for the first resonance frequency at f = 40 kHz is defined. As the resonance at the second frequency at f = 53.3 kHz is having a bit higher damping for most sensor combinations, it is better to increase the amplitude A_2 related to the amplitude A_1. For that reason the amplitude A_2 is defined to be 20 % bigger then A_1 and A_1 is limited to $A_1 = 100\,V_{pp}$.

The phase shift φ_2 is not important because the frequencies f_1 and f_2 are not related, which means that a phase φ_2 will not influence the signal shape, only the time when it will look like that. For simplification it is simply set to $\varphi_2 = 0\,°$.

So the final input signal is

$$U_{Input} = 50sin(2\pi 40\,\mathrm{kHz}t) + 60sin(2\pi 53.3\,\mathrm{kHz}t) \tag{4.15}$$

and can be seen in Figure 4.19.

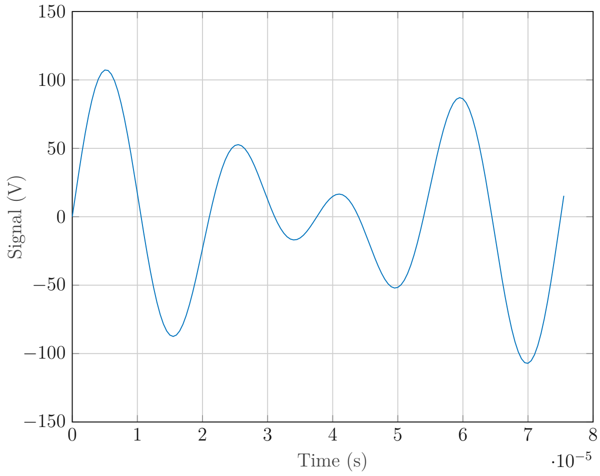


Figure 4.19: Input signal

4.5.2 Filtering and Phase

After the measurement the signals, input and output, are filtered using two bandpass filters to get the individual results for f_{res1} and f_{res2}. For the bandpass a Butterworth filter with a bandwidth of $f_{BW} = 6\,\mathrm{kHz}$ and an order of 2 is used. The centre frequency is set equal to the used resonance frequency, so 40 kHz or 53.3 kHz. For the signals always one batch measured by oscilloscope is used which is at standard $t_{Osci} = 2\,\mathrm{ms}$ and for precision measurements extended up to $t_{Osci} = 10\,\mathrm{ms}$.

To identify the phase between input and receiver signal the filtered signals are analysed. The location of zero crossings including the gradient are stored. The gradient is important to be able to distinguish the zero crossings between 180 ° and 360 °.

The time delay between zero crossings from input signal related to receiver signal is now compared and averaged over the length of the whole signal. This time difference leads to the interested phase

$$\varphi = 360° \frac{\Delta t_0}{T_{f_{res}}} \tag{4.16}$$

where Δt_0 is the average time between two zero crossings and $T_{f_{res}}$ is the time period of the resonance. This calculation is done for the signal filtered at 40 kHz and also 53.3 kHz.

Using Equation (4.4b) the distance difference from one measurement to another can be calculated by using

$$\Delta k = \frac{\Delta \varphi}{360°}, \tag{4.17}$$

where $\Delta\varphi$ is the change of phase from one measurement to another.

The way how the signal is filtered is important, because it is a trade of between measurement rate and precision. A longer measurement signal enables the possibility of lower bandwidth and also of higher averaging for phase calculation. A short time signal enables the possibility to repeat measurements more often and therefore increases the measurement rate. This is a basic advantage when using this method, because this degree of freedom can be defined due to measurement needs. If the object is expected to move slowly, the precision of movement can be high due to long signal averaging. If the object is expected to move fast, it is possible to stable follow it when reducing signal averaging and therefore avoid phase changes $\Delta\varphi$ too close to 360 °.

4.5.3 Weighting

As the same input and receiver signal now leads to two distance values, once for the result of the filtered 40 kHz signals and once for the filtered 53.3 kHz signals, it must be defined which result is used. To do so a weighting function

$$\Delta s = \frac{w}{100}\Delta s_{res_1} + \frac{100 - w}{100}\Delta s_{res_2} \tag{4.18}$$

is introduced. w represents here a weighting factor between 0 % and 100 %, Δs_{res_1} represents the distance calculated from the first resonance frequency signal and Δs_{res_2} the calculated distance from the second resonance frequency signal. If the factor w is set to 0 %, it is practically the same as the standard continuous sine method where only one frequency is used.

