DISSERTATION

Variable Rotor Speed Drivetrain Investigation

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from

Dipl.-Ing. **Hanns Amri**
Matr.Nr.: 00425340
Untere Hauptstraße 1, 2424 Zurndorf, Austria

under the supervision of

Univ.-Prof. Dipl.-Ing. Dr.-Ing. **Michael Weigand**
Institute of Engineering Design and Logistics Engineering
Vienna University of Technology
Karlsplatz 13, 1040 Vienna, Austria

reviewed by

Prof. PhD, Dipl.-Ing., MAI **Vladimir Zhuravlev**
Department of Pre-Design and Effectiveness of Complex Aviation Systems
Aviation Engineering Faculty
Moscow Aviation Institute
125080 Moscow, Russia

Univ.-Prof. Dr.-Ing. **Franz Heitmeir**
Institute of Thermal Turbomachinery and Machine Dynamics
Graz University of Technology
Rechbauerstraße 12, 8010 Graz, Austria

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I confirm, that going to press of this thesis needs the confirmation of the examination committee.

Affidavit

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume. If text passages from sources are used literally, they are marked as such. I confirm that this work is original and has not been submitted elsewhere for any examination, nor is it currently under consideration for a thesis elsewhere.

Vienna, August 2018

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Hanns Amri

"Disce Quasi Semper Victurus, Vive Quasi Cras Moriturus"

"Learn as if You would Live Forever, Live as if You would Die Tomorrow."

- Edmund of Abingdon -

Abstract

The research presented in this thesis focuses on the development of a transmission ratio variable transmission system for rotorcraft to enable a variable rotor speed. Different drivetrain technologies were investigated according to their potential for rotor speed variation. The benefits of rotor speed variation in the context of missions and under consideration of different drivetrain technologies was calculated for different rotorcraft configurations.

Transmission systems were rated according to the requirements of rotorcraft on the drivetrain to find the most suitable transmission technology. A functional failure mode and effects analysis was performed for the most suitable transmission system. Furthermore, a kinematic and a mass analysis of the most suitable transmission system was carried out and the influence of the shifting process on the whole drivetrain was simulated.

The investigation should show if rotorcraft rotor speed variation as performed by transmission ratio variable transmission systems can improve rotorcraft efficiency and flight envelope. Furthermore, a possible design for a transmission-variable gearbox should be defined.

Four rotor speed variation technologies, rotor, electric, turbine and gearbox technology, were investigated according to their usability. Only turbine and gearbox technology are applicable in the near future, the turbine technology for small, about 10%, and the gearbox technology for large variation range.

The mission analysis showed that high speed rotorcraft configurations such as tilt rotor need a large rotor speed variation range of about 50% but only two rotor speeds, one for hover and one for fast forward flight. Utility rotorcraft configurations gain most benefits from continuous rotor speed variation. The variation range within one mission is about 20% and about 36% if more missions are taken into account.

Compound split transmission systems are most suitable for rotor speed variation according to the requirements analysis. The failure mode and effects analysis showed that there are additional risks with this new technology but they can be negated with additional compensation actions like free wheel clutches. The mass and kinematic analysis showed that compound split configurations can be distinguished by their stationary transmission ratio of the planetary gears and that they have a different mass depending on the basic transmission ratio and the transmission ratio variation.

The simulation of the shifting process showed that in principle a two-speed and a continuous-variable transmission ratio variation is possible with a compound split. The continuous-variable transmission ratio variation enables a smooth transition and less load peaks on the drivetrain. Therefore, this is the preferable variant.

The research in this thesis is the basis for the development of a new variable transmission ratio drivetrain system for rotorcraft. It enables different rotorcraft configurations to increase their flight envelope and efficiency. This could be one corner stone for a more ecologically efficient rotorcraft aviation.

Zusammenfassung

In dieser Dissertation wird die Entwicklung eines übersetzungsvariablen Getriebes zur Variation der Rotordrehzahl eines Drehflüglers beschrieben. Verschiedene Antriebsstrang- Technologien zur Variation der Rotordrehzahl wurden auf ihre Einsatzmöglichkeit untersucht. Das Potential der Drehzahlvariation wurde in verschiedenen Missionen unter Berücksichtigung möglicher Antriebsstrang-Technologien für verschiedene Drehflügler aufgezeigt.

Diverse Getriebetechnologien wurden auf ihre Erfüllung der Anforderungen der Drehflügler an den Antriebsstrang untersucht. Für die bestgeeignete Technologie wurde eine funktionelle Fehler Analyse (FMEA) und eine Analyse der Masse und Kinematik durchgeführt und Schaltverhalten und dessen Einfluss auf den gesamten Antriebsstrang simuliert.

Ziel der Dissertation war es mögliche Effizienzsteigerung und Flugbereichserweiterung durch Drehzahlvariation des Rotors mittels übersetzungsvariablem Getriebe aufzuzeigen und ein Getriebekonzept zu erstellen.

Die vier Antriebsstrang- Technologien, Rotortechnologie, Turbinentechnologie, elektrischer Antrieb und Getriebetechnologie, wurden auf ihre Anwendbarkeit untersucht. Nur die Turbinentechnologie, für kleinere Drehzhalvariationen bis ca 10%, und Getriebetechnologie, für beliebig große Drehzahländerungen besitzen in nächster Zukunft ein Potential.

Die Missionsrechnungen haben gezeigt, dass Hochgeschwindigkeits- Hubschrauber, wie Kipprotorflugzeuge, eine Drehzahlvariation von 50% benötigen, aber dabei nur zwei ausgeprägte Rotordrehzahlen, eine zum Schweben, 100%, und eine zum schnellen Vorwärtsflug, 50%. Mehrzweckhubschrauber profitieren am meisten von kontinuierlicher Drehzahlvariation, bei einer Drehzahl- variation von 20% in einer Mission und bis zu 36% über mehrere Missionen.

Die Anforderungsanalyse der Getriebetechnologien hat ergeben, dass kombiniert- leistungsverzweigte Getriebe diese am besten erfüllen können. Durch diese Getriebe entstehen zusätzliche Risiken, welche durch entsprechende Maßnahmen, wie Freiläufe, kompensiert werden können. Verschiedene Ausführungen der kombiniert- leistungsverzweigten Getriebe können anhand der Standübersetzung ihrer Planetengetriebe unterschieden werden. Die Ausführungen haben unterschiedliche Massen abhängig von der Grundübersetzung und der Spreizung des Getriebes.

Sowohl Zwei-Gang-Getriebe als auch kontinuierlich übersetzungsvariable Getriebe können mit kombiniert-leistungsverzweigten Getrieben im Drehflügler realisiert werden. Kontinuierliche Übersetzungsvariation ermöglicht einen sanften Übergang zwischen den gefor- derten Drehzahlen mit geringeren Belastungsspitzen. Dies ist die bevorzugte Variante.

Die vorgestellte Forschung ist die Grundlage für die Entwicklung von neuen übersetzungsvariablen Getrieben für Drehflügler. Sie ermöglicht verschiedenen Konfigurationen eine Steigerung der Effizienz und Einsatzenveloppe und kann somit ein Grundstein für eine umweltfreundlichere und effizientere Luftfahrt im Bereich der Drehflügler sein.

Contents

Nomenclature

Symbol	Description
RPM	Revolutions per Minute
UAV	Unmanned Aerial Vehicle
NASA	National Aeronautic and Space Administration
CEAS	Council of European Aerospace Societies
NACA	National Advisory Committee for Aeronautics
FMEA	Failure Mode Effects Analysis
TUW	Institute of Engineering Design of the Vienna University of Technology
TUM	Institute of Helicopter Technology of the Munich University of Technology
VARTOMS	Variable rotor speed and torque matching system
SFC	specific fuel consumption
NDARC	NASA Design and Analysis of Rotorcraft
SAR	Search and Rescue
MP	mechanical point
TSE	turbo shaft engine
MG	motor- generator engine
PGS	planetary gear set
N	stationary transmission ratio
MTOW	maximum take off weight
FVL	future vertical lift
JMR TD	Joint Multi-Role Technology Demonstrators

Chapter 1

Introduction

Today the single main and tail rotor rotorcraft configuration is the generally used rotorcraft configuration in the world. This rotorcraft configuration produces their lift and propulsion with a single main rotor. The tail rotor is used for torque balancing of the main rotor. Both rotors are driven by a turbo shaft engine or in the case of small helicopters by an internal combustion engine with constant engine speed. The power is transferred via a gearbox with constant transmission ratio and the rotors are driven with a constant speed in every flight state.

Currently, there is a new way of thinking taking place in rotorcraft research and development in the US as well as in Europe and Russia. There are two major rotorcraft research programs. In the United States, the "Future Vertical Lift" (FVL) program, and in Europe, the "Clean Sky 2 - Fast Rotorcraft" program. Both programs intend to develop high speed rotorcraft with excellent hover and vertical take-off and landing (VTOL) capabilities. In Russia there is the Russian Helicopters High Speed Program 2010 executed by Mil and Kamov [36].

The commonly used single main rotor and tail rotor configuration is not the only configuration of interest any more. New configurations like the compound rotorcraft or tilt rotor rotorcraft are under development. The FVL intends to build two Joint Multi-Role Technology Demonstrators (JMR-TD). One is the Sikorsky Boeing SB-1 DEFIANT, a coaxial compound rotorcraft, and the other is the Bell Helicopter Lockheed-Martin V-280 Valor, a tilt rotor rotorcraft [4]. The Clean Sky 2 program intends to build two demonstrators the Airbus Helicopters' LifeRCraft or Racer, a single main rotor compound rotorcraft, and the Leonardo Helicopters Next Generation Civil Tilt-Rotor (NextGenCTR), a civil tilt rotor rotorcraft [19]. The reason for this development is the request on fast forward flight. Therefore, the new concepts are designed to be high speed rotorcraft configurations. These new configurations should have good hover performance and the possibility of a fast forward flight.

A good example of this development is the new Airbus Helicopters high speed demonstrator X^3. It is the previous design to the racer. The X^3 is a compound rotorcraft with one single main rotor and two tractor propellers mounted on small wings on each side of the rotorcraft. High speed and highly efficient results could be obtained with a speed reduction of the main rotor during forward flight while additional thrust was provided by the two tractor propellers. The wings on which the propellers are mounted provided additional lift. The main rotors rotational speed was reduced in fast forward flight to overcome the problem of high-speed stall on the advancing rotor blade. The X^3 uses the variability of the turbo shaft engine to vary the rotor speed. This setting enabled the X^3 demonstrator to achieve an unofficial level-flight speed record of 255 kt (472 km/h) in June 2013 [18].

A rotor speed variation in flight is necessary to have good hover performance and the possibility of a fast forward flight because there are different requirements on the main rotor RPM in these two operation conditions. Hover requires a high rotor speed while fast forward flight needs a low rotor speed. Rotor speed variation could have also an additional advantage in that it can increase the efficiency of a rotorcraft. One example for usage of rotor speed variation to increase rotorcraft efficiency is the Large Civil Tilt-Rotor concept invented by the National Aeronautics and Space Administration (NASA) in the Heavy Lift Rotorcraft System Investigation [20].

There NASA analysed different rotorcraft configurations for short and middle range passenger transport. A tilt-rotor concept was identified as the most suitable and efficient variant. The so-called Large Civil Tilt-Rotor Concept has a transport capacity of 90 passengers with a range of 1850 km (1000 nm) with 155 m/s (300 knots). A speed variable rotor with a speed variation range of 50% (hover: 200 m/s (650ft/s); cruise flight: 105 m/s (350 ft/s) is required to reach the economic competitiveness of the concept [8].

The potential of rotor speed variation is not limited to new rotorcraft configurations. Also the well-known single main rotor and tail rotor configuration can gain benefits from it. Boeings UAV Hummingbird A160 is a good example. This rotorcraft set a new record in endurance flight in its class in May 2008. The vehicle was airborne for 18.7 hours [32]. A two stage transmission gearbox and Karem's Optimum Speed Rotor Technology [21] enabled this performance.

The reason for the increase in efficiency with rotor speed variation is based on the thrust control of a rotorcraft. The thrust control of a conventional rotorcraft main rotor is done by varying the collective control of the rotor. A variation of the collective control leads to a variation of the angle of attack of the rotor blade which varies the lift force and the drag force of the rotor blade. The lift force dL or drag force dD of a section of a rotor blade depends on the flow speed at the blade section v, the air density ρ, the cord length of the blade c, the radial length of the blade section dy and the lift coefficient $C_L(\alpha)$ or the drag coefficient $C_D(\alpha)$. Equation 1.1 shows the context of the parameters for the lift force and Equation 1.2 for the drag force.

$$dL = \frac{\rho}{2} \cdot v^2 \cdot C_L(\alpha) \cdot c \cdot dy \tag{1.1}$$

$$dD = \frac{\rho}{2} \cdot v^2 \cdot C_D(\alpha) \cdot c \cdot dy \tag{1.2}$$

To enable a high rotor efficiency it is important that the rotor blade has a high lift to drag ratio. This ratio depends on the actual angle of attack. Figure 1.1 shows the lift to drag coefficient ratio $\frac{c_L}{c_D}$ plotted over the lift ratio of the NACA 23012 [1] blade profile. The most efficient point of the profile is at a lift coefficient of $c_L = 1.$ which is at an angle of attack of 8°.

The Lift force and as a consequence the thrust of a rotor can be varied by varying the lift coefficient c_L due to variation of the angle of attack or by changing the flow speed v at the blade section dy due to variation of the rotor RPM. This relationship can be seen in Equation 1.1. Therefore it could be possible to increase the rotor efficiency with rotor RPM variation.

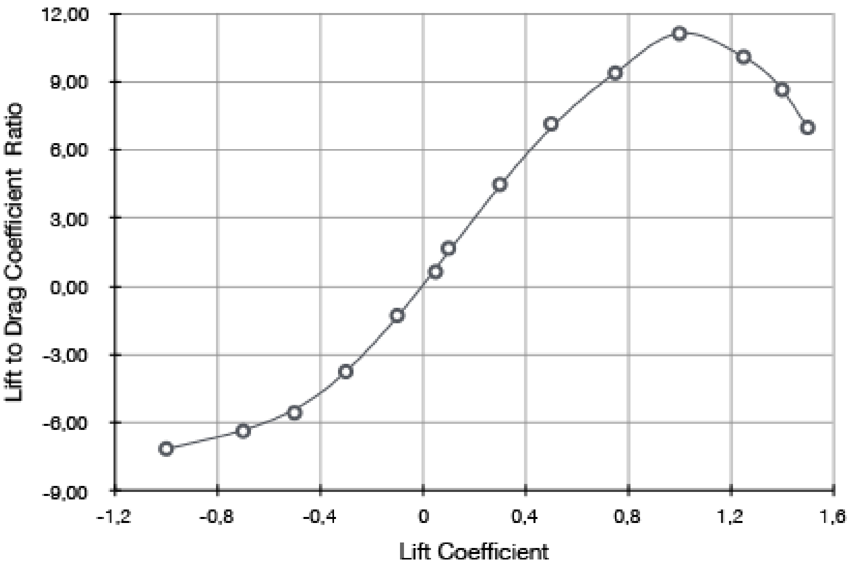


Figure 1.1. *Lift to drag coefficient ratio plotted over lift coefficient for the NACA 23012 blade profile*

Rotor speed variation seems to be necessary for future rotorcraft developments. But how could rotor speed variation implemented? Taking a look at engineered examples delivers different answers.

One of the first rotorcraft inventions which used the possibility of rotor speed variation was the Fairey Rotodyne [14] which was invented in the 1950s. This airborne transport vehicle is a combination of a rotorcraft and an autogiro. The vertical take-off and landing is performed with a single main rotor. The rotor is driven by pressure jets mounted on the rotor blade tips, an idea which was invented by Friedrich Doblhoff [11], an Austrian scientist, during the Second World War. Two turbo prop engines which are mounted on each side of the fuselage on small wings were used to produce thrust in forward flight and in hover the produced the pressure for the jets. After a certain forward flight speed was reached, the pressure jets were turned off. Now the Fairey Rotodyne was flying as an autogiro.

As mentioned in the example of the X^3, it is possible to vary the rotor speed by varying the RPM of the turbo shaft engine. G.A. Misté, in his doctoral thesis, presented an optimization of variable turbo shaft engine performance with main rotor interaction. He presented a simulation model of the T-700 UH-60A engine and the UH-60A main rotor. The goal of his research was to optimize the fuel consumption of the turbo shaft engine in given flight states with variation of the turbo shaft engine RPM and as a consequence the main rotor RPM. He found out that the main rotor RPM influences the specific fuel consumption of the turbo shaft engine. This leads to an increase of fuel consumption although the power demand of the main rotor is decreased. He therefore concluded that the optimum RPM for the rotorcraft is a sub optimum of the optimum main rotor speed and the optimum RPM for the turbo shaft engine [25].

The A160 uses a two stage transmission variable gearbox to achieve the efficiency increase. The gearbox used is a double clutch transmission system similar to that used in the automotive industry. NASA was also investigating different possibilities to vary the rotor speed within the drivetrain in the Concepts for variable/multi-speed Rotorcraft Systems

[34] project. Their research was focused on discrete and continuous variable transmission systems.

Based on these examples, it can be seen that there are three different basic methods available for rotor speed variation:

- to vary the RPM of the power source
- to vary the transmission ratio in the drivetrain
- to vary the behaviour or the motion of the rotor itself during flight

All these different technologies have their advantages and disadvantages. Their possible usage depends on many factors such as the size of the helicopter, the demanded range of speed variation or the rotorcraft configuration.

1.1 Problem Description

This thesis deals with the investigation of a transmission system suitable for rotorcraft rotor speed variation. The main research question which should be answered is:

What are the prerequisites for a reasonable application of transmission systems to vary rotorcraft rotor speed and how could such a transmission variable system look like?

- Main Research Question -

The following problem areas are identified which need to be solved to answer the research question.

1.1.1 Technology Benchmark

As discussed in the introduction there are different technologies known for rotor speed variation. In this thesis, a transmission system for rotor speed variation should be invented. Therefore it is necessary to find out where the transmission technology is positioned in the field of possibilities. What has to be investigated are the advantages and the disadvantages of the transmission technology in comparison to the power source technology and the rotor technology. This step enables how to define the right application area.

1.1.2 Impact on the Rotorcraft Configuration

Nowadays there are different rotorcraft configuration under development as shown in the introduction. All these different types use rotor speed variation. However, it is not clear what the different requirements on the rotor speed are. Is the rotor speed variation limitation based on the demand of the rotorcraft configuration or is it the limit of the used technology to vary the rotor speed? Therefore, research needs to be conducted which shows the potential of rotor speed variation for different rotorcraft configurations. Then the impact of the used method to vary rotor speed has to be investigated. The configuration with the best benefits from rotor speed variation with transmission system technology is the one for further studies. This step enables how to define the requirements for the rotorcraft on the transmission system.

1.1.3 Concept and Design of the Transmission System

There are many technologies known for RPM variation from other industries such as the automotive industry or plant engineering. RPM variation can be done on the one hand discretely with clutches and gears or freewheel clutches and planetary gears. On the other hand, it is possible to vary the RPM continuously with friction based systems or with hydraulic systems directly or in combination with planetary gears. Electric and electronic components could also be used to vary the RPM. The most suitable transmission technology has to be found. There are several aspects which have to be taken into account.

The first aspect is the additional mass of the transmission system. If the mass increase is too high, all the benefits from rotor speed variation could be negated. So it is absolutely necessary to have a minimum mass increase. Therefore, the systems used have to have a high power to mass ratio and also a high torque to mass ratio.

The system must also be able to transfer high power in an efficient manner. The known technologies from the automotive industry work at some hundreds of kilowatts but rotorcraft power demand can be as high as one thousand kilowatts. The design space and the place of the speed variation in the drivetrain also have to be taken into account.

One very important aspect is the reliability and safety of the designed system. The transmission system is a critical part of a rotorcraft. If it fails it leads to a catastrophic failure of the rotorcraft. Therefore it must fulfil all criteria for reliability, power transfer and autorotation. Finally, it must be also conform to the certification specifications.

1.2 Aims of the Thesis

A change of the rotor RPM in a given flight state could increase the rotor efficiency and reduce the overall power demand of a rotorcraft which could lead to a more ecological friendly rotorcraft aviation. This is the basic idea of the thesis. For the first investigation of this idea the following four aims were defined.

1.2.1 Feasibility Study

In the fist step of the investigation it is necessary to show that the idea of rotor speed variation in the drivetrain is possible. Two criteria must be fulfilled to prove the validity of the idea. First, the efficiency increase must be possible. This should be evaluated on a generic rotorcraft. Second, there must be a transmission technology which enables rotor speed variation within the drivetrain. Therefore the first aim was defined as:

The aim is to show on a generic rotorcraft that a reduction of the power demand is possible and that rotor speed variation is in principle feasible within the drivetrain.

- First Aim -

1.2.2 Advantages of variable Gearboxes

After successful demonstration of the feasibility, one prerequisite for the research was the use of a transmission system. The rotor speed variation should be enabled by a transmission variable gearbox. It is therefore necessary to know the advantages of a transmission variable gearbox to enable utilization of its whole potential. This leads to the second aim of the thesis.

The aim is to find the advantages of speed variable gearboxes compared to other technologies.

- Second Aim -

1.2.3 Suitable Rotorcraft Configuration

Nowadays, there are different rotorcraft configurations under development. The most dominant rotorcraft configuration on the market is the single main rotor and tail rotor configuration. In addition, there are also coaxial rotor and tandem rotor rotorcraft configurations available. Tilt rotor rotorcraft and compound rotorcraft with additional propeller for thrust are under development. An investigation is needed to find out if all the rotorcraft configurations can gain benefits from rotor speed variation and under which limitations. Furthermore, the implementation of transmission variable gearboxes should be the best option for the rotorcraft configurations. This leads to the third aim of the thesis.

The aim is to find out which rotorcraft configuration is most suitable for rotor speed variation with a transmission variable gearbox.

- Third Aim -

1.2.4 Transmission variable Gearbox

A lot of transmission variable gearboxes already exist, for example in cars or in heavy duty machines. The gearbox transmissions are discrete variable or continuous variable based on different technologies. It is necessary to find the pros and cons of those technologies for use in a rotorcraft. Furthermore, a concept for a transmission variable gearbox should be developed based on the investigated limitations from the third aim. The fourth aim was therefore defined as:

The aim is to define a possible design for a speed variable gearbox for a given rotorcraft configuration.

- Fourth Aim -

1.3 Contribution of the Author

This thesis consists of five publications, one journal publication and four presented conference contributions. In two of these conference publications the author of the thesis was the co-author. The contribution of the author in every publication is given in detail below.

- **Publication 1**: The first publication is a peer reviewed journal publication in the *"CEAS Aeronautical Journal"* with the title *"Possibilities and difficulties for rotorcraft using variable transmission drive trains"*. The author initiated the idea of investigation of rotorcraft efficiency based on rotor speed variation and investigated the gearbox technology including the shifting behaviour.

- **Publication 2**: The second publication was presented at the *"42nd European Rotorcraft Forum 2016"* with the title *"Possible Technologies for a variable Rotor Speed Rotorcraft Drivetrain"* . The author defined the investigation method, investigated parts of the rotor technology, the whole gearbox technology, parts of the turbine technology and parts of the electric technology. He conducted the analysis and evaluation.

- **Publication 3**: The third publication was presented at the *"Deutscher Luft- und Raumfahrtkongress 2016"* with the title *"Helicopter Configurations and Drivetrain Concepts for optimal variable Rotor Speed Utilization"*. The author made the research in the drivetrain technology together with Mr. Mileti and evaluated the usability of rotorcraft with different drivetrain technologies.

- **Publication 4**: The fourth publication was presented at the *"43rd European Rotorcraft Forum 2017"* with the title *Compound-Split Drivetrain for rotorcraft*. The author conducted the research in compound-split drivetrain together with Mr. Passchinger and the comparison of the different gearbox technologies together with Mrs. Hartenthaler.

- **Publication 5**: The fifth publication was presented at the *74th American Helicopter Society Forum 2018"* with the title *Mass and Kinematic Analysis of Compound Split with Simulation of the Shifting Process for Variable Rotor Speed*. The author performed the mass and kinetic analysis of the different compound split and built some parts of the simulation model together with Mrs. Hartenthaler.

Chapter 2

Methodology

Two major scientific research fields are addressed to achieve the defined goals. The first is machine and gearbox design, which is the main research field of the author. Secondly, research in rotorcraft and rotor design is necessary. In the beginning, a exploratory investigation should prove the idea of variable rotor speed with transmission systems to have a decision basis for further research. It was conducted by the Institute of Engineering Design of the Vienna University of Technology (TUW)and the Institute of Helicopter Technology of the Munich University of Technology (TUM). It was performed to have a decision basis for the project.

On the basis of the exploratory investigation results a research project, called *"VARI-SPEED"* was defined by the author. The major working packages of this research project are given in Figure 2.1. The project VARI-SPEED is an international project supported by the German Federal Ministry for Economic Affairs and Energy in the program LuFo and by the Austrian Federal Ministry for Transport, Innovation and Technology in the program Take Off. The partners are Vienna University of Technology (Austria), Munich University of Technology (Germany) and Zoerkler Gears GmbH (Austria). In addition, there were three subcontractors, the FZG (Institute of Engineering Design) from Munich University of Technology for clutches and brakes, the Institute of Thermodynamics from Vienna University of Technology for questions concerning the turbo shaft engine and the Moscow Aviation Institute for definitions of the missions for different rotorcraft.

The Project VARI-SPEED aims to invent a speed variable drivetrain for different rotorcraft configurations to reduce the required propulsion power, which enables a modern and ecologically efficient aviation. The methodology and the aims to each major working package are described below.

2.1 Feasibility Study

The feasibility study was part of the exploratory investigation. It created the basis for further research. The outcome of this working package fulfils the first aim of the thesis and is presented in the CEAS journal article: *"Possibilities and difficulties for rotorcraft using variable transmission drive trains"*. The aim was to show the advantages and possible applications for variable transmission drivetrain within rotorcraft and the prospects for this technology. Furthermore, the influence of rotor speed variation on the dynamic behaviour of

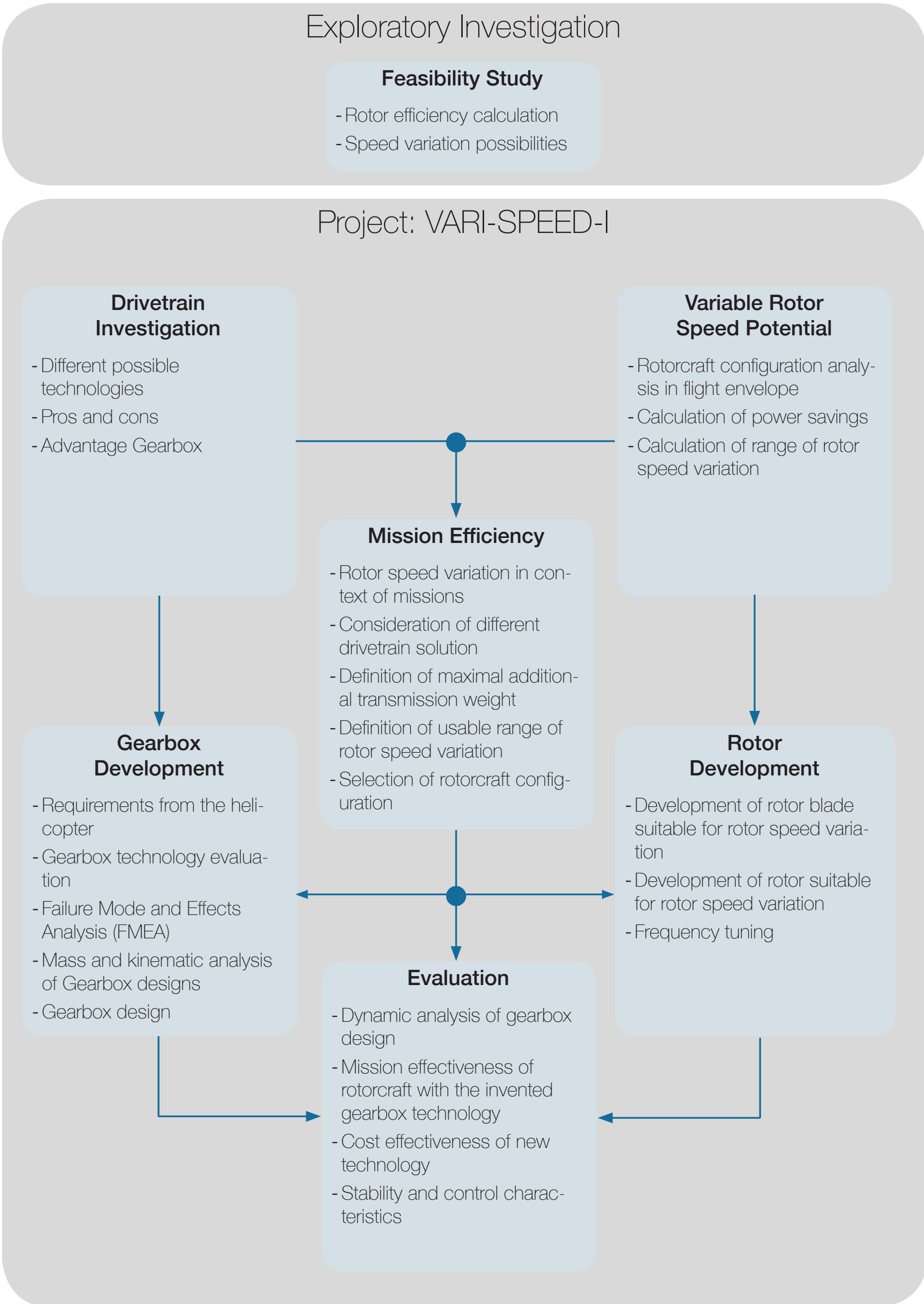


Figure 2.1. *Main Steps of the VARI-SPEED-I Project Plan*

a rotor should be discussed. This should lead to further areas that need to be investigated for a successful use of rotor speed variation in rotorcraft.

A generic physical model of a helicopter similar to the BO105 was prepared in CAMRAD II. Performance calculations with constant and variable rotor speed were performed. Different types of transmission systems, which are presented in patents or in special literature, were analysed according to their function and their behaviour during change of rotor speed. The switching operation of a continuous variable gearbox and a 2-speed-transmission was then discussed.

2.2 Drivetrain Investigation

The drive train investigation was the beginning of the VARI-SPEED project for TUW. The aim was to find possible technologies for rotor speed variation or increased rotor efficiency. Following which these technologies should be classified. The pros and cons of each technology class should be compiled and the advantages of the gearbox technology should be elaborated.

The kinematic principle of the Derschmidt rotor [10] was calculated in Matlab to show the advantages of this invention over a conventional rotor. Other research at the same time showed that the Derschmidt rotor would not work due to its high vibrations [17]. The UH-60A Black Hawk Helicopter was used as reference for the investigation of the drivetrain technologies. A simplified simulation model of a turbo shaft engine was set up in Matlab to investigate the off-design point behaviour in terms of torque, available power and fuel consumption. Different basic design concepts for electric drivetrain in full-hybrid version were elaborated to estimate the weight of the electric drivetrain. The known transmission variable gearbox concepts were configured and designed to the Black Hawk drivetrain to enable a prediction of the functionality and additional weight. A summary of the drivetrain investigation working package is in the second publication of this thesis, titled *"Possibilities and difficulties for rotorcraft using variable transmission drive trains"*.

2.3 Variable Rotor Speed Potential

As the exploratory investigation showed that there is an increase of rotor efficiency and an extension of the flight speed and height are possible, the question occurred if this is true for different rotorcraft configurations. Therefore the TUM started an investigation of the variable rotor speed potential. The aim of this working package was to analyse the flight envelope of different rotorcraft configurations according to the optimal rotor speed. Furthermore, the power savings should be calculated in every point of the flight envelope and the maximal range of rotor speed variation should be defined.

Five rotorcraft configurations were defined to be investigated. For each configuration a representative real rotorcraft was chosen. First, there was a single main rotor and tail rotor configuration which was represented by the UH-60A "Black Hawk". This helicopter was chosen due to its wide range of use and the good available database. The second configuration was a tandem rotor configuration presented by the CH-47 "Chinook". The Chinook is one of the most successful tandem rotor rotorcraft and there is data available for validation. Next, a coaxial rotor rotorcraft was selected. This rotorcraft is presented by the XH-59 experimental helicopter. This rotorcraft was built for tests in fast forward flight conditions. Additional jet engines were therefore also mounted on the XH-59. This is the reason why it was also chosen for the fourth configuration, the coaxial compound rotorcraft.

The last configuration was a tilt rotor rotorcraft, which was presented by the XV-15, an experimental helicopter. A detailed description of the calculation method is given in [16].

2.4 Mission Efficiency

The working package "Mission Efficiency" is the combination of the results of the drivetrain investigation and the variable rotor speed potential analysis. The aim of the working package was to show the efficiency of variable rotor speed for different rotorcraft configurations in the context of missions. The influence of different drivetrain technologies should be considered in the mission efficiency calculation. Based on this study, the maximum possible additional weight for the gearbox should be defined for every rotorcraft configuration and drivetrain technology. The usable or necessary range of rotor speed variation should be defined for every rotorcraft configuration. Finally a rotorcraft configuration should be defined for further research, with best results considering the drivetrain technology.

The missions were calculated with finite steady state trim solutions of the flight envelope, as established in the variable rotor speed potential analysis. This means that no manoeuvres are taken into account. Typical missions for every rotorcraft configuration were defined. In the first step, the missions were calculated with the reference rotor speed of every rotorcraft configuration. Then, the same missions were calculated with the optimum rotor speed in every finite steady state trim solution. The turbo shaft engine always operates at its design speed. This simulated a continuous variable transmission. There was no additional weight estimated for the gearbox. Based on the results of all the missions of one rotorcraft configuration a second rotor RPM was defined. The RPM was defined to deliver the optimal efficiency benefits over all calculated missions. The reference RPM and the optimized RPM were then used to simulate a two speed transmission with no additional weight. The mission benefits of the two speed transmission and the continuous variable transmission were calculated. In the final step, the empty mass of the rotorcraft configurations were increased as long as the benefits form the variable systems were negotiated. The difference in the mass from the reference empty mass and the increased empty mass is the maximal possible additional mass for the new drivetrain. All the missions of each rotorcraft configuration were analysed according to their maximum and minimum used rotor speed. The difference was defined as the necessary range for rotor speed variation within a continuous variable transmission. Using the full range of RPM variation is reasonable because the benefits of RPM variation and the range are in a linear correlation [16].

A decision making process was started to define a rotorcraft configuration for further investigation. The process considered the results of the mission calculation as well as boundary conditions from the drivetrain technology. The goal was to find the configuration where the gearbox technology has the most advantages and where rotor speed variation is highly beneficial. The mission efficiency is presented in the third publication of this thesis with the title *Helicopter Configurations and Drivetrain Concepts for optimal variable Rotor Speed Utilization"*.

2.5 Gearbox Development

This working package is the main working package in the gearbox design. The goal here is to define a concept for a transmission variable gearbox for the chosen rotorcraft configuration. Therefore requirements form the rotorcraft should be taken into account. Different possible gearbox technologies should be evaluated according to their usability in the rotorcraft. A Failure Mode and Effects Analysis (FMEA) of the most promising technology should be carried out after which a mass and kinematic analysis of this technology should show the optimum transmission ratios of the transmission variable module.

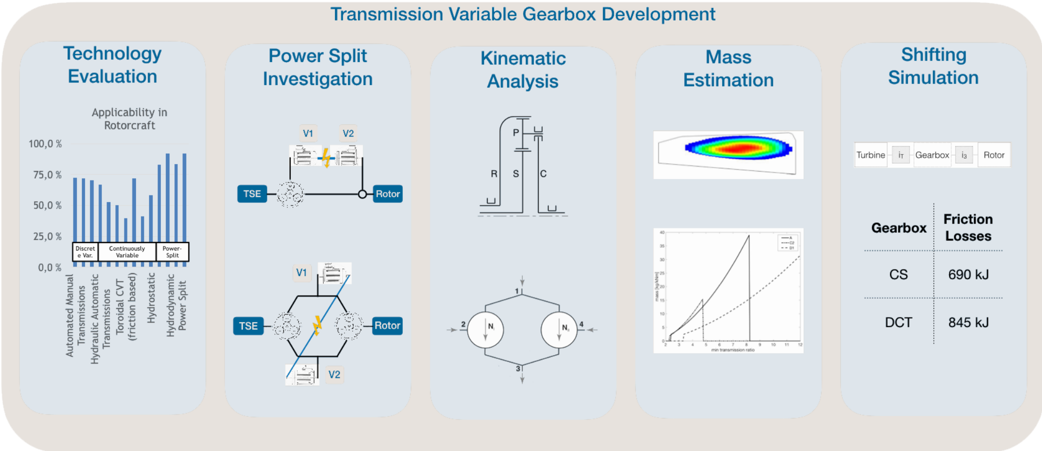


Figure 2.2. *Steps of the gearbox development working package*

In the beginning, a literature study was carried out to find and classify different transmission variable gearbox technologies. Then the requirements of the rotorcraft were listed. A utility analysis of the requirements was carried out to define the importance of the parameters. The gearbox technologies were rated according to their ability to fulfil the requirements. A ranking of the gearbox technologies was created. A Concept investigation based on power and torque flow and estimated mass for the most suitable technology was carried out. Different solutions were evaluated and an FMEA of the most promising technology concept was done. This work is presented in the publication *Compound-Split Drivetrain for rotorcraft*, the fourth publication of this thesis.

Different design concept solutions of this technology concept were analysed according to their mass and kinematic properties depending on the transmission ratio. An analysis of the shifting behaviour and the influence of the shifting process on the drivetrain was made. On basis of this solution a final concept decision was made. A summary of this work is presented in the fifth publication of this thesis, titled *Mass and Kinematic Analysis of Compound Split with Simulation of the Shifting Process for Variable Rotor Speed.*

2.6 Rotor Development

The working package "Rotor Development" is in the responsibility of TUM. It is still in progress. The aim of this working package is to develop a rotor blade and a rotor which can be driven in the defined range of rotor speed variation without any problems due to resonance. The method for the rotor blade design is presented in [30].

2.7 Evaluation

The evaluation section should prove the functionality of rotor speed variation. The benefits of rotor speed variation with the final gearbox design should also be evaluated in case of environmental efficiency and cost efficiency in the context of missions. This working package is still in progress and is not part of the thesis.

A mission catalogue with 126 typical missions in 13 industry branches were defined by our partner of the Moscow Aviation Institute. This mission are calculated according to the methodology presented in the working package "Mission Efficiency". This time the additional gearbox mass is taken into account. Parameters such as the fuel flow were used to calculate the different environmental impacts of the reference technology and the variable rotor speed rotorcraft.

In the next step the costs were calculated for every finite steady trim state and so the costs of one mission can be calculated. This enables a validation of variable rotor speed technology in economics. The cost model was invented by our partners from the Moscow Aviation Institute.

In addition to the mission efficiency the power flow in the transmission variable gearbox and the dynamic behaviour is also simulated in a Matlab model [29]. The stability and control characteristics will also be investigated. However, this is not part of this thesis.

Chapter 3

Short Overview of the Scientific Publications

The following chapter presents a short summary of the investigation in the scientific publications. The focus is on the results and the discussion. An overview of the methodology of the publications is presented in the Methodology chapter. Details can be found in the publications in the appendix.

3.1 Publication 1

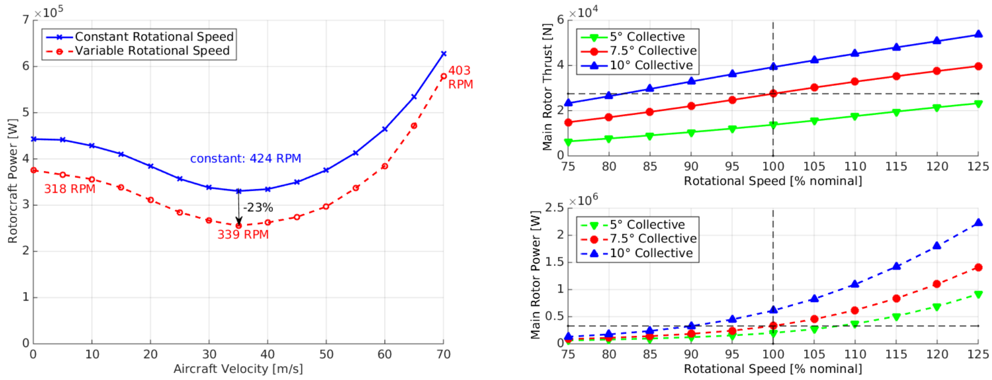
Possibilities and difficulties for rotorcraft using variable transmission drive trains

The research in this publication was focused on two parts. First, there was an investigation into the benefits and difficulties of rotor speed variation for rotorcraft, and second, there was research in drivetrain technologies. It was the basis for further research.

3.1.1 Rotor Speed Variation

A CAMRAD II model of a generic physical helicopter similar to the Bo105 was set up. Calculations were performed for the required power of the reference rotor speed and the optimized rotor speed in given flight states. Figure 3.1a shows the calculation results for the required rotorcraft power in different forward flight speeds with nominal and optimized rotor speed. In hover mode there is a possible reduction of 25%. At 40kts flight speed there is a possible reduction of 31% and at 70kts there is a possible reduction of 11%. This indicates that a variable speed rotor can increase the efficiency of a helicopter.

The reason for the improved rotor efficiency can be found in the different angle of attack for the same thrust with various rotor speeds. Figure 3.1b shows the connection between main rotor thrust, speed, and required power. Assuming a helicopter has a collective pitch of 7.5° (dotted line) by a maximum forward speed of 100% (vertical dashed line). A collective pitch of 10° (triangle line) increases not only the rotor thrust but also the required power if the rotor is driven with the same rotational speed. If the rotor speed can be decreased to have the same thrust at 10° collective pitch that is necessary for a flight at 100% (horizontal dashed line), the required power can be reduced. There is now a power margin at the given flight speed. This margin can be used for example to increase the forward flight speed.



(a) *Required Power* **(b)** *Angle of Attack*

Figure 3.1. *Benefits of rotor speed variation for main rotor: (a) Required power of the generic helicopter displayed over the forward flight speed for nominal rotor speed and optimized rotor speed. (b) Thrust and power of the main rotor for different angles of attack plotted over the rotor speed.*

With rotor speed variation it could be possible to increase the flight envelope to a higher ceiling. Flight at a higher ceiling requires a higher main rotor thrust. This leads to a higher counter torque which has to be compensated for by the tail rotor. However, the tail rotor thrust is decreasing with the increase of the ceiling due to lower density. The loss of tail rotor thrust can be countered with an increase of the rotational speed. This results in higher ceiling levels for the rotorcraft range of operations. The turboshaft engine has to have enough power reserve to enable this operation since the power increases as a cubic function while thrust increases linearly.

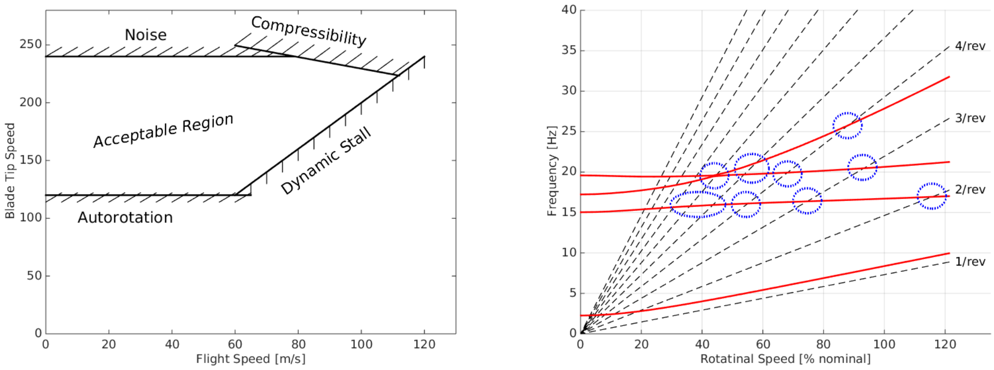
Rotor speed variation has to be accomplished within the framework of feasibility, certification specifications and compliance with the general limitations of the flight envelope which are presented in Figure 3.2a.

A rotational speed that is too low may not comply with the autorotation requirements. A rotational speed that is very high affects noise limits. Compressibility effects may occur in high speed flight conditions. In order to counteract a retreating blade stall, the rotational speed of a rotor must also be above a certain minimum in high speed flight. The aforementioned limits are based on physical requirements as well as on safety and certification standards.

The use of variable speed rotor systems offers the opportunity to operate the rotor with an arbitrary rotational speed. As a consequence, the rotor system must be able to be operated at different rotor speeds.

The rotor blade design for a single rotor speed enables the prevention of a coincidence of the rotor harmonics and the blade eigenfrequencies at nominal rotor speed. Figure 3.2b shows the frequencies of a stiff-in-plane rotor blade. The rotor harmonics are plotted in the dashed lines. The frequencies of the blade are mapped over different rotor speeds.