The big advantage of this weighting is, that influences on distance result that are dependent on the absolute distance, object shape and size can be reduced. In Section 4.4 we see such effects that are highly dependent on the wavelength of the used signal. By using a weighting factor of w = 50 %, this influence will of course still be present, but the influence of each individual distance error is reduced. As the wavelength of 40 kHz and 53.3 kHz are not related, the distances where both frequencies will have worst case scenarios of cancellation or superposition are much lower then the periodic repetition at $\frac{\lambda}{2}$ for each individual frequency.

CHAPTER 5

Measurement Results

To have a fair comparison between already known methods and the approach using the Dual Frequency method described in the Chapter before, there will be results in the following for the different methods by using the same equipment, test setup and environment. This enables an analysis for the different methods including quantitative values like repeatability, measurement time and dynamic range. The measurements are done without an object opposite, so the receivers are directly placed opposite to the transmitter like explained in Section 3.1 and Figure 3.4. Doing so the comparison can be made independent on object properties, which size, shape, surface and reflectivity parameters would influence measurements and would add several parameters.

5.1 Time of Flight Methods

As described in Section 2.3.2 one of the most common methods is using a Time of Flight measurement. Therefore several variants of this measurement principle are implemented in this thesis, which includes the threshold measurement and correlation measurement.

5.1.1 Threshold Measurement

This method is very simple to handle and implement. The theory about it is described in Section 2.3.2. As input signal a pulse with a time length of $t_{Pulse} = 100\,\mu s$ and Amplitude $U_{Input} = 50\,\mathrm{V}$ is used, like in Figure 5.1.

The receiver response, where receiver is placed opposite to the transmitter, can be seen in Figure 5.2. The threshold level is set slightly over the noise level of the receiver signal, for this measurement to a fixed value of $U_{threshold} = 5\,\mathrm{mV}$. The threshold level is shown as red dashed line in Figure 5.2.

Using Equation (2.2) the distance can be calculated, where t_{flight} is the measured time between the start of the pulse signal and the time when the receiver signal first exceeds the threshold level.

Now the moving stage moves the transmitter away from the receiver in defined steps, and between each step the measurement is repeated. The measured distance over the real distance is shown in Figure 5.3. It can be seen that there is a linear increase of the measured distance compared to the real one, but the fluctuation of the measurement result can be clearly seen as the constant step of the moving stage is not leading to a constant change of the measured distance. Sometimes this steps are measured too big and sometimes too small. One explanation is the constant threshold which will react on different parts of the receiver signal dependent on distance and related damping.

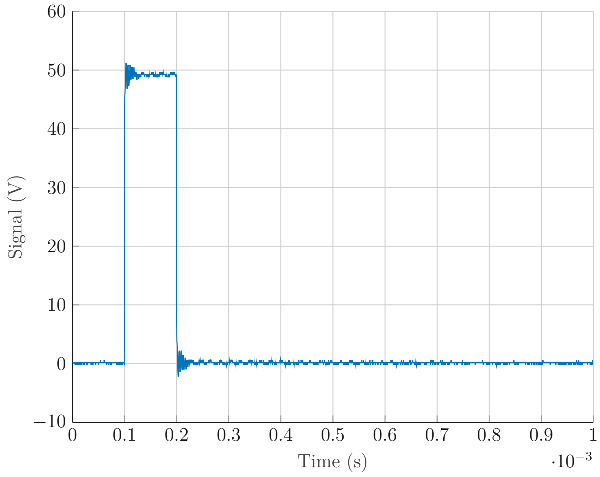


Figure 5.1: Input signal for a threshold Time of Flight measurement

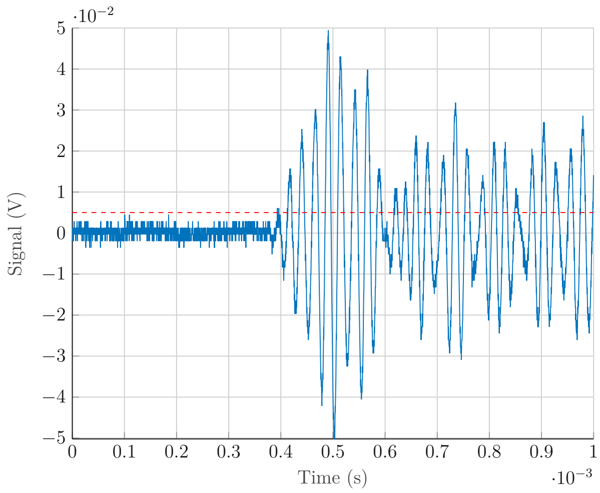


Figure 5.2: Receiver signal for a threshold Time of Flight measurement

To evaluate the repeatability of this measurement method the whole system is kept in the same position and measurements are repeated several times. The change of measured distance can be seen in Figure 5.4, where as always a linear relation between the really measured Time of Flight and the shown measured distance is assumed. This linear relation is the constant speed of sound. The standard deviation