Blade frequency tuning is usually done by varying the structural properties of the blade. This leads to a good dynamical behaviour. The eigenfrequencies are only crossed through the



(a) *Flight Envelope* **(b)** *Frequency Diagram*

Figure 3.2. *Benefits of rotor speed variation for main and tail rotor: (a) General limits of the rotor speed in the flight envelope. (b) Frequency Diagram of a stiff in plane rotor blade.*

rotor harmonics during acceleration and deceleration of the rotor. This is usually performed without blade loading when the rotorcraft is on ground. However, this is not true for rotors designed for variable rotor speed. This rotor must be able to deal with loadings equal to or close to a rotor harmonic. High vibratory loads must be tolerated. Hence blade design concerning stability and stiffness is essential.

3.1.2 Drivetrain

Looking at known drivetrain solutions for speed variation it can be seen that there are differences in the technique of power transfer and in the way of changing the transmission ratio. There are several different concepts and designs possible to vary the transmission ratio but it is hard to say which one is suitable to be used in rotorcraft.

The transmission ratio can be changed continuously or discretely. This can have a certain impact on the flight behaviour and the efficiency of the rotorcraft. Discrete transmissions are designed for single operation points. This is advantageous for the rotor design as there is one design point for every stage of the gearbox. Therefore, there are only discrete points of optimum efficiency. For a two-speed transmission system, one gear would be optimized for hover and the second for fast forward flight. In between there is a region where the rotorcraft efficiency is decreased. The behaviour is presented in Figure 3.3. Continuously variable transmission enables the operation of the rotor speed always in the optimal region.

The technique of power transfer can be critical for the safe power transmission of the gearbox. Discrete variable transmission systems are mainly based on gears. Gears have a positive connection to each other which enables a secure power transfer. This is not true for continuous-variable transmission systems. The power flow of continuous-variable transmissions is based on friction, fluid or electric.

The disadvantage of the friction-based system is wear. The amount of wear depends on the amount of power transfer. With increased power, wear and surface temperature increase. With increased wear, the maximal possible power transfer decreases. In high power demanding flight states this relationship between power and wear can lead to a total loss of power transmission. The same is true for fluid-based continuous-variable transmission systems.

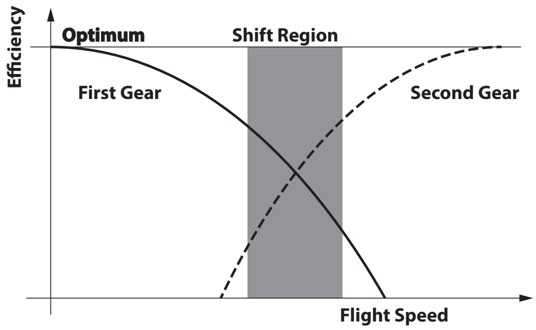


Figure 3.3. *Schematic of gear efficiency (rotor speed efficiency) for different flight speeds.*

There, the high power flow increases the fluid temperature with the effect that the viscosity decreases. The maximum possible power transfer is then decreased and the temperature rises further until there is a total loss of power transmission. Electric components have to be redundant due to their abrupt damage behaviour. This might lead to an unacceptable weight increase of the transmission system.

3.1.3 Conclusion

Advanced research in the variable rotor speed technology may lead to a significant potential for rotorcraft. Rotor speed variation could lead to power efficient, ecological and high-performance rotorcraft architectures with increased flight envelope. It seems to be possible to realize rotor speed variation within the drivetrain. The additional mass has therefore to be minimized and it has to be a safe and efficient system which meets the requirements of the certification specifications. Further research and development are necessary to find the pros and cons of the different technologies and rotorcraft architectures.

3.2 Publication 2

Possible Technologies for a variable Rotor Speed Rotorcraft

The focus of the research presented in this publication was on the comparison of different technologies for rotor speed variation. Four different technology categories were defined an analysed in a morphological box. The technologies were analysed according to their usability in rotorcraft and the pros and cons of every technology were under investigation.

3.2.1 Rotor Technology

The first technology category is that of rotor technology. Alternative impellent concepts of the rotor like the blade tip jet streaming [11, 12, 13] or the Turbine Driven Rotor [5, 6, 7] are not considered in the publication because they do not provied RPM variation or similar effects on the rotor.

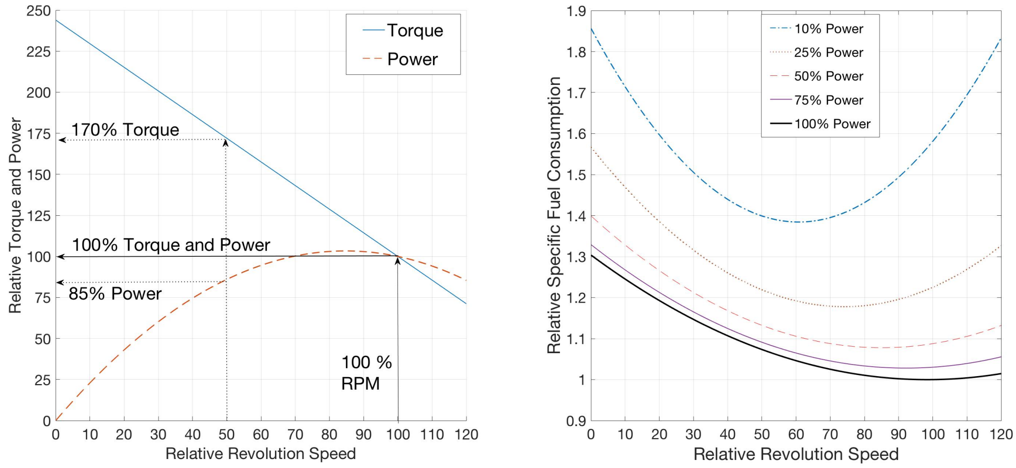
The first patent dealing with variable rotor speed is the Karem Optimum Speed Rotor [21]. It is not a technology which influences the rotor behaviour but it describes a method to design a rotor blade for a range of RPMs. The idea is to design a rotor blade with new materials which is very light and stiff. All eigenfrequencies are then shifted to a higher level. So they are not reached during normal operation.

The idea of changing the rotor behaviour was realized by Hans Derschmidt. He invented the so-called Derschmidtrotor in 1960 [9]. His idea was to add a forced lead leg motion to the rotor blades. The advancing blade should retread in a circular motion while the retreading blade should have an additional angular speed. As the forced motion is by design in the resonance, it does not work because of the high vibrations [17].

Another research topic is the variation of the rotor radius [27]. In this invention, the radius of the main rotor is adapted to the current flight conditions. This enables an efficiency increase of the rotorcraft but it is not in opposition to rotor speed variation. Furthermore, with additional rotor speed variation, higher benefits could be achieved. Therefore, it is a good addition to rotor speed variation.

3.2.2 Turbine Technology

The second category is that of turbine technology. In the beginning, different turboshaft engine designs were analysed according to their potential for RPM variation. Twin-shaft turboshaft engines with a fixed blade geometry with an incidence tolerant blade geometry and an additional stage for the working turbine seems to be the best option for RPM variation. The power and torque characteristics and the specific fuel consumption (SFC) were analysed for this type of turboshaft engine. The characteristics can be seen in Figure 3.4. The relative power and torque behaviour is plotted over the relative turboshaft engine revolution speed in Figure 3.4a. With decreasing of the RPM the power decreases and the torque increases. Figure 3.4b shows the change of the specific fuel consumption (SFC) over the relative revolution speed of the turboshaft engine. It can be seen that the specific fuel consumption increases with deceasing RPM and a decrease of the load on the turboshaft engine. This behaviour has to be considered in the rotor speed variation.



(a) *Torque and Power* **(b)** *Specific Fuel Consumption*

Figure 3.4. *Characteristic of the turboshaft engine in terms of torque, power and specific fuel consumption with different RPM.*

3.2.3 Electric Drivetrain

The third category is the electric drivetrain. Research from Airbus Helicopters presented by C. Mercier et al. [24] showed different possibilities for electric hybrid propulsion. Four different types were defined. First is the *Micro Hybrid* with maximum 50kW as a booster. Second is the *Mild Hybrid* with about 300kW with the main characteristic that pure electric driven flight states are not possible. Third is the *Full Hybrid*. Pure electric driven flight states are possible but there is a thermal engine as the energy source. Fourth is *Full Electric* with no thermal engine on board. C. Mercier et al. concluded that *Micro Hybrid* is possible, *Mild Hybrid* can be possible in the near future due to an investigation in high power density electric engines. *Full Hybrid* and *Full Electric* will not be possible in the near future due to the mass of the batteries and electric engines with high power.

In the presented investigation, five different full hybrid concepts were designed based on the data of the S-70 Black Hawk. These components were included in the design: The generator, the power electronics, main and tail rotor electric motor, the cooling system and, in some cases, an additional gearbox. The used components are off-the-shelf. The concepts were 10 to 15 times too heavy to be used in rotorcraft in every investigated design.

In a next step, super conducting engines were used for the rotorcraft drivetrain according to the research of C.A. Luongo et al [23]. Even with this technology there is a factor of three compared to the actual main gearbox weight of the S-70 Black Hawk.

3.2.4 Gearbox Technology

The fourth category is the gearbox technology. In the beginning, a general interpretation of the gearbox technology was done which showed that a huge range of speed variation is possible without changing the turboshaft engine's speed. It is also possible to have an independent speed variation of different rotors. This could be especially useful in new rotorcraft configuration or in the single main rotor and tail rotor configuration. It is also possible to drive the auxiliary units such as oil pumps, cooling fans or generators, at a constant speed. Furthermore, gearbox technology is an already accepted technology in the rotorcraft industry.

A literature study showed different patents and ideas for rotor speed variation with gearbox technology which are presented in the following section.

One interesting invention is magnetic gears [31, 35]. Here, the torque is transferred by magnetic interdependency. Changes of revolution speed or torque are based on the different numbers of magnetic poles of the pinion and gear. For a high efficiency and a high torque density it is important to have as many magnets as possible in parallel mashing. This leads to wobbling magnetic gears. A special construction of wobbling gears enables a transmission variation. Magnetic gears do not need any lubrication and they are tolerant to contamination. This is ideal in case of loss of lubrication. They also have an integrated overload protection because there is no positive contact. The major drawback is the unsolved problem of cooling. There are power losses due to magnetic hysteresis resulting in temperature increases in the magnetic gears. Also, the torque and power density are not comparable to conventional gears which leads to an increase in mass in the transmission system.

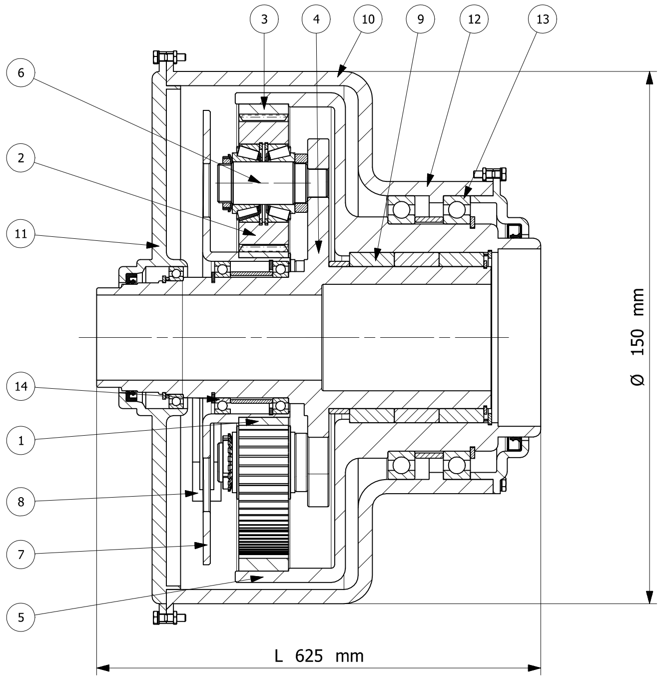


Figure 3.5. *Siemens NX construction drawing of Moore's Helicopter rotor transmission system. Designed for the S-70 Black Hawk.*

An invention based on planetary gears was made by R. Moore [28]. It consists of a planetary gear, a free-wheel clutch and a brake. A drawing of this invention is given in Figure 3.5. One transmission ratio is the drive through which all shafts of the planetary gear run at the same RPM. The sun gear is locked to the housing in the other transmission ratio. There is a transmission from the planet carrier shaft to the ring shaft. This enables only a speed change to higher speeds. Therefore, this system is not really useful in rotorcraft because the turboshaft engines work at high speeds and the rotor at low speeds. The construction showed a mass of 380kg for this invention placed inside the S70 Black Hawk drive train which is about 60% of the main gearbox weight. However, the additional necessary reduction stage is not considered there.

X. Ai [2] invented a two-speed transmission with smooth power shift based on epicyclic gears and electric engines. The limiting factor of this invention is the electric components in particular the two electric engines which are used, as only one of them is in operation at any one time; the other engine at this time is only ballast.

NASA made some transmission variable gearbox inventions for their Large Civil Tiltrotor [34]. A design of these inventions for the S70 Black Hawk showed that this invention is made for high speed and low torque regions which is not the case for the investigated application. Therefore, the gearboxes weigh around 800kg which is 120% of the main gearbox and too heavy to be used.

3.2.5 Pros and Cons Analysis

There are only two technologies which have the potential to vary the rotor speed. These are the gearbox and turbine technologies. There is no rotor technology available which enables rotor speed variation or which gains similar effects. Electric full hybrid technologies are too heavy to be used in rotorcraft but it is possible to use small electric engines as support for rotor speed variation.

The advantage of turbine technology is the low weight increase of about 5% of the turboshaft engine. Also, the layout of the gearbox is simpler. There is no need for an additional gear. The disadvantage is the high torque in the whole gearbox at lower RPM. Therefore, the whole drivetrain needs to be designed for these high torques. Also, the auxiliary units have to be designed for low RPM leading to an additional increase in mass. All the rotors of the rotorcraft change their speed simultaneously which is not the best option for the rotorcraft. Especially for the main and tail rotor configuration, where the optimum tail rotor speed is counter proportional to the main rotor speed.

Using a transmission variable gearbox affects only the part of the transmission system after the variation. The turboshaft engine, auxiliary units and the first part of the transmission system are not affected by the transmission ratio variation. This also enables an independent speed variation of the different rotors. To gain these benefits a complex transmission system is needed which has a high mass.

3.2.6 Conclusion

It could be shown that turbine technology and gearbox technology enable a variable rotor speed over the full required speed range. Due to the characteristic of the turbine technology it seems to be suitable for small rotor speed variations to increase the efficiency. Gearbox technology can deliver the full power over a large range of rotor speed variation. The rotors can also be controlled individually. Therefore, the gearbox technology seems to be suitable for increasing the flight envelope with an efficiency increase.

3.3 Publication 3

Helicopter Configurations and Drivetrain Concepts for optimum variable Rotor Speed Utilization

The benefits of rotor speed variation in the context of missions with different drivetrain technologies was the focus of the work presented in this publication. Ind addition, possible solutions for rotor speed variation within the transmission system are presented.

3.3.1 Mission Calculation

The effects of a variable-speed rotor design on power savings and flight envelope are discussed for various existing helicopter configurations in the variable rotor speed potential analysis [16]. NDARC (NASA Design and Analysis of Rotorcraft) was used to perform these calculations. Five aircraft types were chosen for the study: the UH-60A single main-rotor and tail-rotor helicopter, the CH-47D tandem helicopter, the XH-59A coaxial lift-offset helicopter and the XV-15 tiltrotor. The investigation showed areas of possible power savings, ranges of rotational speed and a possible increase in the flight envelope.

Furthermore, the sensitivity of additional transmission weight relating to the possible power savings with variable rotor speed could be shown. There are always regions where the reference rotor speed is the optimal rotor speed. Depending on the points of the flight envelope, rotor speed variation could be beneficial or not. Mission calculations are needed to decide whether the variable rotor speed technology is favourable compared to a lighter reference configuration.

The used missions for calculation are based on published reference missions for those types of rotorcraft. The missions' calculations consider finite steady state flight conditions. Manoeuvres are not taken into account. The types of the calculated missions are given in Table 3.1. Except for the high-speed mission profiles, the missions consist of a variety of different flight conditions. A detailed description of the missions is given in publication 3 in the appendix.

Multi purpose configurations		**High speed configurations**	
UH-60A	maritime SAR	Compound	transport mission
UH-60A	high altitude external transport	Compound	passenger transport
UH-60A	troop transport	XV-15	transport mission
CH-47D	high altitude external transport	XV-15	long range transport
CH-47D	supply mission		
XH-59A	passenger transport		
XH-59A	rescue mission		

Table 3.1. *Calculated types of missions for different rotorcraft configurations.*

When observing the UH-60A mission calculations, the rotor speed ranges approximately from -26% to +10% for the optimum rotor speed. The two-speed transmission provides optimum rotor speeds of -16% and +2%. For each isolated mission the difference in rotor speed minimum and maximum is approximately 20%. The external transportation mission requires the highest rotor speed due to the high altitude. The maritime search and rescue (SAR) mission requires the lowest rotor speed during hover at sea level. The difference between optimum and reference rotor speed is small for the troop transport mission. The mission durations are comparable.

In the UH-60A search and rescue (SAR) mission, the hover segment can significantly be improved by up to 9.7% using a continuously-variable transmission. During the external transport mission, fuel savings of 6.3% or payload improvements of 18% are possible. The improvements of the troop transport mission are small because this is the design mission for the helicopter. The dual speed approach is always less efficient.

The XH-59A has a speed variation of +2% and -7% in the passenger transport mission and in the rescue mission compared to an optimized reference RPM. 2.5% fuel savings, range increase and speed increase can be achieved. The CH-47D has a speed variation of -22% in both missions in the unloaded section. In the loaded sections the reference RPM is equal to the optimum RPM. The speed variation enables an increase of up to 10% in payload and 2.5% in range and 5% fuel savings. Two-speed transmission and continuous-variable transmission gain almost the same results for those types. Table 3.2 gives an overview about the variation range and the benefits with rotor speed variation.

Rotorcraft	**two speed**		**continuous variable**	
	variation range	benefits	variation range	benefits
UH-60A	18%	5.0% payload 5.0% endurance 2.5% fuel	36%	18.0% payload 10.0% endurance 6.0% fuel 3.0% range
CH-47D	22%	10.0% payload 4.0% fuel 2.0% range	22%	10.0% payload 5.0% fuel 2.5% range
XH-59A	9%	2.5% fuel 2.5% range 2.5% speed	10%	2.5% fuel 2.5% range 2.5% speed
XH-59A Compound	8%	6.0% fuel 7.0% range 6.0% speed	13%	6.0% fuel 7.0% range 6.0% speed
XV-15	43%	8.0% fuel 10.0% range 9.0% speed	54%	8.0% fuel 10.0% range 9.0% speed

Table 3.2. *Speed variation range and mission benefits for different rotorcraft configurations.*

The high-speed compound configuration in the passenger transport mission uses a main rotor speed reduction of -8% and gains about 5% in fuel savings, range and speed. In the transport mission there is a rotor speed variation of about -13% which leads to benefits of about 7% in the three mentioned categories. The two-speed transmission and the continuously-variable transmission lead to the same results.

The same is true for the XV-15. During the XV-15 long range transport mission range, fuel savings and speed improvements of 9% are obtained using the tow-speed transmission. A rotor speed reduction of -43% is needed to gain those benefits.

Based on the mission benefits, the additional possible empty weight is calculated that compensates the achieved fuel savings by variable main rotor speeds in relation to the single reference rotor speed. The numbers are given in Table 3.3. For the high speed configurations, there is no difference between the two-speed and the continuously-variable transmission for the XV-15 and the XH-59A. The other configurations are more tolerant to the continuously-variable transmission than to the two-speed transmission. This is especially true for the UH-60A Black Hawk.

Mission	**two speed**		**continuous variable**	
	Absolute	Relative	Absolute	Relative
UH-60A	10.000 kg			
maritime SAR	250 kg	2.5%	445 kg	4.5%
high altitude external transport	140 kg	1.4%	415 kg	4.2%
troop transport	7 kg	0.1%	190 kg	1.9%
CH-47D	22.700 kg			
high altitude external transport	175 kg	0.8%	220 kg	1.0%
supply mission	730 kg	3.2%	840 kg	3.7%
XH-59A	4.000 kg			
passenger transport	140 kg	3.5%	170 kg	4.3%
rescue mission	190 kg	4.8%	200 kg	5.0%
XH-59A Compound	4.000 kg			
passenger transport	485 kg	12.1%	485 kg	12.1%
transport mission	765 kg	19.1%	765 kg	19.1%
XV-15	6.800 kg			
transport mission	705 kg	10.4%	705 kg	10.4%
long range transport	1.120 kg	16.5%	1.120 kg	16.5%

Table 3.3. *Possible additional gearbox mass for rotor speed variation at different missions absolute and related to the rotorcraft maximum take-off weight*

3.3.2 Gearbox Concepts

First, a two-speed transmission concept was developed which enables a shifting process under full load. An epicyclic gear stage was used due to its high-power density with respect to mass. Besides the epicyclic gear, the systems consists of a clutch and a free-wheel clutch. When the clutch is engaged the system rotates as a block, causing no losses and has a transmission ratio of one. When the clutch opens, the absolute velocity of the carriers reduces until the free-wheel clutch catches up. This leads to an overall ratio smaller than one depending on the geometry of the epicyclic gearbox. Double planets are used to overcome the problem of change of direction of rotation of output shaft when shifting.

The concept of a self-shifting multi-disk clutch was developed combined with a dog clutch to achieve a form-locking to guarantee a fail-safe behaviour of the clutch. The high torque at the clutches leads to high friction work and high temperatures in the clutch which needs additional measures to compensate for.

The overall weight of this system is about 300 kg for the UH-60A Black Hawk when it is mounted directly in front of the rotor with an input speed of about 260 RPM. An investigation of the influence of the input speed to the weight showed that significant weight reduction is possible when the input speed is increased.

Second, a continuously-variable transmission was investigated. Known CVT solutions from the automotive and industrial segment can hardly be adopted as a shifting module for a rotorcraft due to its high torque requirements. Therefore, a power spit concept was conceived. For the concept a total mass of about 600 kg was estimated.

3.3.3 Rotorcraft Analysis

Looking at the benefits of the rotorcraft, it can be seen that rotor speed variation provides benefits for all the investigated rotorcraft types with a continuously and discrete transmission ratio. Depending on the rotorcraft configuration there is one type of transmission system preferable.