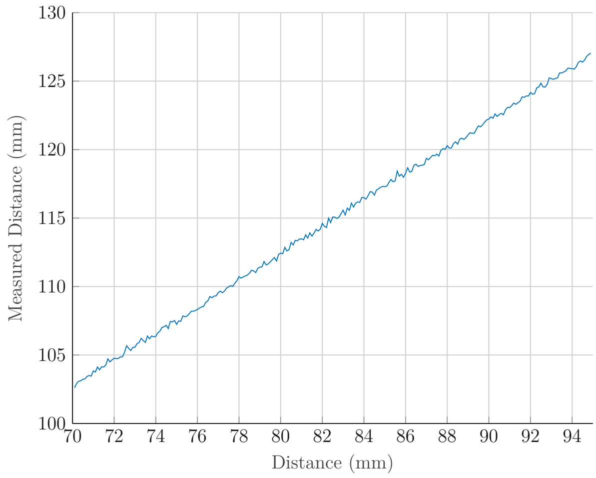


Figure 5.3: Distance values for a threshold Time of Flight measurement

is for this measurement $\sigma_{Pulse} = 132.6\,\mu m$. This repetition was made at a distance of $s_{Object} = 12.6\,\text{mm}$.

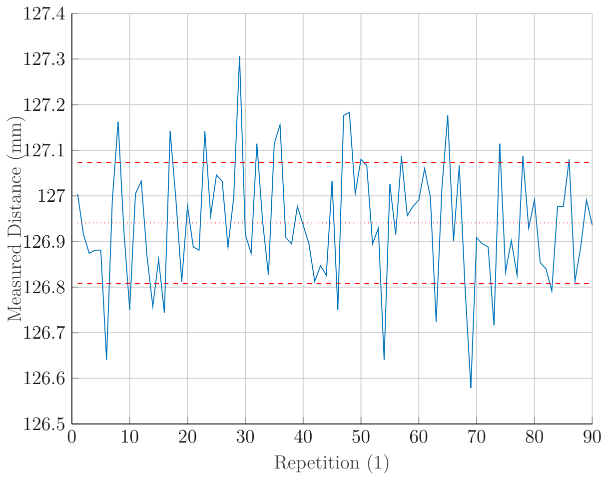


Figure 5.4: Fluctuation of distance for repeated measurement at same conditions

5.1.2 Correlation Measurement

The same setup is now used, but instead of a simple pulse signal, a better suitable signal for the used sensors is applied. Furthermore instead of simple threshold more information from the receiver signal will be taken into account to get a more precise Time of Flight t_{flight}. The theory is described in Section 2.3.3.

To get a valuable correlation result an important factor is the input signal. Theoretically also a simple pulse could be used, but as explained in Section 4.2.2 major part of such an input will be already highly damped at the transmitter. For that reason an input signal which is closer to the resonance frequency is preferred, to get a valuable receiver signal for each part of the input signal.

So for the further measurements as input signal a Chirp will be used which linearly changes the frequency from $f_{low} = 35\,\text{kHz}$ to $f_{high} = 45\,\text{kHz}$ within $t_{Chirp} = 1\,\text{ms}$ and an amplitude of $U_{Chirp} = 50\,\text{V}$. This signal measured on the transmitter can be seen in Figure 5.5. It should be mentioned that a change of amplitude can be seen which is dependent on resonance frequency of transmitter, but also to actual distance to the receiver and its resonance frequency, as the reflected signal will interact with the transmitter signal. This can also be seen as after the end of the chirp input on the transmitter, still a voltage at the transmitter can be seen, which is nothing else then measuring the ultrasonic wave arriving at the transmitter combined with swing out of transmitter. Also other chirp signals with different bandwidth, time length and also with non linear frequency change were tested, but this one showed the best results.

The receiver signal is shown in Figure 5.6. Also here a change in amplitude over time can be seen which is again related to involved resonance frequencies of both sensors and the distance between those. The length of $t_{Chirp} = 1\,\text{ms}$ from the chirp signal applied to the transmitter is here much longer up to about $t_{receiver} = 3\,\text{ms}$ because the resonances are not highly damped.

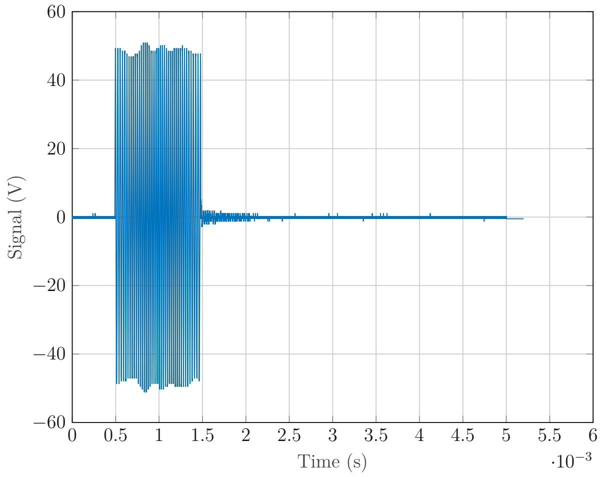


Figure 5.5: Input signal for a threshold correlation measurement

For a movement of transmitter away from the receiver the results of the distance measurement is shown in Figure 5.8. It can be seen that there is a linear relation between the real distance and the measured distance. Compared to the simpler threshold measurement in this case the fluctuations between single steps is much smaller. The Time of Flight is measured by evaluating the correlation result for each comparison according Equation (2.3). A correlation result for one distance measurement can be seen in Figure 5.7. The time shift of the maximum, marked with a red cross, of this correlation result is now used for the Time of Flight value. This correlation result is not having one sharp peak because the bandwidth is limited and when the signals of transmitter and receiver are shifted closer together, they already correlate. When transmitter input is turned off for sure only the much smaller signal is present there, which explains why the correlation coefficient drops faster as it increases. For a perfect peak a pseudo noise signal would be the best input, but due to the high damping of most frequencies for piezo sensors this is not possible.

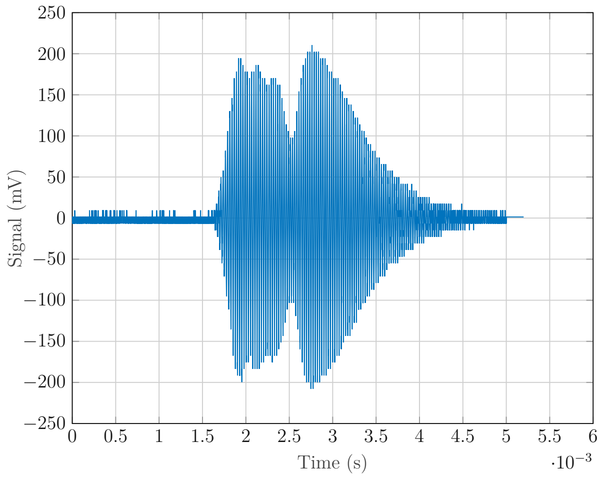


Figure 5.6: Receiver signal for a correlation measurement

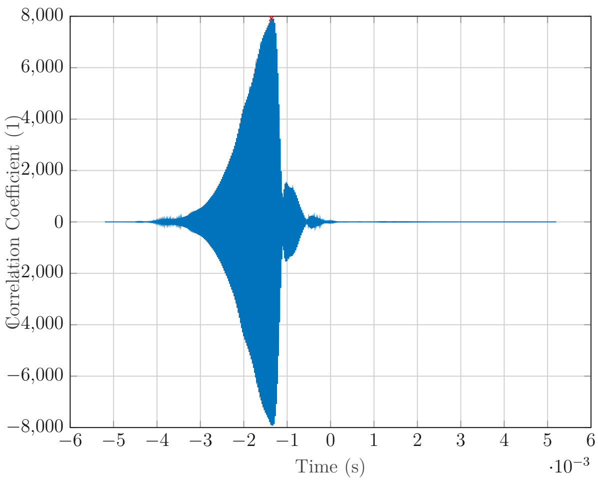


Figure 5.7: Result of correlation between input and receiver signal

To evaluate the repeatability of this measurement method the whole system is kept in the same position and measurements are repeated several times. The change of measured distance can be seen in Figure 5.9. Again this is a calculated value by using the measured Time of Flight and using a linear relation to the distance with the factor speed of sound. The standard deviation is for this measurement $\sigma_{Corr} = 65.4\,\mu m$. This repetition was made at a distance of $s_{Object} = 45\,\mathrm{mm}$.

5.2 Continuous Sine Method

For the following measurements instead of sending repeated signals for each measurement, a continuous signal is used. The background for this measurement method is described in Section 4.1 and an explanation of influence from reflections is described in Section 4.3.2.