The high-speed configurations XV-15 and XH-59A Compound gain the same benefits with two-speed transmission or with continuous transmission. These benefits are gained within one mission. The XV-15 has a speed variation range of 43% and the XH-59A has a variation range of 8%. The additional mass of a continuously-variable transmission system is higher than for a two-speed transmission system as the drivetrain investigation showed. Therefore, a two-speed transmission is preferred for the XV-15. For the XH-59A a two-speed transmission would be the best choice from this point of view. As the variation range is small, the XH-59A Compound could also use a speed variable turboshaft engine as an option. On the other hand, the use of a continuously-variable transmission for the XH-59A Compound could enable new missions for this rotorcraft and then this could be the most beneficial variant.

The multi-purpose rotorcraft configurations show different results. The XH-59A gains only small benefits with both variants of transmissions. The variation range is about 9%. Therefore, a speed-variable turbine seems to be the best option for this type of rotorcraft. For the CH-47D the results with the continuous-speed variation are slightly better than with the two-speed variation. The variation range of 22% is the same for both transmission types. Therefore, a two-speed transmission would be preferable. The tolerance to the additional gearbox mass is very low with only 0.8%. Such a light weight design will be a very challenging task. Of all the configurations shown, the UH-60A can gain the most benefits of rotor speed variation. Furthermore there is a huge difference between continuously-variable and two speed transmission. The two-speed variation range is about 18% while the continuously variation range is about 36% with much higher benefits. Therefore, a continuously-variable transmission would be the best choice.

3.3.4 Conclusion

The analysis of rotor speed variation for different rotorcraft configuration in the context of mission showed that rotor speed variation is useful for all configurations. High speed configurations can use a two-speed variation while multi-purpose configurations benefit from continuously variable transmission. Speed variation within the turboshaft engine seems to be useful with the XH-59A configuration.

The gearbox investigation showed that in principle both types are realizable. The mass of the presented inventions is too high to be used in rotorcraft. One reason therefore is that the assumed variation range of the gearboxes is much higher than it is needed for the rotorcraft. Nevertheless, further research is needed to find a light weight solution for the transmission variation.

3.4 Rotorcraft Decision

The rotorcraft decision process is not part of the publications in the thesis but is important for understanding the further investigation. Therefore, it is presented in this chapter. The rotorcraft decision process is published in the conference notes of the 2^{nd} Vienna Vertical Lift Day [3]. The flow chart of the decision-making process is given in Figure 3.6.

The rotorcraft decision process is based on boundary conditions and technological conditions. The boundary conditions result from the mission efficiency calculations and the variable rotor speed potential analysis. The technological conditions are based on the investigation of the drivetrain and the invention of the gearbox concepts for the mission calculations. Economical aspects are not considered in the decision process. The proof of feasibility should first be done.

3.4.1 Boundary Conditions

Taking a look at the mission benefits shows two principle differences between high speed rotorcraft and utility rotorcraft. High speed configurations gain all the benefits within one mission. Also, a two-speed variation is sufficient for high speed configurations. One rotor speed is used in fast forward flight and the other is used in hover. A mass increase of up to 10% of the maximum take-off weight (MTOW) is possible for the transmission variable gearbox.

Utility rotorcraft need to have a variety of missions to gain all the benefits. Continuous-variable transmission enables an additional efficiency increase especially for multi-purpose operations. A mass increase of about 4% of the maximum take-off weight (MTOW) is possible for the variable transmission gearbox.

3.4.2 Technological Conditions

The single main and tail rotor configuration is the most common in the rotorcraft industry and has a comparatively simple transmission system design.

The continuous-variable transmission system enables full control of the rotor speed at every operation point. It enables a smooth and slow change of the rotor speed and every transmission ratio can be used during operation. The turboshaft engine speed and the rotor speed are completely decoupled and so both can be driven at their optimum speed. Continuous-variable transmission always has the best performance in mission calculation but is much heavier than a two-speed transmission.

The two-speed transmission system is the light weight alternative to the continuously-variable transmission system. There is no control of the rotor speed during the shifting process and this process must be fast which could lead to dynamic problems of the rotor. There are only two operation points where the rotor is driven at its optimum speed.

3.4.3 Decision Process

The decision is divided into two categories. One is the usage of the rotorcraft and the other is the transmission system used. First, a decision in the rotorcraft category is made

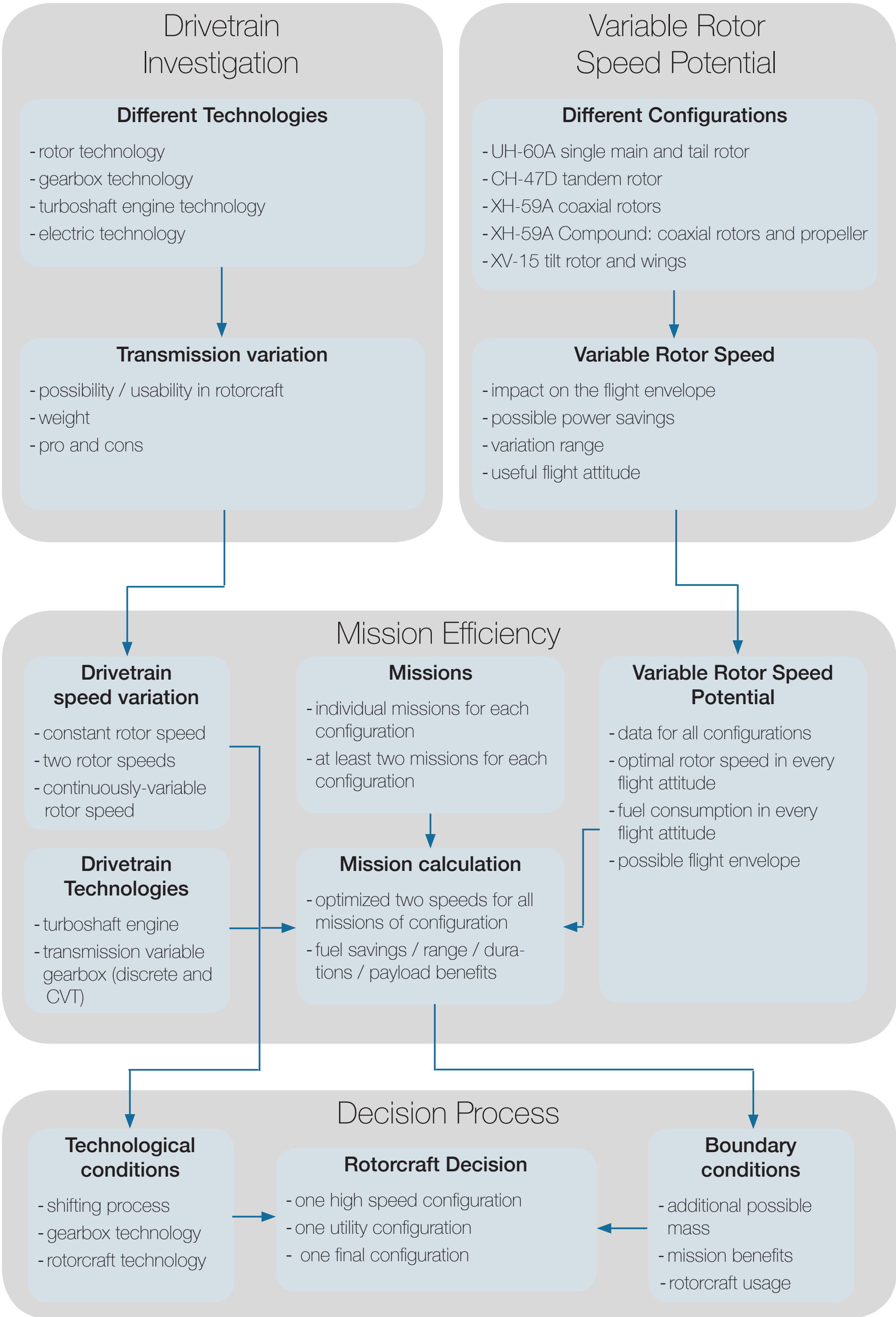


Figure 3.6. *Decision-making process for the further investigation on rotorcraft configuration with a transmission system.*

followed by one in the transmission system and finally between the best configurations with the chosen transmission system.

High Speed Configurations: The compound rotorcraft configuration has only very small additional benefits with the continuously rotor speed variation. It can also fly missions with moderate forward flight speeds. Therefore, the continuously rotor speed variation can increase the usage of the compound rotorcraft.

The tilt rotor configuration hardly gains any additional benefits from the continuously rotor speed variation. Flying at moderate speeds is not an option for this type of rotorcraft. The efficiency increase is very high for this rotorcraft and a rotor speed variation is necessary for a competitive usage of the type.

Therefore, the compound rotorcraft configuration is preferred when a CVT is chosen and the tilt rotor configuration is preferred for the two-speed transmission system.

Utility Rotorcraft Configurations: Single main and tail rotor configurations are used in every weight class. They are seen on multi-purpose helicopters and have a wide range in flight speed variation. Therefore, CVT is the best solution for them. The additional weight increase is restricted.

The coaxial rotor configurations are also used in a wide weight class range. They are used for heavy lift operations and mostly slow forward flight speeds. The gearbox system is complex compared to the single main and tail rotor configuration. They can use a two-speed or a continuous-variable transmission.

The tandem rotor configuration is used only in heavy weight classes for transport operations with moderate forward flight speed. They can gain less benefits from rotor speed variation other than an increased forward flight speed. The transmission system is complex.

If a CVT is preferred then the single main and tail rotor configuration will be chosen. For the two-speed transmission system the coaxial rotor configurations seem to be the best option.

Transmission System: Due to the uncertainty in the shifting process the CVT solution is the preferred one. Only if the problem with the weight increase cannot be solved will a two-speed transmission be considered.

Final Decision: The single main and tail rotor configuration is the chosen rotorcraft configuration based on the UH-60A. It offers the best benefits for the CVT system and if necessary, an upgrade to a compound configuration like the Airbus X^3 is possible.

3.5 Publication 4

Compound-Split Drivetrain for rotorcraft

The work presented in this publication is a deeper investigation of the variable transmission ratio systems. It is based on the findings of the technology investigation of the second publication and the outcome of the mission simulation. Transmission systems were analysed according to the requirements from the rotorcraft and a failure mode and effects analysis of the most suitable solution was made.

3.5.1 Comparison of different variable Transmission Ratio Systems

In the beginning, different types of already existing transmission systems for realizing variable transmission ratios were listed. They were taken from several fields of engineering such as the automotive industry or the plant engineering industry. The most common types are discrete variable transmissions ratio systems based on positive (form) fit and continuously-variable transmissions ratio systems based on friction, hydrodynamics, hydrostatics or electric / electromagnetic.

Then the requirements from the rotorcraft on the transmission system were elaborated. These parameters were ranked after an evaluation based on a utility analysis which represents their importance of the requirement for the rotorcraft (weighting process). The utility analysis compares the parameters against each other under the aspect if one criterion is more important, equal or less important than the others. The utility analysis was conducted by five experts in rotorcraft transmission design. The requirements and their ranking are given in Table 3.4. The most important requirements are a high system reliability, it should be suitable for high power demand for rotorcraft of the CS-29 class and there should be a controllable shifting process.

Requirement (Evaluation Parameter)	**Importance**
high system reliability	9.42 %
suitable for high power demand (CS-29)	9.00 %
controllable shifting process (speed can be controlled at any time)	8.83 %
low system weight	8.42 %
possibility to transmit high torques	8.17 %
reversible power flow	7.25 %
possibility to operate at high speeds (21000 RPM)	6.58 %
high amount of gear ratios/continuously variable	6.50 %
controllability (possibility to compensate disturbances quickly)	6.50 %
form (positive) fit	6.42 %
high overall gear ratio	6.42 %
high system efficiency	6.08 %
high accuracy of gear ratio	3.25 %
low available space	3.25 %
simple structure (complexity)	2.25 %
less maintenance requirements	1.66 %
Sum	100.00 %

Table 3.4. *Weighting of the evaluation parameters (requirements from the rotorcraft) for the transmission system selection*

The rated evaluation parameters were used for the usability analysis of the different transmission systems. Four rating factors were defined for evaluating every transmission system with every evaluation parameter. It should be identified if the gearbox technology is best (factor 1.00), good (factor 0.66), less applicable (factor 0.33) or in the worst case not suitable (factor 0.00) for the evaluation parameter. The results are displayed in Table 3.5. The investigation showed that power split transmission systems are most suitable for rotorcraft rotor speed variation. Therefore, this type of transmission system is further investigated.

Transmission System	**usability**
Discrete Transmission Ratio Variation	
Automated Manual Transmissions	72.5 %
Double Clutch Transmissions	71.8 %
Shiftable Planetary Gearboxes	70.4 %
Continuous Transmission Ratio Variation	
Hydraulic Automatic Transmissions	66.9 %
Belt Transmissions	52.9 %
Link-Plate Chain Transmissions	50.2 %
Toroidal CVT (friction based)	39.5 %
Electric	72.0 %
Hydrodynamic	41.0 %
Hydrostatic	58.4 %
Power Split Transmission Ratio Variation	
Mechanical Power Split	82.8 %
Electrical Power Split	92.2 %
Hydrodynamic Power Split	83.4 %
Hydrostatic Power Split	92.2 %

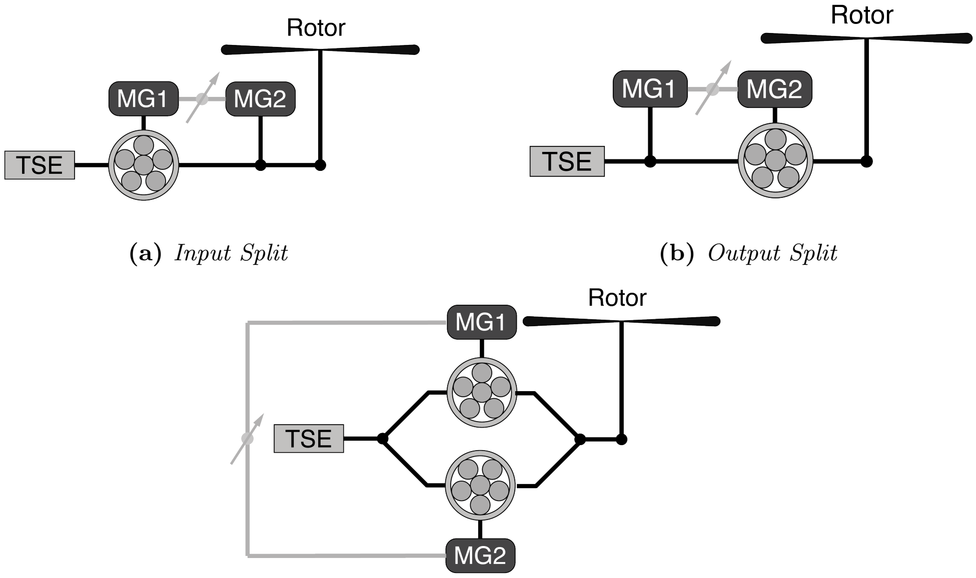
Table 3.5. *Investigated transmission systems with the value of usability in rotorcraft*

3.5.2 Power Split Transmissions in Rotorcraft

Fixed ratio gear transmission has a high efficiency while continuously-variable transmissions - such as hydrostatic or electric engines - offer an output shaft speed variation with lower efficiency. To achieve a continuous-variable transmission system with high efficiency it is necessary to split the input power, provided by the thermal engine, into a mechanical path with high efficiency and a variation path with the opportunity to change the RPM. This is possible by using epicyclic gears which are also called planetary gears. An epicyclic gear set has two kinematic degrees of freedom, i.e., the rotational speeds of two shafts can be varied independently, and the third one is determined by them.

Every power split transmission of this kind has at least one mechanical point (MP) which denotes a transmission ratio at which the total propulsion power is transmitted via the mechanical path. Therefore, this is a highly efficient operation condition. A transmission ratio apart from the mechanical point requires a power flow in the variation path. Because the variation path is less efficient than the mechanical it is important to minimize the required power flow in the variation path to reach a defined offset of the mechanical point.

There are three basic power split transmission system configurations with planetary gears possible: the input split transmission system, the output split transmission system and the compound split transmission system. A schematic of the three types is given in Figure 3.7.



(a) *Input Split* **(b)** *Output Split* **(c)** *Compound Split*

Figure 3.7. *The three basic power split configurations*

Input Split Transmission System: (Figure 3.7 a) The power from the turboshaft engine is transferred with constant RPM to the planetary gear set. There it is divided into two parts. One, the mechanical part flows directly to the rotor. The second is transferred in the motor-generator 1 (MG1) and converted to an other power form, e.g. electric power. Then the variation element, e.g. a frequency transformer, changes the characteristic of the power flow. The motor-generator 2 (MG2) transfers the power back to mechanical power and feeds it via a gear pair to the rotor shaft. Depending on the RPM and power of MG1 the speed of the rotor shaft changes while the RPM of the turboshaft engine stays constant. This type of power split has one mechanical point (MP).

Output Split Transmission System: (Figure 3.7 b) A portion of power from the turboshaft engine (TSE) is taken via a gear pair from the motor-generator 1 (MG1). The rest of the power is transferred at constant RPM to the planetary gear set. Between MG1 and MG2 the power is converted twice and MG2 feeds the power back into the system at one shaft of the planetary gear set. Depending on the power and RPM of MG2 the speed of the rotor shaft changes while the RPM of the turboshaft engine remains constant. This type of power split also has one mechanical point (MP).

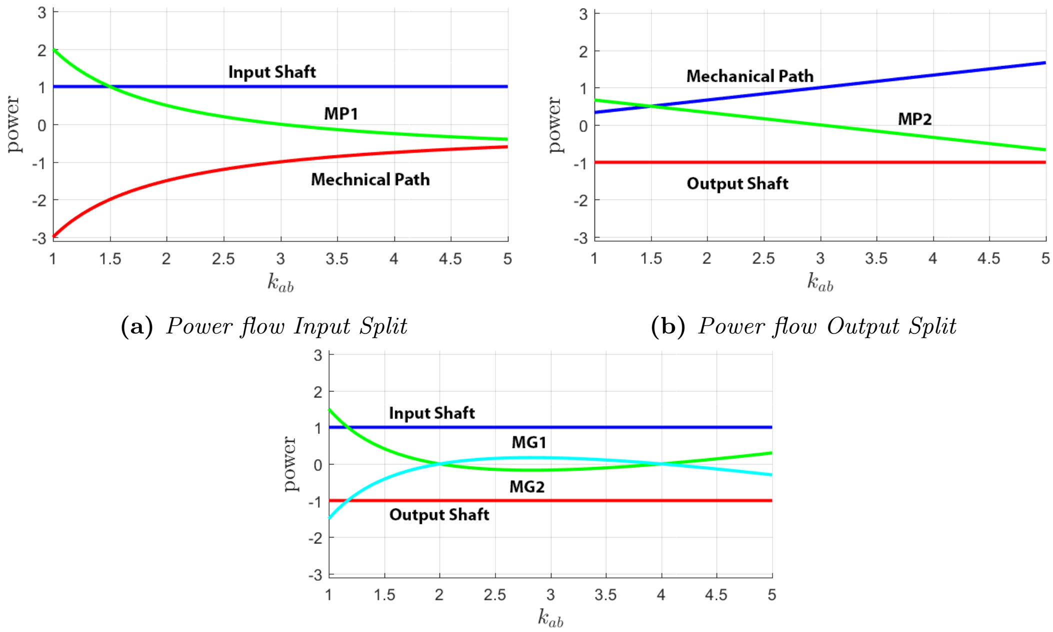
Compound Split Transmission System: (Figure 3.7 c) The compound split transmission system can be seen as a combination of the input and output split transmission system. The power from the turboshaft engine is split into two mechanical paths. On each path there is a planetary gear set. One shaft of each planetary gear set is connected with the rotor shaft. The third shaft of the planetary gear sets is connected via MG1 and MG2 to the variation path. The compound split transmission system also has only two degrees of freedom because of the connections of the shafts. In this configuration there are two mechanical points due to the two epicyclic gear sets.

Figure 3.8 shows the power flow in the different shafts of the planetary gear sets depending on the transmission ratio. The mechanical point for the input speed and the output speed is set at a transmission ratio of three. The variation range should be from two to four. Therefore, the mechanical points of the compound split are at these transmission ratios.

For the input split (Figure 3.8 a) it can be seen that a reduction of the transmission ratio leads to a reactive power flow in the variation path. Therefore, this type should only be used to increase the transmission ratio. This means the mechanical point should be at a transmission ratio of two.

The opposite characteristic can be seen for the output split (Figure 3.8 b). Only a decrease of the transmission ratio is possible there without a reactive power flow in the variation path. This means the mechanical point should be at a transmission ratio of four.

In the compound split (Figure 3.8 c) there is no reactive power flow between the two mechanical points. Every transmission ratio between the mechanical points can reached. Therefore, the mechanical points are at the right place.



(a) *Power flow Input Split*

(b) *Power flow Output Split*

(c) *Power flow Compound Split*

Figure 3.8. *Comparison of the power flow in the of the power split transmission systems configurations*

The maximum power flow in the variation path is an important factor when comparing transmission variable power split systems due to the lower efficiency in this part. The maximal power flow in the input split is 66% for the given configuration. It can be decreased to 50% when the mechanical point is at a transmission ratio of two. The output split has a maximal power flow in the variation path of 75% in the given configuration and it can be decreased to 50% if the mechanical point is at a transmission ratio of four. The compound split has a maximum power flow of 17% in the given configuration.

The compound split transmission system has the lowest power flow in the variation path. Furthermore, it has its mechanical points at both ends of the variation range. If it is used in a rotorcraft, one mechanical point can be used for hover and the other for fast forward flight. High speed rotorcraft will operate most of the time in or close to these two points. This enables a highly efficient power transmission for most of the time.

3.5.3 Failure Mode Effects Analysis

A major topic in aerospace applications is safety when a new technology is introduced, especially in drivetrain applications. Therefore, a functional Failure Mode and Effects Analysis (FMEA) in accordance with to SAE ARP4761 [33] was performed for the compound split transmission system.

Four functions were defined for the compound split transmission system for an electric variation path and also four functions for the compound split with hydrostatic variation path. The four functions are:

- electric motor / hydraulic motor
- electric generator / hydraulic Pump
- epicyclic gear set 1
- epicyclic gear set 2

The analysis showed that 24 functional ***failure modes*** are possible within the variation path. The modes can be reduced to one of the three following failure cases:

- total loss of an output quantity
- low value of an output quantity
- high value of an output quantity

For the epicyclic gear sets the following five ***failure modes*** are possible:

- driving shaft gets stuck
- driven shaft gets stuck
- variation path shaft gets stuck
- breakage of any shaft
- gear set gets stuck

The defined failure modes can lead to the following ***failure effects***:

1. limited power transfer
   In this *Major Failure* effect the power transfer in the variation path is limited but the rotorcraft can still be operated as the main power flow is on the mechanical path.