Results from continuous sine measurement are identical to measurements using the Dual Frequency method with a weighting of $\mathrm{w} = 0\,\%$. The results of this measurements

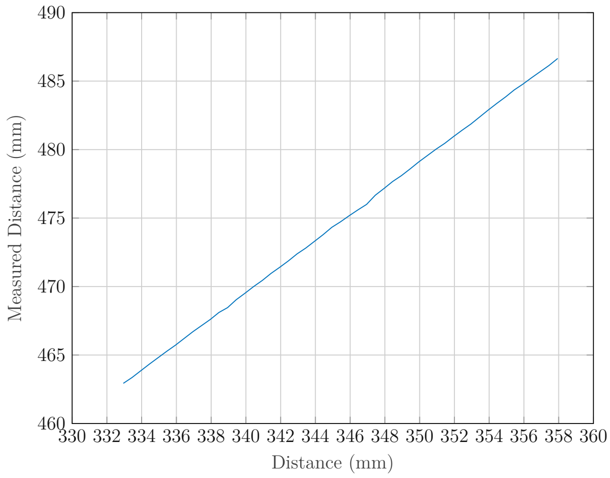


Figure 5.8: Distance values for a correlation measurement

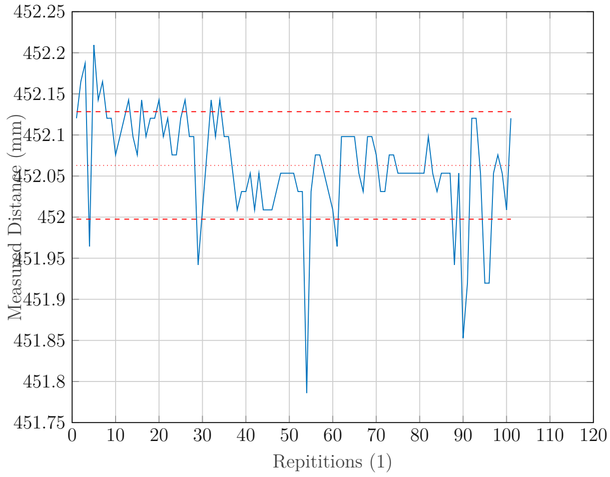


Figure 5.9: Fluctuation of distance for repeated correlation measurement at same conditions

where only basic frequency f_{res_1} is taken into account can be seen in the following Section.

5.3 Dual Frequency Method

A signal combining the first and second resonance frequency of $f_{res_1} = 40\,\text{kHz}$ and $f_{res_2} = 53.3\,\text{kHz}$ is used for the following measurements. The theory for that measurement principle is described in Section 4.5.

As this is a new principle for ultrasonic distance measurements which is not described so far in state of the art literature, more detailed measurements are done.

The input and receiver signal is shown in Figure 5.10 and 5.11. The shape of the receiver signal is here dependent on the actual distance and also on how big the influence of reflection is. If there is big part of the 53.3 kHz signal extincted, but a superposition for the 40 kHz signal for the actual distance the receiver signal will mainly look like a sine wave with 40 kHz. The same can happen the other way round or of course everything in between.

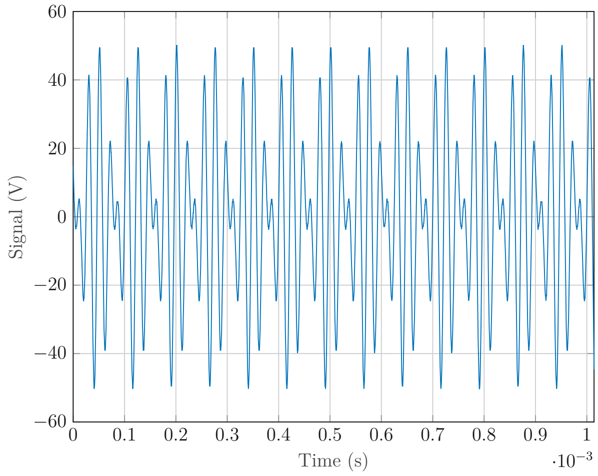


Figure 5.10: Input signal for a Dual Frequency measurement

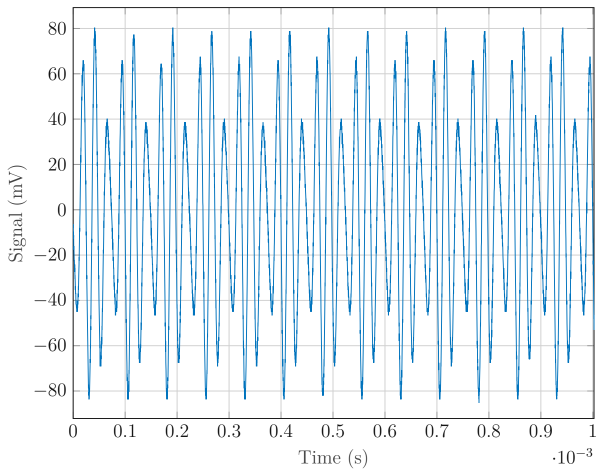


Figure 5.11: Receiver signal for a Dual Frequency measurement

After an initial distance measurement which defines the absolute start value the further movement of the object is traced using the Dual Frequency method. A result for such a movement under same conditions like in the Sections before is shown in Figure 5.12. The ideal line shows what a perfect measurement result would look like. Ideal line with corrected offset has the correct distance difference, but with an offset corrected to the first initial measurement. It can be seen that also for a movement over 25 mm the moved distance can be followed. A linear movement also leads to a linear increase of the measured distance and fluctuation between constant steps is shown here relatively low.