2. no power transfer
   In this *Catastrophic Failure* effect there is a cut-off of the power transfer from the turboshaft engine to the rotor. The main rotor can rotate free and there is no torque transfer in the system.

3. no power transfer and damage on the drivetrain
   In this *Catastrophic Failure* effect there is a cut-off of the power transfer from the turboshaft engine to the rotor. However, in this case there is no transfer of rotational speed possible. The main rotor and the turboshaft engine cannot rotate freely which leads to an additional damage in the drivetrain.

4. poor efficiency
   This *Minor Failure* effect decreases the efficiency of the variator path but has no influence on the functionality of the compound split.

5. fixed transmission ratio
   In this *Major Failure* effect, the Compound Split loses its ability to change the transmission ratio from the turboshaft engine to the rotor.

Different ***compensation actions*** were defined to reduce the criticality of the failure modes.

1. overrunning clutch
   An overrunning clutch mounted at the variation path shaft enables a power transmission from or to the variation path, but in the case of no torque from the variation path at the shaft the overrunning clutch locks the shaft and the power flow from the turboshaft engine to the rotor is possible with a fixed transmission ratio. With this action it is possible to reduce all failure effects within the variation path to at least minor effects.
2. clutch system
   The clutch system enables the separation of one epicyclic gear set from the main power flow. In this case the whole power is transferred via the other epicyclic gear set with a constant transmission ratio. With this action it is possible to reduce the failure effects of the epicyclic gear sets from catastrophic to major.

3.5.4 Conclusion

The investigation could show that continuously-variable transmission for rotorcraft can be realised with the Compound Split gearbox configuration. The Compound Split offers a high efficiency because of the low power flow via the variation path. Using Compound Split architectures in rotorcraft is an additional risk but it could be shown that the risks of these new failures are low and that there are countermeasures to negate these risks.

3.6 Publication 5

Mass and Kinematic Analysis of Compound Split with Simulation of the Shifting Process for Variable Rotor Speed

The research described in this paper focuses on the applicability of compound split transmission systems in rotorcraft and their possible design variations. A classification of the different constructive solutions with a kinematic modelling method and a mass estimation model is presented. The shifting process of a compound split and its effects on the drivetrain is simulated and compared to a double clutch transmission and a CVT.

3.6.1 Kinematic Analysis

The structure of a compound split is given in Figure 3.9. The mechanical part of a compound split transmission system consists of two planetary gear sets (PGS I and PGS II). Two shafts of the planetary gear sets are connected with each other (A_I & A_{II} and B_I & B_{II}) in two nodes (Node 1 and Node 3). There are two rotational degrees of freedom and two torsional degrees of freedom. There are four shafts for connections (1-4). It is possible to connect the turboshaft engine, the rotor shaft and the two variator engines on each shaft. This enables eight kinematic design possibilities. Four of them are independent of each other (variant A, B, C, D). The other four are a change of the assignment of the mechanical points to the planetary gear sets (variant 1 and 2).

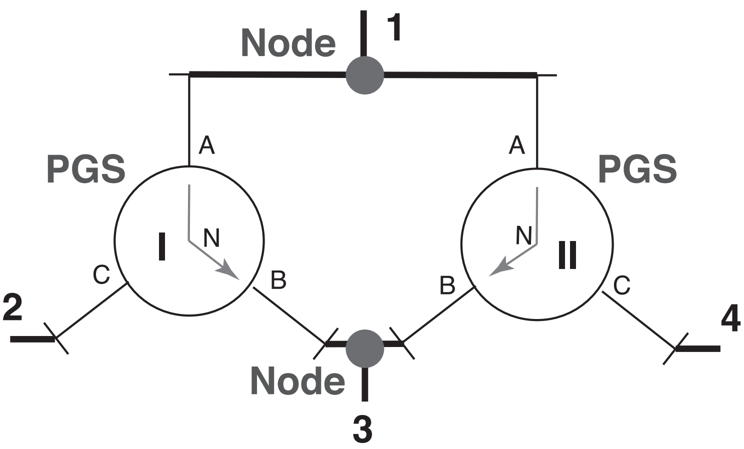


Figure 3.9. *Kinematic diagram of a compound split transmission system*

The assignment of the three shafts of each planetary gear set to the shafts A, B and C is determined by the value of N_I respectively N_{II}. Due to the kinematic scheme, it is possible to also analyse the constructive assignment of the shafts of the planetary gear sets without changing the mathematical system.

A compound split consists of 4 different kinematic elements, two nodes and two planetary gear sets. At the nodes, the sum of the torque must be zero (Equation 3.1 for node 1 and Equation 3.2 for node 3) and the speed of the shafts must be equal (Equation 3.3 for node 1 and Equation for 3.4 node 3).

$$M_1 + M_{I_A} + M_{II_A} = 0 \tag{3.1}$$

$$M_3 + M_{I_B} + M_{II_B} = 0 \tag{3.2}$$

$$\omega_1 = \omega_{I_A} = \omega_{II_A} \tag{3.3}$$

$$\omega_3 = \omega_{I_B} = \omega_{II_B} \tag{3.4}$$

For the planetary gear sets the transmission ratio N defines the relationship of the rotational speed (Equation 3.5) and the relationship of the torques (Equation 3.7) under the consideration of the torque equilibrium (Equation 3.6) in a planetary gear set. N is the transmission ratio from shaft A to shaft B when shaft C is not rotating. N is called stationary transmission ratio.

$$N = \frac{\omega_A - \omega_C}{\omega_B - \omega_C} \tag{3.5}$$

$$M_C + M_A + M_B = 0 \tag{3.6}$$

$$-N = \frac{M_B}{M_A} \tag{3.7}$$

For the analysis it is assumed that the system is in equilibrium without any accelerations. Therefore, the input power of a turboshaft engine (P_{in}) to the compound split is equal to the output power to the rotor (P_{out}) (Equation 3.8). There is no power storage in the variation path. Therefore, the power of the variator generator has to be equal to the power of the variator motor (Equation 3.9).

$$P_{in} = P_{out} \tag{3.8}$$

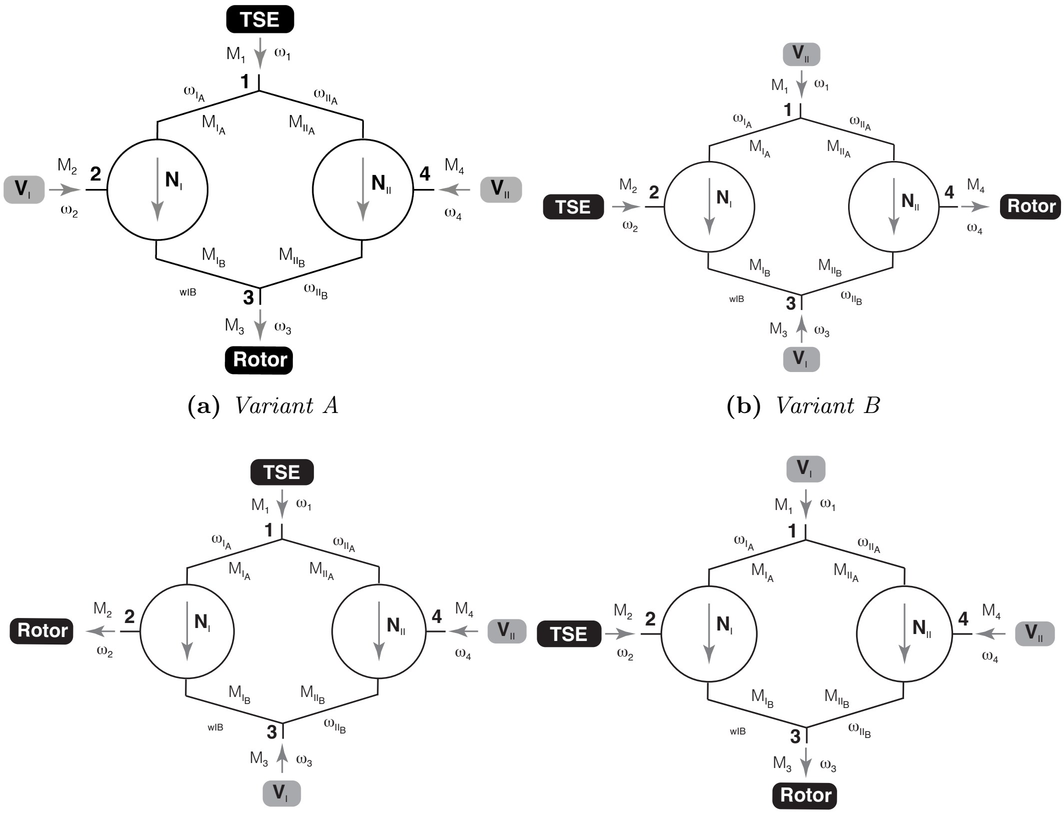
$$P_{V_I} = P_{V_{II}} \tag{3.9}$$

The operation conditions are defined as follows: The compound split reduces the rotational speed from the input shaft to the output shaft and varies this reduction. The lowest reduction, or transmission ratio, is called basic transmission ratio i_B where the rotor rotates at its highest speed. The ratio between the highest rotor speed and the lowest rotor speed is called the variation range φ. A compound split can vary the transmission ratio between its two mechanical points. This means that one mechanical point enables the transmission ratio of i_B (Equation 3.10) and the other mechanical point has the transmission ratio of $i_B \cdot \varphi$ (Equation 3.11).

$$MP_I : \frac{\omega_{in}}{\omega_{out}} = i_B \tag{3.10}$$

$$MP_{II} : \frac{\omega_{in}}{\omega_{out}} = i_B \cdot \varphi \tag{3.11}$$

The different compound split variants are presented in Figure 3.10. The investigation showed that variant A1 and A2 are identical because of the symmetric arrangement. The same holds for variant B1 and B2. In variant C there is a difference between two possible assignments of the mechanical points to the planetary gear sets. If the second mechanical point (MP_{II}) is assigned to the first planetary gear set (PGS_I) then idle power accrues. Also, in Variant D there is a difference in the two possible arrangements.



(a) *Variant A* **(b)** *Variant B*

(c) *Variant C* **(d)** *Variant D*

Figure 3.10. *The four basic compound split variants. Variant 1 and 2 of each variant can only be distinguished by the definition of the mechanical point and so by N.*

First the power flow in the variation path was investigated. Computing the Equations 3.1 to 3.9 shows that the power flow in the variation path depends only on the actual transmission ratio i, the basic transmission ratio i_B and the variation range φ (Equation 3.11). These are only boundary conditions and therefore the same for all variants of compound splits.

$$\frac{P_{V_I}}{P_{in}} = \frac{(i - i_B \cdot \varphi) \cdot (i_B - i)}{i \cdot i_B \cdot (\varphi - 1)} \tag{3.12}$$

Next, the fixed carrier train ratio of the planetary gear sets was under investigation. This is an important design factor of planetary gears. Computing the Equations 3.1 to 3.11 for all eight kinematic compound split variants showed that the stationary transmission ratio N is different for the different compound split variants. N has an influence on the fixed carrier train ratio and therefore on the design and the mass of the planetary gear sets.

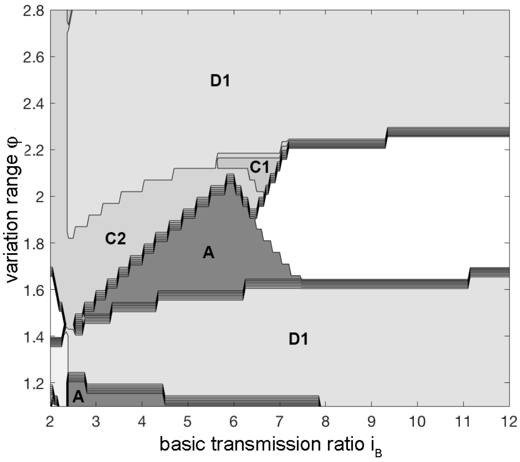
3.6.2 Mass Calculation

The mass of a planetary gear set depends on its strength and the loads which act on it. Therefore, the design and calculation rules of ISO 6336 [15] were used for calculating the surface durability and the tooth bending strength. The gears were estimated as cylinders.

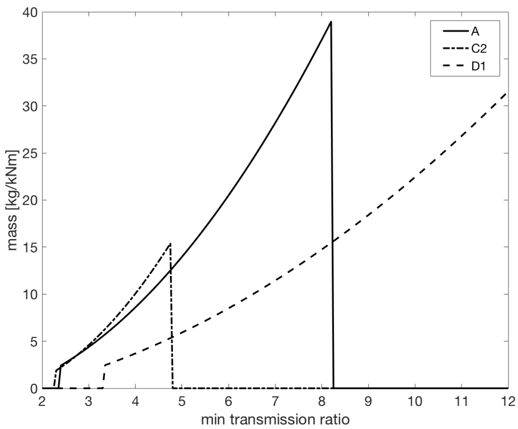
With the density of steel of 7850 $^{\text{kg}}/_{\text{m}^3}$ the mass could be calculated. The calculations of mass depend on the input torque of the planetary gear set and the fixed carrier ratio.

With the knowledge of the calculation of mass of one planetary gear set and the results of the kinematic analysis it was possible to compute the mass of a compound split configuration depending on the basic transmission ratio i_B and the transmission ratio variation ϕ.

Rotorcraft need a speed variation range of about $\varphi \sim 1.5$ according to the mission calculation in publication 2. The absolute value of the basic transmission ratio should be higher than one $|i_B| > 1$ because the turbine speed is higher than the rotor speed. An additional transmission stage is necessary if the basic transmission ratio is smaller than one. Figure 3.11a shows which variant has the lowest mass. D1 is the dominating variant, but there is an area in which A and C2 are better than D1.



(a) *Variant with the lowest mass*



(b) *Mass of variant at* $\phi = 1.5$

Figure 3.11. *Investigation of mass of the different variants. Figure a shows the variant with the lowest mass depending on* i_B *and* ϕ*. Figure b shows the mass trend for different variants at* $\phi = 1.5$

Figure 3.11b is a cross section through the area in Figure 3.11a at a variation range of $\phi = 1.5$ to illustrate how the mass behaves with variation of the basic transmission ratio i_B. C2 is the first possible variant at a basic transmission ratio of 2.25 and the mass increases with an increasing basic transmission ratio. Variant A starts at a basic transmission ratio of 2.4 but is heavier than C2 until 2.8. Its mass also increases with an increasing basic transmission. At a basic transmission ratio of 3.3 variant D1 is possible. Its weight is far less than A and C2 at this point. The mass is more or less equal than C2 at 2.25. As a higher transmission ratio is more suitable for rotorcraft transmissions, D1 is the preferable variant at a basic transmission ratio of 3.5. Higher basic transmission ratios for D1 adds no additional benefits because an ordinary planetary gear stage has a better mass to torque ratio than any compound split.

3.6.3 Shifting Process

The chosen compound split transmission system can vary the transmission ratio continuously using two machines in the variation path or discrete as a two-speed transmission with the transmission ratio of the mechanical points using clutches and breaks in the variation path.

An investigation of the shifting process was initiated to understand the different behaviour of the compound split. Therefore, the whole drivetrain, including the turboshaft engine and the rotor, of the UH-60A black Hawk was mapped in the simulation. The rotor was mapped based on the blade element theory with one blade element in hover. A controller was defined which holds the rotor thrust constant in every operation condition. The turboshaft engine model from the second publication was used for the simulation.

Three different types of transmission variable systems were used in the drivetrain. One was a classic CVT system which represents the continuous variation of transmission ratio in the compound split. The second system was the compound split with two brakes on each shaft of the variation path. The third variant was a double clutch transmission system known from the automotive industry.

The simulation showed that the transition from one rotor speed to the other causes high loads on the whole drivetrain when a two-speed transmission is used. The turboshaft engine cannot run at its designed speed during the shifting process. This is caused by the short shifting times of 0.04 seconds under full load. This short time is necessary because of the friction energy in the brakes. The simulation showed that there is less friction energy in the brakes of the compound split than in the double clutch transmission system. With a CVT system a smooth transition between the two speeds is possible and no friction energy occurs. Therefore, this system should be preferred.

3.6.4 Conclusion

It could be shown that all eight compound split variations have the same power flow in the variation path and the power flow depends only on the variation range φ. Compound split variations can be distinguished by the fixed carrier ratio of their planetary gear sets and this has an influence on the mass. Every compound split configuration can have the best mass to torque ratio depending on the basic transmission ratio and the variation range but variant D1 seems to be the best to be used in rotorcraft for speed variation.

A compound split can be used as continuous-variable transmission or as two-speed transmission. Less torque and less friction work occur at the clutches of a two-speed compound split transmission system than on a comparable double clutch transmission. A continuous variation of the transmission ratio in the compound split systems has no friction work and enables a smooth transition between different rotor speeds. Therefore, this seems to be the most suitable variant for the investigated case.

Chapter 4

Concluding Remarks

Fist Aim: The investigation presented in this thesis showed that rotor speed variation for a rotorcraft can gain benefits in efficiency and can increase the flight envelope. These results are well prooven nowadays for example by Mistè [25] and NASA [22].

Second Aim: The comparison of different possibilities of rotor speed variation showed that the variation can be conducted in the transmission system or in the turboshaft engine. A full hybrid electric drivetrain is too heavy to be used in rotorcraft. This result was proofed by Mercier et. al. [24]. Rotor based concepts like the Derschmidt [9] rotor do not work [17].

Rotor speed variation by changing turboshaft engine RPM is a lightweight solution. The weight of the turboshaft increases by only about 5% and there is no complicated drivetrain needed. A drawback is the torque increase in the whole drivetrain when the RPM is decreased. The whole transmission system has to be designed according to the high torque. Also, the auxiliary units have to be designed to variable speed. This increases the weight of the drivetrain further. All rotor speeds of a rotorcraft can only be varied simultaneously. This is not the best option for rotorcraft - especially for main and tail rotor configurations because the optimum tail rotor speed is counter proportional to the main rotor speed. Miste [25] investigated the possibility of rotor speed variation with the turboshaft engine. He concluded that optimum drivetrain speed is not the optimum rotor speed. The reason therefore is a decrease in the turboshaft engine efficiency in a off-design point operation. This means that the full potential of the rotor speed variation could not be used.

The investigation of different transmission ratio variable gearbox concepts, such as Moore's helicopter transmission system [28] or Ais' two-speed transmission system with smooth shifting process [2], showed that these inventions are not suitable for high torque and low speed regions. Therefore, they cannot be used in the investigated application.

Third Aim: To analyse the potential of rotor speed variation in the context of missions with respect to the possible transmission systems offered additional information. It could be seen that high speed rotorcraft configurations benefit from two different rotor speeds. This is in line with the heavy lift rotorcraft systems investigation from NASA [20].

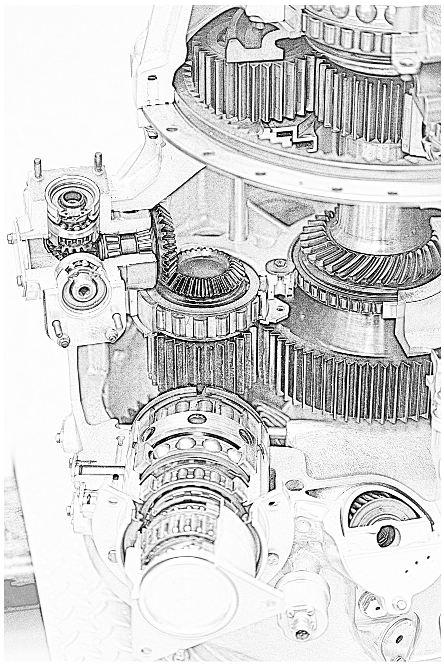
Utility rotorcraft, especially main and tail rotor configurations can gain additional benefits from continuous rotor speed variation. This is in contrast to the investigation of Miste [26]. He concluded that continuous transmission ratio variation and fixed ratio transmission do not have significant performance differences. The reason therefore could be that continuous transmission ratio variable systems gain the additional benefits not within one mission but if more than one mission is taken into account. The results presented in this thesis showed that for the UH-60A a rotor speed variation of 20% is sufficient for each single mission. In total, over the simulated three missions, there is a rotor speed variation range of 36% is needed.

Fourth Aim: A closer investigation of transmission ratio variable gearbox systems showed that power split systems can best meet the requirements from rotorcraft. There are three basic power split concepts, input split, output split and compound split. The compound split has the lowest power flow in the variation path. This is an important indicator for the efficiency of the transmission system.

The compound spilt was investigated according to additional risks in the rotorcraft drivetrain. The FMEA showed that all additional risks can be negated with compensation activities.

There are four kinematic different compound split configurations possible. A mass and kinematic analysis showed that all these configurations have the same power flow in the variation path but the planetary gear sets have different fixed carrier ratios for the same boundary conditions. Therefore, the compound split configurations can be distinguished by the mass depending on the basic transmission ratio and the transmission variation range.

The simulation of the shifting process showed that in principle a two-speed transmission system and a continuous-variable system are possible. A two-speed compound split has less friction energy in the clutches than a double clutch transmission. The shifting process in a two-speed variant leads to high loads in the whole transmission system and in the turboshaft engine. Using a continuous-variable compound split system enables full speed control during the shifting process and a smooth transition between the different speeds.



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Appendix

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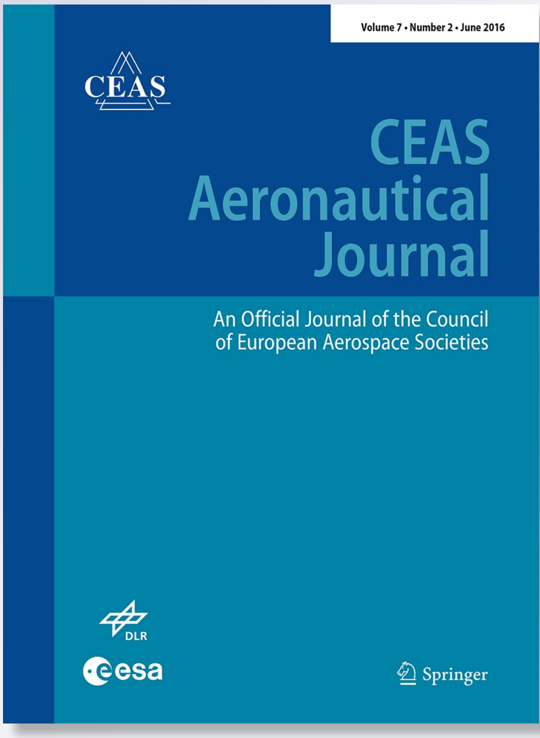

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ORIGINAL PAPER

Possibilities and difficulties for rotorcraft using variable transmission drive trains

H. Amri[1] · R. Feil[2] · M. Hajek[2] · M. Weigand[1]

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Abstract This publication shows advantages and possible applications for variable transmission drivetrains within rotorcraft. The power requirement of a generic helicopter with constant and variable rotor speed was calculated. Various drive train technologies that support a variable transmission were described. The prospects of this technology, its influence on the dynamic behaviour of a rotor and further areas that need to be investigated extensively are presented. This technology is applicable to some rotorcraft architecture. Requests from the rotorcraft industry underline the necessity for future rotorcraft using variable rotational speeds. However, the A160 or the EC145 and Mi-8 already show the potential of this technique. Reduction of required power of the rotor should be possible and also an extension of the flight envelope towards higher flight speeds, higher altitudes, better manoeuvrability, etc. By using a variable transmission gearbox, turbine and auxiliary units can still be driven at their design point, independent of the current rotor speed. Excessive loads may occur when discrete speed transmission are used. Frictional or fluid transmissions with continuous variable ratio may fail due to overheating. Other continuous concepts are favoured. The design of a variable speed rotor focuses specifically on its dynamic behaviours and on structural and geometrical optimisation to avoid operation at rotational speed resonance frequencies. Morphing structures may support this. Some rotorcraft architectures can benefit from a variable speed rotor technology. It probably will increase efficiency, decrease noise levels, fuel consumption and CO_2 production, and the flight envelope may be extended.

Keywords Variable speed rotor · Variable transmission drivetrain · Power optimisation · Economic rotor craft · Flight envelope extension · Future technology

This paper is based on a presentation at the German Aerospace Congress, September 16–18, 2014, Augsburg, Germany.

✉ H. Amri
hanns.amri@tuwien.ac.at

[1] Vienna University of Technology-IKL, Getreidemarkt 9, 1060 Vienna, Austria

[2] Technical University of Munich-HT, Boltzmannstr. 15, 85748 Garching, Germany

1 Introduction

Current research indicates the necessity for variable speed rotor technologies in future rotorcraft. However, there are questions that are yet to be addressed. For example: (1) How much can performance be increased? and (2) How can such a system be realised according to the requirements and needs of a modern rotorcraft? This paper summarises *the state of the art* and performs preliminary analyses to address these questions.

1.1 Hummingbird

Boeing's A160 Hummingbird is a good example of how the efficiency and the flight envelope of a rotorcraft can be influenced by varying the rotor speed using two gears. The unmanned air vehicle is shown in Fig. 1. In May 2008 the A160 set a new record in endurance flight in its class. The vehicle was airborne for 18.7 h [1]. This performance was accomplished ability to shift to another gear and by specially constructed rotor blades that support two rotor speeds by avoiding critical rotor dynamical behaviour in this special case. The dynamical behaviour of a rotor using different RPM is still problematic. The rotor and the blades

Fig. 1 Boeing A160 Hummingbird [US Army: Boeing A160 Hummingbird (2001)]

were designed according to the invention, called "Optimum Speed Rotor Technology", proposed by Karem [2]. Karem invented a method of designing radially extending light and stiff blades which can be operated at different RPM.

1.2 Variable RPM turbine

Airbus Helicopters invented a so-called VATROMS (Variable rotor speed and torque matching system) for the helicopter BK117-C2, also called EC145 or H145 (given in Fig. 2). It is a control system regulating the driving speed of the turbine. The system controls the rotor speed, based on air density and flight speed. Furthermore, the torques delivered by the two turbines are balanced. The goal was to improve handling qualities and reduce noise, especially in urban areas. A speed range of 96.5–103.5 % of the nominal RPM was shown to be possible [3].

The Mi-8 helicopter class and its modifications also use such a system [4].

1.3 Electric tail rotor

Eurocopter Deutschland GmbH (now Airbus Helicopters) invented a special type of an electrically driven tail rotor or better say fenestron for helicopters [5]. There is a housing around the tail rotor and at least one, or preferably two, permanent magnet energised synchronous engines are used for impellent. The synchronous engine is integrated as a torus around an opening of the housing. The blades of the tail rotor are fixed to a rotating component of the engine. The blade pitch control means are provided at the torus. The design ensures that the rotational speed of the rotor can be changed according to the current flight situation and requirement of tail rotor thrust. Additionally, the pitch of the rotor blades can be adjusted. A highly efficient tail rotor system is obtained due to the combination of pitch and speed control. The power supply and control of the system is not part of the invention.

Fig. 2 H145 [©Airbus Helicopters (Carl Ockier)]

1.4 Heavy lift rotorcraft systems

The National Aeronautic and Space Administration (NASA) initiated the "Heavy Lift Rotorcraft System Investigation" [6] programme in 2005. This study investigated different rotorcraft configurations for passenger transport in short and middle range flights. Three concepts were investigated. One was a "Large Advancing Blade Concept" that used a co-axial main rotor with additional propellers for propulsion. The second was a "Large Civil Tandem Compound", that was a compound rotorcraft with two main rotors in tandem configuration and additional propellers as well as fixed wings. The third was a "Large Civil Tiltrotor" concept. A sketch is of the rotorcraft is given in Fig. 3. The investigation identified the Large Civil Tiltrotor as the configuration with the best potential to be economically competitive, with the potential for substantial impact on the air transportation system. The design is able to transport 90 passengers within a range of 1850 km with a cruse flight speed of 155 m/s. In this study a variable speed rotor with a speed range of 50 % was required, to reach an economically competitiveness.

Fig. 3 NASAs large civil tiltrotor concept [©NASA Glen Research Center]

1.5 Turbine efficiency

Misté and Benini [7] made a study about turboshaft engine performance for variable speed rotors using fixed or variable ratio transmission systems. The basic idea was to operate the turboshaft engine in the optimum range, independent of the current flight situation. This is only possible by using a variable transmission ratio gearbox. There they showed that a reduction of fuel consumption up to 13 % is possible by using variable ratio transmission system. This number is only valid when the gearbox has no additional weight.

2 Technology consideration

2.1 Modelling

Conventional helicopters produce their lift and propulsion with a main rotor. Main rotor and tail rotor are driven by a turbine with constant speed while power transmission is conducted by a constant transmission gearbox. Using constant rotor speeds during operation requires a less complex blade design for this single design point. Eigenfrequencies and rotor harmonics are separated. This leads to good dynamical behaviour. Eigenfrequencies only cross through harmonics while accelerating the rotor up to its nominal speed. This is usually performed without blade loading, using zero collective and cyclic control. Both lift dL (1) and drag dD (2) of a blade depend on the flow speed at the blade section v, the air density ρ, the chord c of the blade, radial length of the blade section dy and the lift coefficient C_L or the drag coefficient C_D, respectively.

$$\mathrm{d}L = \frac{\rho}{2} v^2 c C_L \mathrm{d}y \tag{1}$$

$$\mathrm{d}D = \frac{\rho}{2} v^2 c C_D \mathrm{d}y \tag{2}$$

A high lift to drag ratio is intended for an efficient blade design (see Fig. 4) [2].

Figure 5 shows the power requirements of a helicopter with various flight speeds. The total rotorcraft power (circle line) consists of induced power (crossed line) (3), parasite power (starline) (4) and profile power (dotted line) (5). These can be calculated as follows [8]:

$$P_i = \kappa \sqrt{\frac{T^3}{2\rho\pi} \frac{1}{R}} \tag{3}$$

$$P_p = \frac{1}{2} \rho V_\infty^3 C_{Dp} A \tag{4}$$

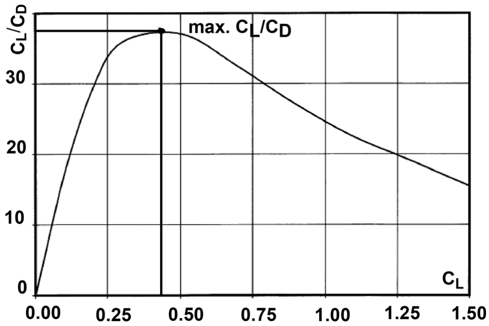

Fig. 4 Lift-over drag coefficient drawn over lift coefficient for a typical rotor blade [2]

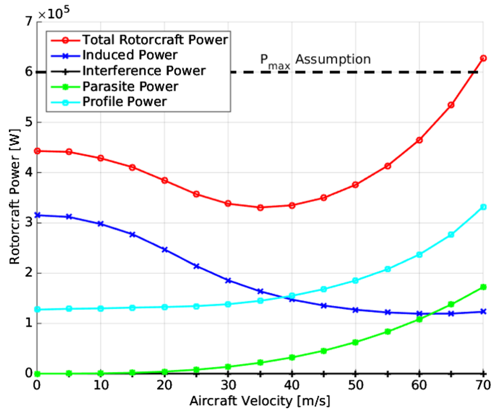

Fig. 5 Power requirements of a helicopter with various flight speeds

$$P_0 = \frac{1}{8} \rho A V_{\mathrm{TIP}}^3 \sigma C_{D0} (1 + 4.65\mu^2) \tag{5}$$

$$\mu = \frac{V_\infty}{V_{\mathrm{TIP}}} \tag{6}$$

where R is the rotor radius, A is the rotor disk area, κ the induced power coefficient, T the rotor thrust, μ the advance ratio of the rotorcraft, $V\infty$ the rotorcraft velocity, V_{TI} the blade tip speed, CDp the drag coefficient of the whole aircraft, C the drag coefficient of blade profile at zero lift and σ the solidity of the rotor. Hover and low speed flight are dominated by the induced power while the parasite power increases significantly with the third power of flight speed. Profile power increases with the third power of the rotational speed. Thus, profile power is highly dependent on rotational speed. Parasite power and profile power dominate high speed flight conditions.

Fig. 6 BO 105 [© Airbus Helicopters (Jay Miller)]

Table 1 Parameters of the generic model

Number of blades (N_B)	4
Radius	4.92 m
Cord	0.2705 m
Airfoil	NACA23012
Weight	2400 kg

The calculations herein were performed by implementing a generic physical model of a helicopter similar to the Bo105 (Fig. 6) in CAMRAD II. Positions and geometries of the generic model were provided along with the required aerodynamic parameters. The parameters of the generic model are given in Table 1. CAMRAD II is an aeromechanical analysis of helicopters and rotorcraft that incorporates a combination of advanced models, including multibody dynamics, nonlinear finite element structural dynamics, and rotorcraft aerodynamics [9]. Nominal rotor rotational speeds are Ω_{main} Rotor = 424 RPM and Ω_{tail} Rotor = 2220 RPM. A NACA23012 was used as an airfoil. Aerodynamic coefficient tables representing the fuselage as well as the vertical and horizontal stabilisers were approximated.

2.2 Gearbox technology

The concept of using a gearbox with variable ratio has been employed since the 1980s by Moore [10]. His invention and some other ideas and inventions are summarised below.

Shifting gears during flight in a rotorcraft is a complex and difficult task, because the transfer of power must be secured while shifting and a speed change of the rotor should not be abrupt. Hence, continuous solutions may be favoured to ensure not only a smooth speed variation but also that the turbine works at its intended design point.

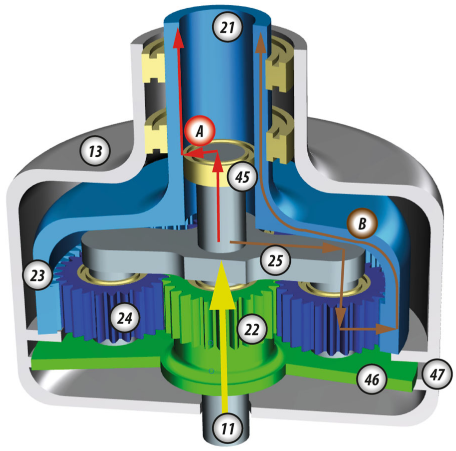

Fig. 7 Sectional view of a model based on Moore's invention

2.2.1 *Helicopter transmission system*

Moore [10] was one of the first researchers to identify the advantages of a variable rotor speed by using a variable transmission gearbox. In 1986, he invented a gearbox with two gear ratios, suitable for helicopters.

The system basically consists of a planetary gear, an overrunning clutch and a break system (see Fig. 7). It receives power form the input shaft 11. The input shaft 11 is connected to the planet carrier 25. The ring gear 23 is connected to the output shaft 21. The output shaft 21 is rotatably mounted within housing 13. The sun gear 22 is rotatably mounted to the input shaft 11 and is connected to the brake ring 46. The hydraulic brakes 47 are mounted in the housing 13.

If the hydraulic brakes 47 are open (A), the sun gear is able to rotate relative to the housing 13. In this case, the planet carrier 25, the ring gear 23 and the sun gear 22 all rotate at the same speed. The power is transmitted from the input shaft 11 by the overrunning clutch 45 to the output shaft 21. The output shaft operates at the same speed as the input shaft.

If the hydraulic brakes 47 are engaged (B), there is no rotation form the sun gear 11 relative to the housing 13. The planetary gears begin to rotate. Therefore, there is relative movement between the sun gear 22 and the planet carrier. This causes relative movement between the ring gear 23 and the planet carrier 25. Due to the configuration, the ring gear 23 rotates at a higher speed than the planet carrier 25 and the input shaft 11. Power is transmitted from the input shaft.

11 to the planet carrier 25 across the planet gears 24 to the ring gear 23 and the output shaft 21. The overrunning clutch 45 does not transmit any power or moment. Consequently, the output shaft 21 runs at a higher speed than the input shaft 11. It is not possible to enable a lower speed than the input speed. This is the main drawback of this invention.

2.2.2 Two speed transmission with smooth power shift

In 2006, Ai invented a system for smooth shifting with high efficiency [11] (see Fig. 8). The system consists of two planetary gears, U1 and U2, which are connected via a common planet carrier 16 and two electric motors, 3 and 4. The power input shaft 7 is connected with the sun gear of the first planetary gear. The output shaft 17 is connected with the sun gear of the second planetary gear. The two planetary gears U1 and U2 are connected via the planetary carriers 16. The ring gears 10 and 13 are equipped with a locking device. The electric units 3 and 4 are also connected with the ring gears 10 and 13. One ring gear is always locked during operation. When there is a request for changing the gear ratio, the locked ring gets unlocked. So both rings are able to rotate. One electric machine decelerates one ring gear. With the energy of deceleration the second electric unit accelerates the second ring gear. When the revolution of the first ring gear is almost zero the ring becomes locked and the other transmission is then used. The change of the transmission ratio is because of different numbers of teeth of the planetary gears.

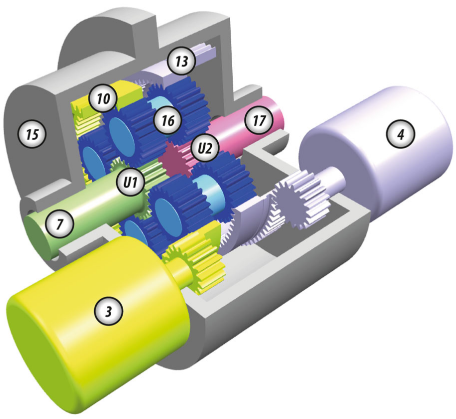

Fig. 8 Sectional view of a model based on Ai's invention

2.2.3 Concepts for variable/multi-speed rotorcraft systems

The outcome of NASAs "Heavy Lift Rotorcraft System" [6] research programme, as mentioned in Sect. 1.4, prompted various research projects related to rotor speed variation, including the project "concepts for variable/multi-speed rotorcraft systems" [12], which was concerned with the identification of multispeed transmission concepts. NASA invented three types of speed variation with two gears and a speed range of up to 50 %. By using a controller unit, these concepts are able to work as a continuously variable transmission. A smooth change of the transmission ratio makes a continuously working gearbox interesting for rotor-craft.

2.2.3.1 Concept 1—inline tow speed planetary The system consists of a planetary gear, an overrunning clutch and a standard clutch. The working principle is similar to the device invented by Moore [10]. The sun gear is connected to the input shaft and the output shaft via the clutch. If the clutch is locked, there is a 1:1 transmission and the overrunning clutch turns free. If the clutch is open, power is transmitted from the sun gear via the still standing planet carrier to the ring gear and then over the overrunning clutch to the output shaft. The transmission ratio in this instance is 2:1. But the direction of revolution would be reversed relative to the first device. To avoid this occurrence, a double planetary system is used. The system is shown in Fig. 9.

2.2.3.2 Concept 2—offset compound gear This concept, given in Fig. 10, is based on an inline two speed planetary system. It uses an offset compound gear instead of the complex double planetary system. The gear on the input shaft, former sun gear, meshes with the ring gear part of the offset compound gear. At the other end, the offset

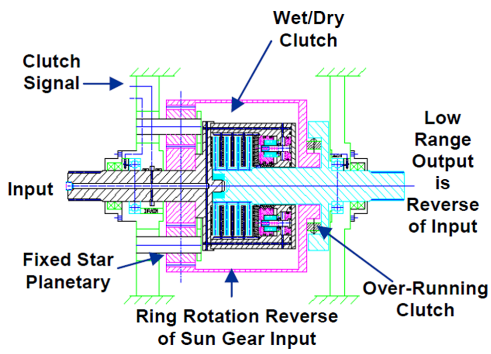

Fig. 9 Inline two speed planetary [©NASA Glen Research Center]

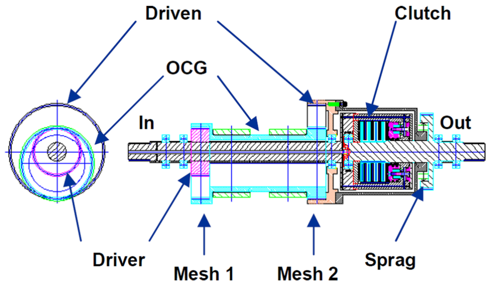

Fig. 10 Offset compound gear [©NASA Glen Research Center]

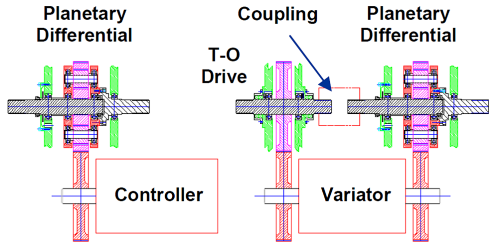

Fig. 11 Planetary differential drive [©NASA Glen Research Center]

compound gear meshes with the ring gear from the former planetary gear system. This system has the ability to have a 1:1 transmission via the input shaft, the clutch and the output shaft or a 2:1 transmission via the gear on the input shaft, the offset compound gear, the ring gear and the overrunning clutch to the output shaft.

2.2.3.3 Concept 3—planetary differential drive This concept consists of a planetary gear and a controller or variator. The input shaft is connected to the sun gear; the output shaft is connected to the planet carrier; and the controller is connected to the ring gear. By changing the speed of the controller, the speed of the output shaft is also changed without altering the speed of the input shaft.

The system also functions with a variator. In this case, there are two planetary gears. The input is connected to the sun gear of the first planetary gear; the planet carrier of the first planet gear is connected to the sun gear of the second planet gear; and the planet carrier of the second planet gear is connected to the output shaft. The ring gear of the first planet gear powers the variator, which changes the speed of the second ring gear and, therefore, forms the output shaft. A drawing is given in Fig. 11.

2.2.4 *Power transmission apparatus for helicopters*

In 1999 the Advanced Technology Institute of Commuter-Helicopter (ATIC) invented a continuous variable transmission system (CVT) that promises to be suitable for main and tail rotors of helicopters [13]. It is called "Power transmission apparatus for helicopter". The CVT system is a roller toroidal transmission combined with planet gears.

Roller toroidal transmissions (see Fig. 12) are friction gears that consist of a driving disc (1) on the input side, a driven disc (2) on the output side and some rolls (3). The rolls are in a concentric circle between the discs and are able to rotate around their axis. The axis (4) of the rolls can be tilted. By tilting the axis the radius between the rolls and the driving disc and the driven disc is changed. Due to this change in the radius, the transmission ratio is altered. This system is frictional and does not provide a positive traction. The background of this invention is a commuter helicopter.

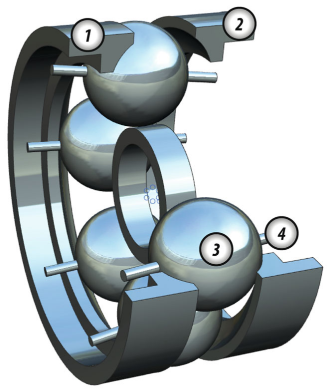

Fig. 12 Principle drawing of a roller toroidal transmission

2.2.5 *Concept study based on NASA concepts*

Based on work performed by NASA, Georgia Institute of Technology developed a high speed rotorcraft design for which a variable speed transmission with a planetary gear system was used [14]. This is a coaxial rotor helicopter with a pusher propeller fan. With variable speed transmission, the conceptually designed helicopter is able to fly 20 m/s faster and can attain a maximum speed of 130 m/s.

2.2.6 *Further inventions*

Another example is the patent of Sikorsky Aircraft Corporation [15]. There are also inventions by Eurocopter [16] and Karem Aircraft [17] that use two or more gear transmissions.

3 Results

3.1 Efficiency

The advantage of drive train with variable rotor speed regulation can be seen in Fig. 13. This figure shows the power requirement for various flight speeds with constant rotor speed (solid line) over the range of velocities, calculated in every given flight state. The calculation results are received using the generic model form chapter 2.1. It includes the rotor dynamics behaviour and trims on targeted flight conditions. The lower line (dashed line) shows the calculated power requirement using an optimal rotor speed in every given flight state. Rotor rotational speed increases with flight speed to account for the increase in lift. Power reduction is a result of reduced profile power. This parameter sensitivity study reveals that a reduction of 23 % of the total rotorcraft power is possible at flight conditions that support maximum flight duration.

The proposed benefit in power must, of course, paid for by additional weight from a variable speed gearbox. Additional weight reduces the payload of the helicopter and therefore reduces the increase in power benefit.

The final power reserve may be used for saving fuel and ecological efficiency. The flight envelope may also be extended, such as flight speed, duration, range and manoeuvrability.