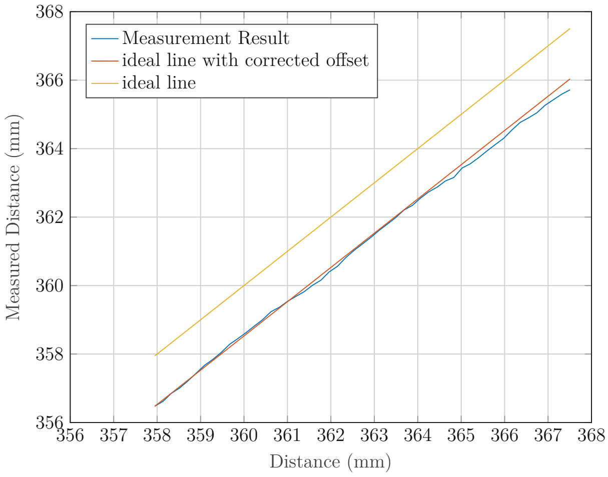


Figure 5.12: Measured Distance result for a Dual Frequency measurement

As we know that depending on distance the two frequencies used will have different relevance we can observe different linearity in the measured distance dependent on the weighting. Looking at Figure 5.13 shows that for weighting factors of $w = 0\,\%$ or $w = 100\,\%$ the linearity is often not good. So for some distances the measured step is too small and for some it is too big. To overcome this effect a weighting between those two weighting factors is used. For example at $w = 50\,\%$ it can be seen that the orange curve in Figure 5.13 is showing a better linearity over the whole distance.

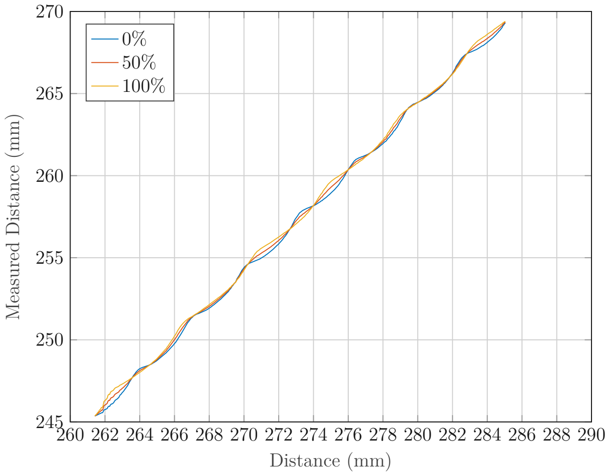


Figure 5.13: Comparison of Distance result for a Dual Frequency measurement with weighting of 0%, 50% and 100%

Especially in case of the continuous signal it is very important that each measurement is repeatable, as a failure in repetitions would sum up over several measurements to bigger errors. To evaluate this stability the same distance profile is repeated with the moving stage and the results are compared. This can be seen in Figure 5.14. For 7 repeated measurements under same conditions the repeatability is very good. So when an object is moving constantly forward and backward and tracked by Dual Frequency measurement, still the absolute position will be known quite precise.

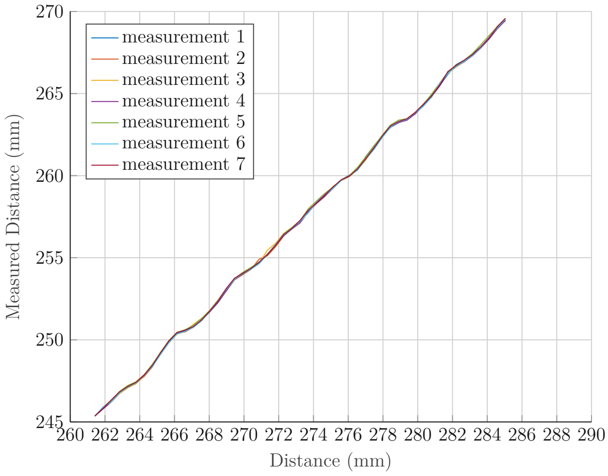


Figure 5.14: Comparison of Distance result for a Dual Frequency measurement by repeating the same distance movement

Of course also the possible range for this distance measurement is of interest. So the measurement is repeated, but receiver is placed 25 mm further away manually after each measurement cycle. The measured result can be seen in Figure 5.15 for a weighting $w = 50\,\%$. For distances of up to s = 50 cm the measurement is stable under this measurement conditions, independent on the weighting factor. For higher distances method starts to get increasing phase errors which lead to wrong distance measurements like it can be seen on the right side in Figure 5.15. It can be seen that there are wrong measured distance steps which gives errors in linearity. Such faulty measurements are very bad because the absolute distance will the be lost and a new initial measurement is necessary. If for one of the two frequencies used the limit is reached where phase can be detected reliable, the limit for the whole measurement principle is reached. This is because for every weighting factor different from 0 % or 100 % a failure of one measurement will influence the whole result.