3.2 Flight envelope: Increase of flight speed

This section gives estimates of the reduction in total rotorcraft power due to varying the rotor speed at fast forward flight. A trimmed forward flight with 70 m/s has a total power requirement of 630 kW, shown in Fig. 5. The trimmed rotor thrust (upper) and power (lower) on 7.5° collective pitch is given in Fig. 14. Maximum power available for the main rotor is estimated to be 600 kW. Hence, the flight condition cannot be reached with a nominal rotor speed of 424 RPM (Fig. 13). The power demand for the constant rotor speed is in all given points higher for the constant rotor speed. This is because the results are only for forward flight. Other flight conditions, like climb or manoeuvre flights while not considered here, require that higher RPM value.

The helicopter can be designed for multiple flight conditions but optimised only for one flight condition. Of course all other conditions are not optimal. A variable speed technology would benefit this.

Assuming that a collective pitch of 10° increases the rotor thrust, one can decrease the rotor speed to have the same thrust that is necessary for a flight at 70 m/s. Thrust and rotor speed have a linear correlation (upper graph in Fig. 14) but rotor speed and power have a polynomial (cubic) correlation (lower graph in Fig. 14). In the example given here, the rotor rotational speed is decreased to 82 % of the nominal speed and power is reduced by 40 % for the same output thrust. The profile power of the rotor is reduced by 130 kW and the optimised total rotorcraft power is 500 kW. The variable speed rotor technology allows an operational speed of 70 m/s and creates the potential to fly at even faster forward speeds. Further aspects will be investigated in the future in order to validate that other rotorcraft requirements, such as autorotation characteristics, retreating blade stall and pitch link load limits do not prevent higher speeds.

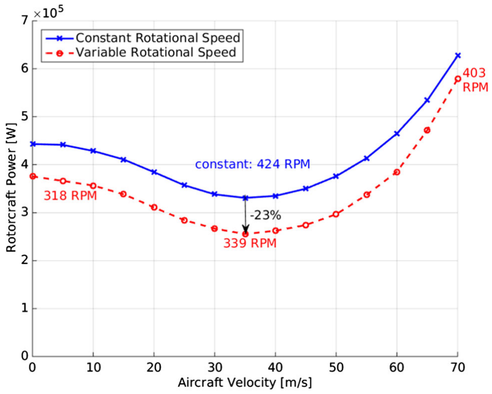

Fig. 13 Power demand with (*dashed line*) and without (*solid line*) variable rotor speed

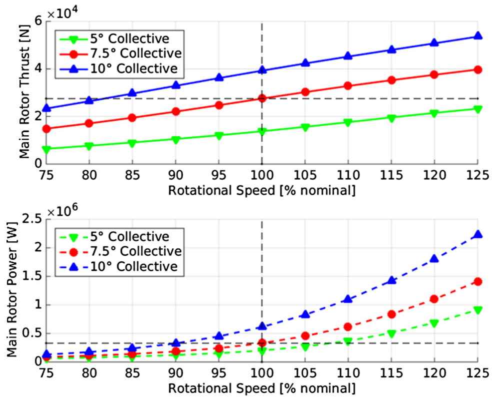

Fig. 14 Thrust and power of the main rotor

3.3 Flight envelope: extension of the ceiling altitude

Considering a main- and tail rotor helicopter configuration, the thrust of the tail rotor can also be variable depending on its rotational speed. Figure 15 shows the requirements of the rotorcraft power, the main rotor torque and the tail rotor thrust while operating at various altitudes. To achieve a trimmed flight condition, the tail rotor thrust must be sufficient to counteract the torque of the main rotor, with the following relationship (7):

$$M_{z,\mathrm{mainRotor}} = T_{\mathrm{TailRotor}} l_{\mathrm{LeverArm}} \tag{7}$$

The lever arm in the chosen model is 5.5 m. The tail rotor has sufficient thrust for a hover ceiling of 4000 m.

The tail rotor is limited to altitudes >4000 m because it cannot provide enough thrust to counteract the torque of the main rotor. Stall limits are reached for a further increase of the collective pitch control of the tail rotor. Here, only the antitorque partition of the tail rotor thrust was analysed. The tail rotor thrust capability must be even higher than the antitorque balance due to the required yaw rate margin.

Extending the flight envelope to higher ceiling requires increased tail rotor thrust. Hence, without affecting the rotor geometry, one can simply increase the rotational speed of the rotor. Figure 16 shows the tail rotor thrust and power for various altitudes and three rotor speeds. Thrust reduction due to lower density in higher altitudes can be controlled by varying the rotational speed. This results in higher ceiling levels for the rotor-craft range of operations. A sufficiently powerful engine supply is assumed as the

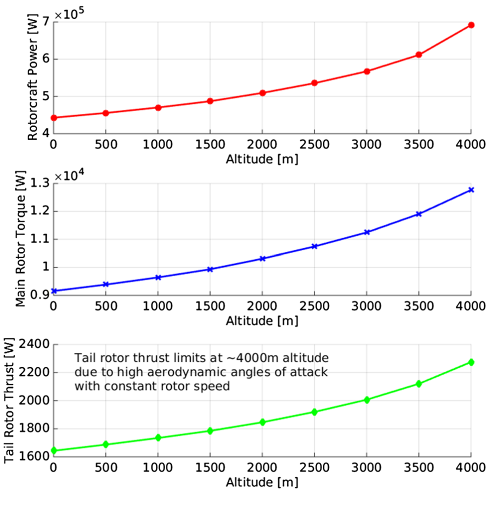

Fig. 15 Hover ceiling altitude limits

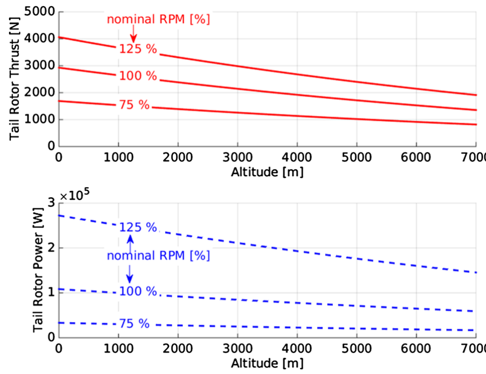

Fig. 16 Thrust and power of the tail rotor

power grows as a cubic function while thrust increases linearly. The conclusion is that the tail rotor, as previously mentioned for the main rotor, can be thrust optimised in accordance with the individual flight state.

3.4 Rotor-dynamic behaviour

The dynamic behaviour of a rotor characterises the vibratory loads of the whole helicopter. Rotor blades are, as a rule, designed so that its flap, lag, and torsional Eigenfrequencies do not match with the rotor harmonics at nominal rotor speed.

Figure 17 shows the frequencies of a stiff-in-plane (1st lag frequency above 1 Ω) rotor blade. Frequencies are mapped with varying rotational speed and rotor harmonics are presented as dashed straight lines. The rotor, which rotates with nominal 7.3 Hz, has its first harmonic 1 Ω at this very frequency, its second 2 Ω at 14.6 Hz, its third 3 Ω

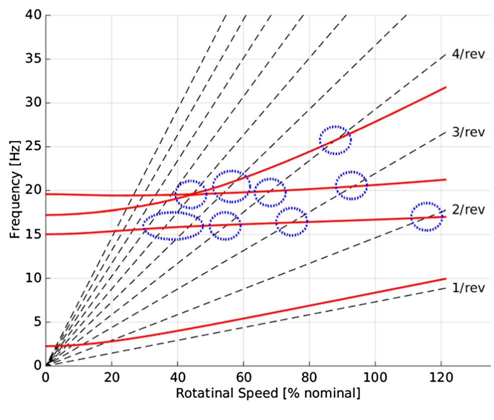

Fig. 17 Frequency diagram

at 21.9 Hz, etc. The progressive rise of lag and particularly flap frequencies is caused by structural stiffening through centrifugal forces. Tuning of blade frequencies is usually performed by varying the structural properties of the blade and by using tuning weights along the blade. It can be safety–critical if any low rotor Eigenfrequency should correspond to a harmonic. Resonance from rotor structure coupling effects can significantly influence the fatigue strength of safety–critical helicopter components. Furthermore, air resonance can also lead to a resonance catastrophe. The $(N_B - 1)\,\Omega$, $N_B\,\Omega$ and $(N_B + 1)\,\Omega$ frequencies are particularly important for the vibrational control in the non-rotating frame. Those vibrational loads can increase significantly, when a resonance occurs. A safety factor of at least ±10 % should be allowed [18]. Based on these requirements, limitations may be expected for the operational use of the technology of variable rotor speeds. An up-to-date and innovative blade design is essential for the safety and the failure performance of the system. Modern materials such as carbon fibres or glass fibres as well as a smart build-up sequence over the blade profile are used in order to develop low vibrating rotor blades. Material and strength characteristics are not fully understood yet. Modern materials will give better effects using mass distribution and form of blade and will therefore also benefit the development of variable speed rotor systems. With respect to tuning of blade frequencies, multiple cases should be differentiated:

The rotor can be calibrated to *a design point* if the intention is to operate with constant rotational speed. Resonances must be avoided.

Operation with *few specific rotational speeds* that are used by shifting gears requires to tune the rotor for multiple design points. Resonances must again be avoided. The rotor will be relieved from loads while shifting between gears. Harmonics are passed through as fast as possible; therefore, the change of gear should be in a flight state with enough power reserve.

The use of continuous gearbox systems offers the possibility to operate with *an arbitrary rotational speed*. As a consequence, the rotor system must be able to be operated with loadings at or close to a rotor harmonic. High vibratory loads must be tolerated. Hence blade design concerning stability and stiffness is essential. Possible solutions may be to use active damping systems or rotational speed controller. Thus, rotational speeds can be changed continuously and dynamic critical areas are avoided by active regulations. The system is dynamically controlled to its lower or higher frequencies in order to avoid the harmonics. An effective and optimised operation can, however, be established over the whole range of flight states. System vibrations are minimised and maintenance costs can be controlled and kept at a minimum.

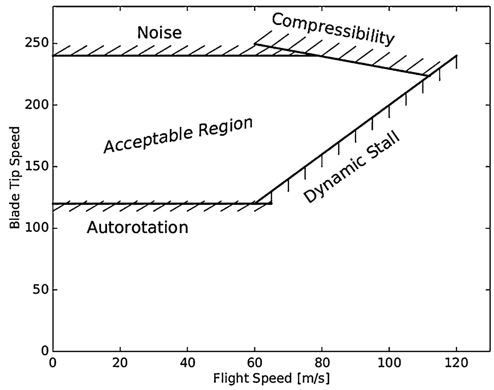

Fig. 18 Limitations of the flight envelope

The variation of rotor speed may be accomplished within the framework of feasibility, certification specifications and compliance with general limitations of the flight envelope (see Fig. 18). A rotational speed that is too low may not comply with the autorotation requirements. A rotational speed that is very high affects noise limits. Compressibility effects may occur in high speed flight condition. To counteract a retreating blade stall, the rotational speed of a rotor must also have a minimum in high speed flight. The aforementioned limits are based on physical requirements as well as on safety and certification standards. Within these limits, one can implement system optimisation with variable speed rotor technologies. Modern materials such as carbon fibres or glass fibres as well as a smart build-up sequences over the blade profile and radial are used to develop low vibrating rotor blades. Material and strength characteristics are not fully understood yet. Modern materials will give better effects using mass distribution and form of blade and will therefore also benefit the development of variable speed rotor systems.

3.5 Gearbox—technology consideration

As described above, there are multiple ways of changing the rotor speed of a rotorcraft. But how do such systems function during flight and what are their disadvantages?

Firstly, gear shifting during flight of a rotorcraft has to be considered. Discontinuous transmissions are designed for single operation points. This is advantageous for the rotor design as there is one design point for every stage of the gearbox. E.g., a two-staged gearbox can be designed on hover and fast forward flight conditions. The mission profile for such a rotor-craft may appear as follows: Take off and hover in the first gear, accelerate and initialise the forward flight in the first gear. At some defined speed, there is a point

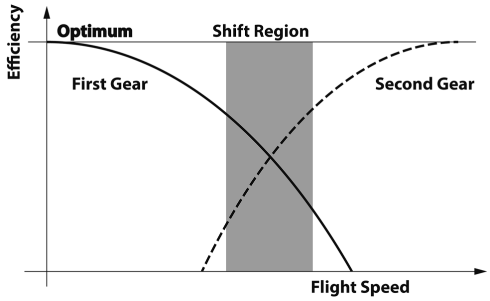

Fig. 19 Gear efficiency over flight speed

where the efficiency of the first gear is less than that in the second gear. The aircraft is then shifted into second gear. The helicopter then accelerates further until the travelling speed is reached and so the design point of the second gear is reached. The process is reversed during deceleration and landing. Figure 19 qualitatively gives the efficiency of a two-stage transmission with varying flight speed.

The graph refers to varying rotor power and therefore varying optimal rotor speed. The minimum is caused by a decreasing demand of induced power from hover to moderate forward flight speed. At high speed, the power is dominated by the parasite and profile drag.

A shift leads to a change of speed and torque on the output shaft. This happens abruptly because one transmission element is engaged and another one is disengaged. The input is on a constant power and speed level. Shocks and vibratory loads affect the whole drive train. In order to avoid system failures, and to reduce vibrations and maintenance costs, it is necessary to enable smooth shifts. Also, for quick changes of flight states as in manoeuvres, a fast change of gear should be supported. This again may lead to shocks and high loading applied to the drive train.

By using a continuously variable transmission the turbine and the rotor can always be driven power optimised. The change of rotor speed can be performed in a smooth way, and it is much more adaptive than a shifting system. Shocks and vibratory loading can be reduced. The question is: how can a continuous variable transmission system be realised?

A disadvantage of frictional solutions is wear. Wear and thermal loading increase during high power flight states and therefore lead to a reduction of the maximal transferable power. This vicious circle continues, and in the worst case can result in total failure of the transmission system. Besides the technical problems, also the certification requirement has to be taken into account.

Electrical transmission systems have to be redundant because of their abrupt damage behaviour. This leads to a weight increase of the transmission system.

The power transmission depends on the viscosity of the fluid for a hydraulic continuous variable transmission. The viscosity of the fluid depends on the temperature of the fluid. The higher the temperature the lower the ability of the fluid to transmit power. The higher the transmitted power, the higher the temperature and the lower the ability of the fluid to transmit the power. This leads to an increase of the temperature. Due to overheating of the hydraulic, the entire transmission system can cease to function properly.

Hence, by using a variable transmission system in rotorcraft new failure scenarios appear, which must be considered carefully and specifications must be chosen accordingly. The efficiency of the rotorcraft increases due to the ability to set the rotor speed according to the current flight conditions. This way the turbine and auxiliaries can also operate in their design point. The required power of the rotor is optimised.

Hence, the additional weight must be considered as well. A variable transmission system is more complex than a single speed gearbox and therefore has an increased weight accordingly. Possible gains due to power optimisation from the rotor are decreased. NASA compared multiple variable speed systems in one of their studies [19]. A two-stage gearbox with variable speed turbines was investigated. This analysis showed that turbines have a good power-to-weight ratio. For their investigation NASA assumed a weight addition of 10 % for a variable transmission gearbox and therefore was the option with the highest weight. The weight penalty for the gearbox is based on different studies from NASA [20]. All systems showed a difference in fuel consumption of only 5 %. The conclusion is that all systems that were compared have potential and a precise analysis is needed for each system.

4 Discussion

Multiple aspects benefit from the use of a variable speed rotor system for rotorcraft. Hence, the technology is needed under extreme conditions and may be an indispensable feature for future rotorcraft configurations. The following points support the necessity of a development of variable speed systems:

- Power efficient operation in arbitrary flight states.
- Fly longer.
- Fly further.
- Fly faster.
- Noise reduction.
- Ecologically efficient. Power optimisation reduces fuel consumption and thereby exhaustion and CO_2 emissions.
- Reduced fuel consumption benefits global resources. Hence, it also reduces operating expenses.

A rotorcraft usually does not work only at its design point. The angle of attack and power demands are set according to the flight state with a constant rotational speed. A variable speed system could reduce the power as well as noise from the blades, especially the blade tip noise emission. Fuel consumption can also be reduced as a matter of reduced power demands [7]. Considering global warming, this is also an ecological issue for future rotorcraft and generally in aerospace technologies. Based on previous considerations, the following fundamental requirements can be used to design a transmission variable gearbox.

4.1 Continuous variable transmission

The transmission ratio should be fitted according to the flight conditions to enable the rotor and the turbine to operate at their optimum operation point. The change of the rotor speed can be performed seamlessly with continuous variable transmissions.

4.2 Minimal possible weight increase

The increasing gearbox weight decreases the efficiency of the rotorcraft. One must ensure that this additional mass is as low as possible because the disadvantage of a weight increase could outweigh any advantage of this design.

4.3 Independent power support of the auxiliary units

The auxiliary units must be driven in their design point and be independent of the current flight situation. An efficient and secure usage must be guaranteed.

4.4 A speed regulation for every rotor

Each rotor, depending on the rotorcraft configuration, should have the possibility to operate at its optimum speed.

4.5 Secure power transmission

The transmission system has to transmit the power securely. System failures must be avoided during the whole design process.

4.6 Efficient system

The transmission system has to be highly efficient. If the efficiency of the transmission system cannot be ensured, the benefit of the speed variation is negligible.

4.7 Certification specification

The system development must be oriented according to the certification specification. The specifications require special tests and checks that must be considered and conducted [CS-29.923(n)] [21].

The results presented above are based on a single main rotor and tail rotor configuration as shown in Fig. 20. The main rotor produces the force for lift and forward flight. It is controlled by the collective and cyclic blade control. The primary function of the tail rotor is to compensate the indicated moment of the main rotor. Furthermore, it is used to control the yaw motion. Based on the certification specifications many modern helicopters use two engines. The power is collected in the main gear box and then separated to the main and tail rotor. Additional auxiliaries are driven by the main gearbox. This must be considered by designing a speed variable configuration.

Figure 21 shows a compound helicopter configuration based on the X^3 demonstrator from Airbus Helicopters that had its first flight in 2010. The helicopter uses a main rotor for lift and it has two additional pulling propellers for horizontal thrust. By using a variable transmission, it is necessary to have an individual control of the propellers and the main rotor. Hence, it is possible to operate the helicopter in a power optimum area and extend the flight envelope.

The given compound configuration has advantages in fast forward flight. By using a variable transmission, it is possible to increase the speed of the propellers to increase the horizontal thrust for forward flight and to decrease the speed of the main rotor. Horizontal wings take over the vertical thrust during forward flight. Supersonic rotor tip speeds can thus be avoided.

This design can only result in an optimum by using variable transmission. The speed variation enables the rotorcraft to be operated power optimised in any flight

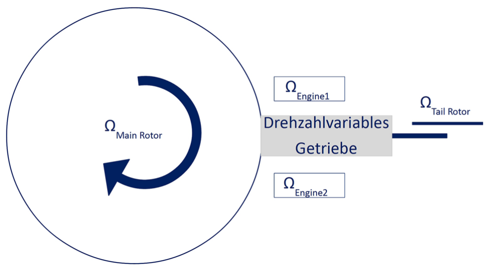

Fig. 20 Schematic of a single rotor configuration

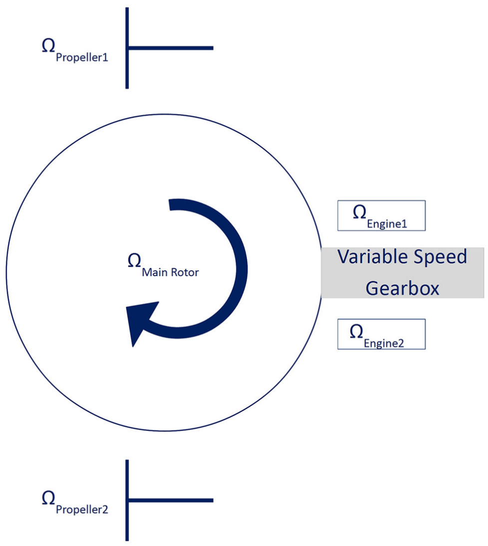

Fig. 21 Schematic of a compound rotor configuration

conditions and to reach higher forward flight speed characteristics.

5 Conclusions

It was shown that advanced research in the variable rotor speed technology may lead to a significant potential for various kinds of rotorcraft architectures. Due to international trends towards more power efficient, ecological and high performance rotorcrafts, it appears to be necessary to use speed variability in modern rotorcraft designs. The technology can be realised by using variable transmission gearboxes. These designs have a high speed range and enable an independent drive for each rotor or auxiliary at optimal turbine speed. Further research and development is needed to design and realise a drive system that complies with these requirements.

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POSSIBLE TECHNOLOGIES FOR A VARIABLE ROTOR SPEED ROTORCRAFT DRIVE TRAIN

H. Amri*[1]
Vienna University
of Technology
Wien, A-1060
Austria

P. Paschinger
Vienna University
of Technology
Wien, A-1060
Austria

M. Weigand
Vienna University
of Technology
Wien, A-1060
Austria

A. Bauernfeind
Vienna University
of Technology
Wien, A-1060
Austria

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Variable rotor speed, variable speed drive train, variable transmission for helicopter, helicopter gearbox transmission

Abstract

This publication shows possible technologies to enable variable rotor speed for rotorcraft. The technologies are divided into four categories: Turbine technology, gearbox technology, electric drive train technology and rotor technology. They were analysed and designed, based on a defined reference configuration. The analysis shows which technologies enable a speed variation, the expected mass increase, the change of efficiency and the possible difficulties in realisation.

Using a turboshaft engine to vary the rotor speed enables wide speed range and adds only about 5% of the turboshaft mass. But due to the possible high torque increase at lower speeds, also the gearbox weight increases. A decrease of maximal available power at lower speed has to be taken into account. The rotor speeds can't be controlled individually and the auxiliary units are influenced by a speed change.

Using a gearbox enables a wide speed range but causes mass increase which is higher, compared to the turbine technology, but not much higher, if the thereby linked gearbox mass increase is taken into account. It is important that the part for transmission variation is not part of the main power flow. To gain most advantages it is necessary to place the gearbox close to the rotor. Then the auxiliaries are not influenced by speed variation, an independent change of the rotor speed is possible and the turbine can operate in the optimum operation point. Existing inventions would have a too high mass increase from 100% to 175% of the initial gearbox.

Variation of the rotor radius could lead as well to increased efficiency of the rotorcraft. It could be an addition to the speed variation. The "Derschmidt Rotor" rotor technology would allow a faster and more efficient forward flight, but due to the unsolved problem of vibrations it doesn't seem to be usable.

An electric drive train is seven times too heavy to be used in the CS-29 class. Small electric engines may be used to support a drive train system in speed variation.

The knowledge of pros and cons of different technologies for rotor speed variation could be used in future rotorcraft designs to enable variable rotor speed and to help to choose the most suitable drive train system. The results are used in the project "VARI-SPEED" to find the best combination of rotorcraft configuration and gearbox design.