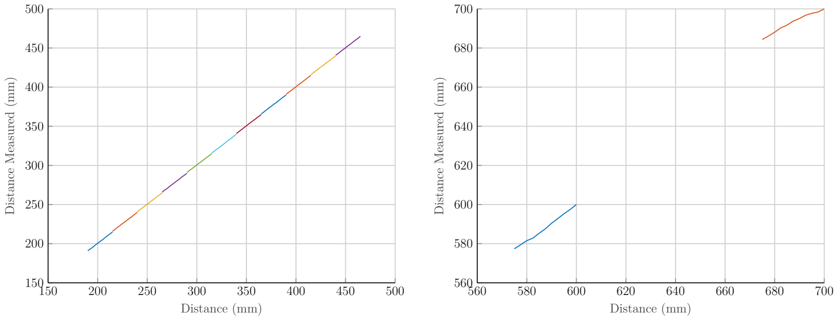


Figure 5.15: Measurement to evaluate the possible measurement range with a weighting factor of w = 50 %

For standard deviation also measurements over several distances are compared. This is shown in Figure 5.16 for weighting factors of 0 %, 50 % and 100 %. It can be clearly seen that precision is getting worse with bigger distance in general. Furthermore for most cases the precision of higher weighting is better, which can be explained because this is taking the higher frequency into account, which means a lower wavelength and therefore better precision if SNR is good enough. In that case single measurements that had bigger errors where removed. If those faulty measurements are not excluded, the result can be seen in Figure 5.17. This again shows what also was seen for bigger distances before, when the distance is getting to big the whole result can be influenced dramatically.

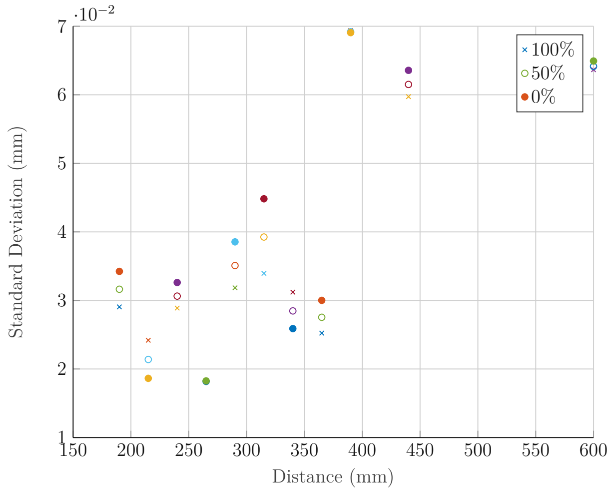


Figure 5.16: Measurement to evaluate the precision with weighting factors of w = 0, 50 and 100 %

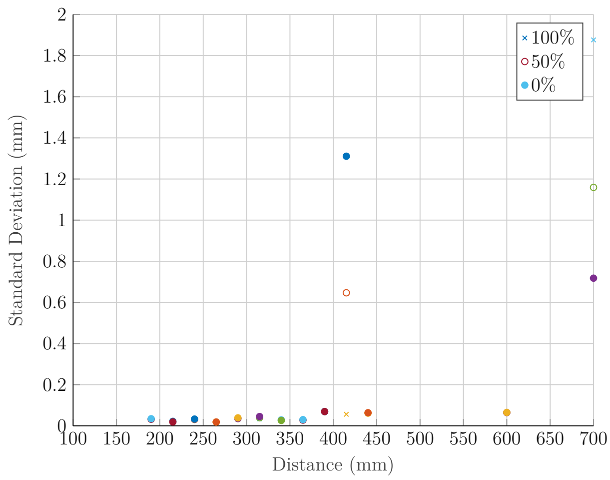


Figure 5.17: Measurement to evaluate the precision with weighting factors of w = 0, 50 and 100 %, including faulty meausurements

5.4 Comparison

Now it is of interest how this Dual Frequency measurement succeeds compared to the other existing methods. Following the results from Sections before are compared, where all results are made with the same measurement equipment under similar conditions.

An absolute distance measurement is not possible using this Dual Frequency method, so the main interest is on the measurement precision. For example following an object within a given distance would be a typical use case where mainly precision is important.

For a simple threshold measurement the standard deviation is at $\sigma_{Pulse} = 132.6\,\mu m$. For correlation measurement this one is already better and reaches a standard deviation at about $\sigma_{Corr} = 65.4\,\mu m$. Using a weighting factor of w = 100 % the best standard deviation reached using Dual Frequency mode is $\sigma_{Dual_{100}} = 15.2\,\mu m$. Using a weighting factor of w = 50 %, which is necessary in case of bigger influence from object to avoid bigger influence due to reflections, the standard deviation still is at $\sigma_{Dual_{50}} = 24.2\,\mu m$.

Table 5.1 shows an overview of the precision results for the three measurement methods under same conditions at a distance of s = 355 mm. If correlation method is defined as reference, this means that standard deviation of Pulse method is worse by a factor of about 2 and Dual Frequency method is better by a factor of 4.

Table 5.1: Comparison of Measurement Method Results

Measurement method	Mean Value	Standard Deviation	Relative Failure
Correlation	449 mm	$\sigma_{Corr} = 65.4\,\mu m$	$1.45e-4$
Pulse	390 mm	$\sigma_{Pulse} = 132.6\,\mu m$	$3.4e-4$
Dual Frequency	-	$\sigma_{Dual_{100}} = 15.2\,\mu m$	$4.28e-5$
Dual Frequency	-	$\sigma_{Dual_{50}} = 24.2\,\mu m$	$6.8e-5$

For sure also the measurement rate is an important factor. When looking at the measurements of Correlation or also Threshold measurement, we get one distance measurement within about $t_{repeat} = 5$ ms. This is to wait until reflections are gone and receiver signal has decreased again to be ready for a new measurement run. In case of Dual Frequency measurement mode it is possible to evaluate with every new time frame a new distance result, which can be also $t_{repeat} = 2$ ms. For sure it must be taken into account here that a change in distance still needs time until the receiver signal will react on this distance change as it must travel the distance between object and receiver with the speed of sound. But this is only a constant time delay, a velocity of an moving object can be followed better using Dual Frequency measurement then Time of Flight measurements.

CHAPTER 6

Conclusions

Measuring distance is an important issue and widely used in a lot of applications. The different methods available are always a trade off between precision, range, price, robustness and measurement time. In this thesis the measurement of distance using low cost ultrasonic sensors is set up with a new approach by using continuous signal consisting of two resonance frequencies. A pair of low cost ultrasonic sensors is analysed and evaluation shows that the first two resonances of this sensors can be used simultaneously. This additional information is used to reduce unwanted influence from object properties the distance is measured to and increase precision at the same time. Compared to state of the art precise Time of Flight measurement principles the proposed dual frequency method increases the precision by a factor of 4. Even when due to robustness of the result the weighting is reduced, still the precision is better by a factor of more then 2. Real measurements confirm that precision can be increased compared to using only one resonance frequency, by keeping the same robustness against environment like other ultrasonic distance measurements have. The setup can be realised by using the same equipment as it is also used for example for correlation measurements. There are degrees of freedom that can be set in this measurement method, like the weighting between the two simultaneous calculated results and also the averaging time for phase calculation. This two degrees of freedom can be easily changed during or also later after measurements are done and gives additional opportunities for a best possible result in individual situations.

6.1 Future Work and Outlook

6.1.1 Absolute Distance Measurement

The absolute measurement of distance in this thesis is made initially by already known principles of Time of Flight methods. An additional concept that changes the signal, like frequency and amplitude modulation, would be possible to be able to measure the absolute and the relative distance without interrupting the continuous signal. This could further increase the measurement rate and reduces the limitation of measurement rate related to object movement.

6.1.2 Lateral Resolution

Available Time of Flight methods most likely measure the closest distance of an object, as they react on first signal receiving. The measurement principle in this thesis is also influenced by the object properties like shape and size. Increasing the lateral resolution, by using focusing of acoustic beam or using higher frequency ultrasonic sensors, would enable fields of application like scanning objects surfaces. When a defined distance is used the influence of such a focused acoustic beam can be predicted precisely as described in this thesis. This enables the possibility to measure also on surfaces that are maybe relatively low reflective for optical principles.

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Eigenständigkeitserklärung

Hiermit erkläre ich, dass die vorliegende Arbeit gemäß dem Code of Conduct, insbesondere ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel, angefertigt wurde. Die aus anderen Quellen direkt oder indirekt übernommenen Daten und Konzepte sind unter Angabe der Quelle gekennzeichnet.

Die Arbeit wurde bisher weder im In- noch im Ausland in gleicher oder ähnlicher Form in anderen Prüfungsverfahren vorgelegt.

Wien, Mai 2024: ....
Philipp Ryback, BSc