1 hanns.amri@tuwien.ac.at
Getreidemarkt 9/ E307-3
1060 Wien / Austria

1. INTRODUCTION

This publication is part of the international research project “VARI-SPEED”. The aim of the project is to invent a speed-variable drive train for different rotorcraft configurations to reduce the required propulsion power, which enables a modern and ecologically efficient aviation. A rotor and a gearbox will be designed and evaluated for their usability. Failures and risks for a chosen rotorcraft are reckoned.

The project is supported by German “Bundesministerium für Wirschaft und Energie” in the program “LuFo” and by the Austrian “Bundesministerium für Verkehr Innovation und Technologie” in the program “TAKE OFF”. Partners are the Technische Universität Wien (in Vienna), the Technische Universität München (in Munich) and Zoerkler Gears GmbH (Austria).

In the analysis “*Possibilities and difficulties for rotorcraft using variable transmission drive trains*” [1] it is shown that variable rotor speed technology could lead to more power efficient, ecological and high performance rotorcraft. First calculations and simulations in CAMRAD II showed a possible reduction of the required power up to 23%, by comparing the optimized rotor speed to the reference rotor speed. The calculations herein were performed by implementing a generic physical model of a helicopter similar to the Bo105.

Some existing ideas are also given in the above mentioned paper [1] for varying the rotor speed. The A160 “Hummingbird” showed that a two gear transmission can increase the flight endurance. It set a new record in endurance flight in May 2008. The vehicle was airborne for 18.7 hours [2]. Another example, the H145 uses an invention of Airbus Helicopters, called VARTOMS (Variable rotor speed and torque matching system) to enable a rotor speed variation [3].

Further examples of patents are given in the publication [1], which show different ideas of using transmission or electric engines or combinations of both, to vary the rotor speed.

Based on this background two questions occur:

- Which technologies are possible to enable a variable rotor speed for a rotorcraft?
- What are the advantages and disadvantages of the different technologies?

This paper gives an overview of different technologies and performed analysis about their usability to address these questions.

2. INVESTIGATION

A literature research was done, to get an idea of different possible technologies. All the discovered ideas, patents and other publications were divided into four categories:

- Rotor Technology
- Electric Drive Train Technology
- Turbine Technology
- Gearbox Technology

Reference requirements were set up to enable a comparison between the technologies in means of mass and range of speed variation. Furthermore it was possible to see the difficulties and the main drawbacks of the technologies by implementing the technologies to an example.

The S-70 Black Hawk was used as a reference helicopter. It has two T700-401C/-701C turboshaft engines with a maximum continuous power of 1240 kW per engine. A tail rotor power demand of 15% was estimated. The power for the main rotor was estimated with 2110 kW. The reference rotor speed of the S-70 is 258 RPM. A demand for a de-

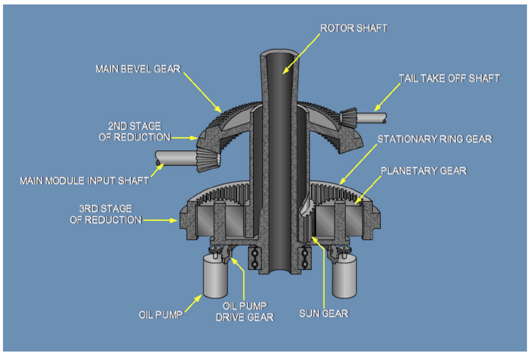

Figure 1: Components of the S-70 main gearbox [6]

crease of the rotor speed was estimated according to the results of the investigation in [1] and [8].

The weight of the S-70 main gearbox is about 650 kg [4]. The weight should serve as reference for the weight increase due to the considered technology. The output RPM of the main gearbox is the rotor speed (258 RPM). The last stage of the gearbox is a planetary gear stage. The input speed of the planetary gear stage is 1207 RPM. The components of the main gearbox are shown in Figure 1.

Based on the "Heavy Lift Rotorcraft System Investigation" [5] from the National Aeronautic and Space Administration (NASA) the range of rotor speed variation was defined with 50%.

The used parameters from the reference configuration are given in Table 1.

Parameter	Value
Power	2110 kW
Rotor speed	258 RPM
Lifetime	5000 hr
Transmission Ratio	1:1 & 2:1
reference output speed 1	258 RPM
reference output speed 2	1207 RPM
Main gearbox weight	650 kg

Table 1: Design parameters for the different technologies

2.1 Rotor Technology

2.1.1 Karem Optimum Speed Rotor

A lot of different inventions for performance improvement of the rotor were found. The first patent which is dealing with variable rotor speed is the "Karem Optimum Speed Rotor" [7]. This patent describes a method of designing a rotor blade in a way that it is usable for a wide RPM range. The blades need to have a high stiffness and a low mass. Both values should decrease wiht increasing radial position. There is no description about the way to vary the rotor speed.

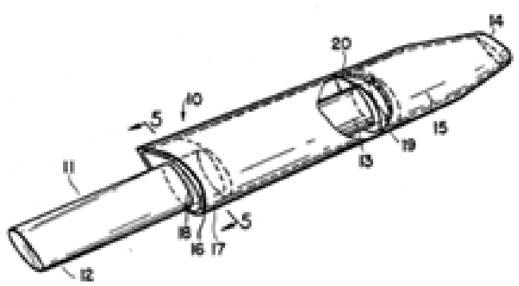

Figure 2: Telescoping rotor blade with linear twist [11]

2.1.2 Telescope Rotor

Another research topic is the variation of the rotor radius. Mistry and Gandhi [8] published calculations of the effects of a telescoping rotor, variable rotor speed and combinations of both concepts for the UH-60A. They studied radius variations between -16% to +17% and speed variations of ±11%, relative to the respective nominal values. The latter is controlled by varying the engine speed, which is possible with the installed turboshaft engines on the UH-60A, in the analysed speed range. As a consequence, no additional weight for speed changing mechanisms, such as variable-speed transmissions, had to be taken into account. The mechanism for extending and retracting the rotor-blades is not described in [8], it is assumed that there is one. Since no transitioning flight states were simulated, the calculations were conducted for different rotor diameters.

Mistry and Gandhi studied three different gross weights (16000 lb / 7257 kg, 18300 lb / 8300 kg and 24000 lb / 10886 kg) of the UH-60A at four levels of flight height (sea level, 4000 ft / 1220 m, 8000 ft / 2440 m and 12000 ft / 3657 m). Twelve flight velocities, linearly spaced between 35 kt / 18 m/s and 170 kt / 87,5 m/s, were analysed. The results show that decrease of RPM reduces the power demand of the rotor at cruise velocities and low-and-light conditions (up to -14%), while increasing the radius was most effective for low velocities and heavy-and-high conditions (up to -20%). The combination allows reduction of power demand between 7% and 30% within the whole domain of parameters studied. In these cases, the optimum rotor RPM, i.e. 89% of nominal rotor RPM, is always the one with minimum power demand. As a consequence, it can be expected that further reduction of rotor RPM could even lead to greater savings. But therefore an additional speed varying mechanism or specialized Variable-Speed Power-Turbines (VSPTs) are needed, both of which will probably increase the helicopters gross weight.

There were several mechanisms, like is shown in Figure 2, developed for changing a helicopter's rotor diameter during flight. Some examples use jackscrews or gearboxes combined with drums and cables. An overview of technologies invented until the 1970s is given in [9], more recent developments are presented in [10]-[17]. However, until today none of these concepts has been used in a serially produced helicopter.

2.1.3 Derschmidt Rotor

The basic principle of the so-called Derschmidt Rotor is a forced lead-lag movement of rotor blades. The aim is to decelerate the advancing blade while the retreating blade is accelerated. This compensates the asymmetrical airflow in forward flight conditions up to some extent. It also reduces the Mach-number at the advancing blade tip and shifts the stall limit towards higher flight speeds up to 400 km/h. To achieve this improvement of forward velocity, the lead-lag oscillation of the blades had to have an amplitude of 40° and a period of 360° rotor shaft angle. To enforce a lead-lag movement of the blades, high control forces would occur at the mechanism due to the centrifugal forces. To overcome the problem, the Derschmidt Rotor has to be operated in resonance. [18]

After promising rig tests of the rotor system, a prototype of a helicopter equipped with a Derschmidt-Rotor – the Bo 46 (Figure 3) – was manufactured in the early 1960s and subsequently tested. The programme was stopped in 1965, because the occurring problems with oscillations and deficient controllability could not be eliminated. Procurement decisions of the German Armed Forces may also have played a role in the suspension of the development of a high speed rotorcraft using Derschmidt's invention. [18]

Figure 3: Bo 46 in hover in Ottobrunn West (Germany) on the 29th of October 1964

In a publication presented at the AHS 70th annual Forum in 2014, 40 years after the maiden flight of the Bo 46, Hajek and Mindt [18] presented a study about the technical possibilities to overcome the problems of the Derschmidt-Rotor with modern technologies. They conclude, that even nowadays the vibrations caused by the principle of the system would pose a technical problem, which may be impossible to solve.

2.2 Electric Drive Train Technology

Two methods were used, to find out the potential of an electric drive train:

- First a literature research was done to see if there are already some inventions on the field of electric drive trains for rotorcraft.
- Second design studies were undertaken for the given design parameters with different electric drive train technologies, to get an idea of the mass increase.

2.2.1 State of the Art of Helicopter Hybrid Propulsion

C. Mercier et al. [20] presented the "State of the Art of Helicopter Hybrid Propulsion", an investigation by Airbus Helicopters, on the 41st European Rotorcraft Forum. He classified different types of hybrid propulsion in the following categories, to get a better idea of the possibilities:

- **Micro Hybrid:** electric power of maximal 50 kW, used for example on the turbine gas generator to get boost power
- **Mild Hybrid:** electric power around 300 kW, used for example as tail rotor drive, in single engine operation or emergency system for auto rotation. The main characteristic is that pure electric driven flight states aren't possible.
- **Full Hybrid**: pure electrically driven flight states are possible but a thermal power plant is needed for delivering energy.

- **Full Electric**: pure electrically driven flight states - no thermal power on board for the whole flight.

Mercier et al. [20] pointed out that helicopters can not recuperate energy in any flight state, as cars can while braking. But there are some advantages of using electric drive trains:

- Increasing the range of rotor speed (variable rotor speed)
- Decoupling main rotor(s) and anti-torque rotor or propellers
- Almost any rotorcraft configuration possible
- Optimized power generation in any flight state

The different hybrid configurations were analysed according to their ability of implementation. Mercier used specifications from state of the art electric components and made a prediction for in five years available electric components.

Table 2 shows a summary of the results found by Mercier [20]. A micro hybrid as a booster would be possible nowadays. Around 2020 it could be possible to have an electric back up system for safe landing in case of an engine failure.

Type of hybrid	E- engine 2015 sufficient	Batteries 2015 sufficient	E- engine 2020 sufficient	Batteries 2020 sufficient	Increase of power or energy density
Micro Hybrid Boost	y	y	y	y	-
Mild Hybrid Emergency	y	n	y	y	-
Mild Hybrid SEO	n	n	n	n	x6
E- Tail Rotor	n	-	n	-	x5
Full Hybird	n	-/n	n	-/n	x7
Full Electric	n	n	n	n	x14

Table 2: Reqirements for implementation of the investigated examples [20]

There is a need of an increase of the energy density of batteries by six times and of power density of engines by five times to enable an electric tail rotor or an single engine operation (SEO) mode. An increase by seven times is needed to enable the rotorcraft to operate some flight states only with electric engines and an increase by fourteen times to have rotorcraft without any thermal engine.

2.2.2 Full Hybrid Drive Train

State of the art components were used for the first design study. The goal was to compare different possibilities of full hybrid drive trains. The following components were considered:

- Generator
- Power electronics
- Tail rotor electric motor
- Main rotor electric motor
- Cooling system
- (Additional gearbox in some cases)

The reference model was used. There were two generators used, one for each turbine, with an input speed of 21000 RPM. Figure 4 gives a schematic of the considered system.

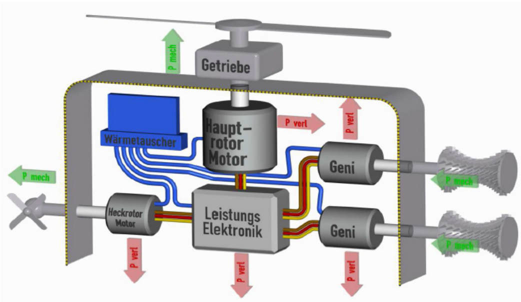

Figure 4: Schematic of the considered system

Different electric configurations for the main rotor drive were analysed. The tail rotor motor was estimated as a synchronous motor, as described in [21]. The weights of the functional parts were estimated according to the state of the art of industrial electric components. These components are not light weight design. Therefore a light weight factor of 2 was implemented to compensate this fact. Heat losses of components were estimated with 2% of the total power. The generators were designed as asynchronous machines. Data for the converter is taken from water cooled ship converters. The following electrical drive train configurations were investigated:

- Direct drive of the main rotor with a Torque Motor
- A Torque Motor and a one stage planetary gear
- Two to six engines driving a collecting gear
- Conventional synchronous motor
- Conventional asynchronous motor

2.2.3 Superconducting Engines

During the literature research an interesting paper from C.A. Luongo et al. [22] was found. He described the potential of "High Temperature Supercondutor Engines" for helicopters. To avoid misunderstanding, high temperature in this case means temperatures around 200 K (-70 °C)! So there is a serious effort for cooling.

A superconducting drive train was designed for the reference case, based on the information of C.A. Luongo [22]. The used electric components are given in Table 3. A planetary gear stage was designed for the main rotor drive. The other components were used from the full hybrid drive train. Cooling for the super-conduction motors were estimated with 0.7 times of the engine weight according to [22].

Component	Power density [kW/kg]	Torque density [Nm/kg]
Generator GE IHA (16000RPM)	8	5
Tail rotor engine URETI axial flux (3000 RPM)	7,5	17
Main rotor engine URETI cylindrical (3000 RPM)	6,5	22

Table 3: Used electric components for the superconducting drive train [22].

2.3 Turbine Technology

This section should show the possibilities of turbine speed variation as well as the consequences on mass, efficiency and power. Furthermore it should be shown how much speed variation is possible.

2.3.1 Types of Turboshaft Engines

Basically turboshaft engines can be divided into three categories, according to their number of shafts. In case of the one-shaft turboshaft engines, the compressor and the expander are on one shaft. The expander powers the compressor and produces the required torque for the output. Two-shaft turboshaft engines also have the compressor and the expander on one shaft. But there the expander powers only the compressor. The rest of the power is in the hot exhaust gas. This part of the turboshaft engine is called "gas generator". A second expander turbine is on its own shaft. It converts the power of the hot exhaust gas into torque and speed for the output. The gas generator of three-shaft turboshaft engines contains a low pressure and a high pressure part, which are mounted each on a separate shaft.

One- and two-shaft turboshaft engines are commonly used for rotorcraft. Three-shaft turboshaft is principally possible, but due to the complexity and the therefore rising mass and costs, not used. They also have no additional benefit for speed variation.

The operating behaviour of one- and two-shaft turboshaft engines is fundamentally different [23]. One-shaft turboshaft engines are good to use for power changes at one design revolution speed. A decrease of revolution speed leads to a decrease of torque and so to a drastic decrease of power. Two-shaft turboshaft engines have an increase of torque by a reduction of revolution speed. The power is up to a certain level almost constant by changing revolution speed.

Regarding the specific fuel consumption (SFC) at full-load operation, the one-shaft turboshaft engine has some advantages. But at turndown operation or at different revolution speed, the two-shaft turboshaft engine performs better. [24]

2.3.2 Fixed or Variable Geometry of the Expander Turbine

Functionality and capability of the turboshaft must be ensured over the whole speed range and the whole power range, when using fixed geometry turbine. The speed range of 50% leads to high changes of the angle of incidence, which could cause stall and further a reduction of power. This problem can be reduced when suitable profiles for the turbine rotor-blades are used. But some decrease of efficiency has to be taken into account.

The problem with variation of the incidence angle can be eliminated by using variable geometry. But the higher efficiency is accompanied by weight, reliability and complexity of the turbine [25]. According to the calculations of C.A. Snyder [26] the mass of a turboshaft engine increases by 5% using variable geometry.

2.3.3 Turbine Stages

The loads on the blades are inversely proportional to the rotational speed of the turbine. A reduction of the rotational speed leads to higher loads on the stages. Besides the stability problem of the blades, it also causes a reduction of the efficiency. Adding an additional turbine stage counteracts this problem. But an additional turbine stage increases the weight. An additional turbine stage causes a mass increase of 5% to 10% of the turboshaft weight, according to D'Angelo [25].

2.4 Gearbox Technology

Gearbox technology with variable transmission is used in many fields of engineering, most known in cars. So it seems to be logical to use it in rotorcraft as well. But the boundary conditions for rotorcraft are stricter than in other fields of engineering. The presented solutions for the gearbox technology in [1] were analysed and designed for the reference model. Magnetic gears were analysed and the general properties of the gearbox technology were discussed.

2.4.1 Magnetic Gears

Besides the well known gear wheel, there is an other interesting technology for torque transfer, so-called magnetic gears. As the name indicates, the torque is transferred by magnetic interdependency.

Change of revolution speed or torque is based on the different numbers of magnetic poles of pinion and gear. It is important that as many magnetic poles as possible are part of the torque transfer, to have a high torque density (= possible torque transfer divided by mass of the unit). Basically all conventional gearbox layouts can be made out of magnetic gears. But only coaxial magnetic gears and wobbling magnetic gears have a acceptable torque density.

The coaxial magnetic gear [27] [28] consists of three coaxial shafts or rings. The inner ring and the outer ring have strong magnetic poles and the middle ring consists of steel elements. These steel elements change the magnetic field. The ratio of the number of magnetic poles on the outer ring and the number of steel elements defines the transmission ratio. Three operation modes are possible. Two rings can rotate, while the third one must be fixed. The coaxial magnetic gear can be extended to a "Pseudo Direct Drive (PDD)" [29] by adding stator windings to the magnetic gear. Then it is possible to add torque to the output shaft. Further modifications lead to an epicyclic magnetic gear [30]. This type can vary the transmission ratio continuously.

Wobbling magnetic gears have the same principle like conventional ones. Magnetic poles are used instead of teeth. Wobbling magnetic gears have a high transmission ratio on a small cross section. [31].

2.4.2 Patent Study

There are already some inventions to vary the rotor speed with a transmission variable gearbox, as given in [1]. Three of these inventions were picked and designed according to the reference case. They were placed at the end of the drive train, close to the rotor. Then the input speed is the initial rotor speed (258 RPM) or the input speed of the planetary gear stage (1207 RPM). This has the following reasons:

- Only in this stage it is possible to operate the auxiliary units and the tail rotor with a different speed.
- An implementation close to the turbine, changes the loads for all gear stages afterwards. So there would be a need for a redesign which influences the mass of the whole gearbox.

The gears, the shafts and the bearings were calculated in a gearbox designing program, called "KISSSOFT". Then the three inventions were de-

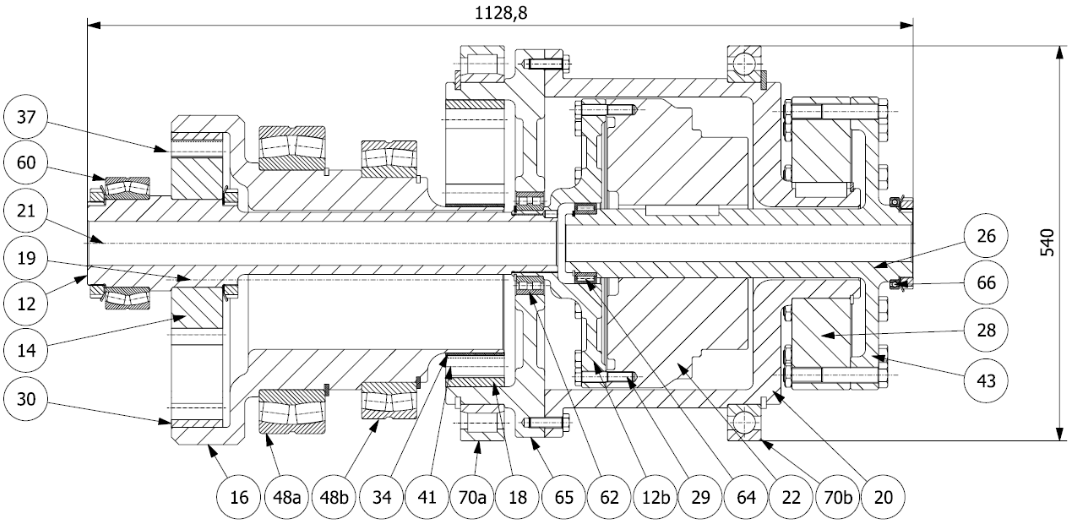

Figure 5: Siemens NX drawing of the designed NASA Offset Compound Gear

signed in a 3D CAD program, called "Siemens NX". In this program the mass of the designed invention was estimated. The investigated inventions are:

NASA Offset Compound Gear (OCG) [32]: It is a two-speed transmission gearbox, shown in Figure 5. The first transmission ratio is 1:1. There the input-shaft (12) is connected to the output-shaft (26) with a multi-disc clutch (22). The second transmission ratio is 2:1. On the input-shaft (12) is a gear (14) which meshes (37) with a ring gear (30). The ring gear (30) is mounted to an eccentric shaft (16). On the rear end of the eccentric shaft (16) is a gear (34) which meshes (41) with a second ring gear (18). The second ring gear (18) is mounted on a shaft (65&20) which is concentric to the input shaft (12). This shaft (65&20) is connected to the concentric output-shaft (26) via a free-wheel-clutch (28).

Helicopter Rotor Transmission Systems [33]: It is a two speed transmission gearbox as well, shown in Figure 6. The input-shaft (1) is connected to the planet carrier (7). The sun gear (2) is rotatable mounted (5) on the input-shaft (1) and connected to a disc-brake (6). The ring gear (4) is connected to the output shaft (9) and the input-shaft (1) is connected to the output-shaft (9) via a free-wheel-clutch (8).

The first transmission ratio is 1:1. Power is transferred from the input-shaft (1) to the output-shaft (9) via the free-wheel-clutch (8). The disc brake (6) is disengaged and the sun gear (2), the planet carrier (7) and the ring gear (4) are rotating with the same speed.

The second transmission ratio is <1. There the disc brake (6) is engaged. The sun gear (2) stops to rotate. Therefore the planet carrier (7) and the ring gear (4) can not rotate with the same speed. The ring gear (4) is accelerated. Due to the higher speed of the ring gear (4) to the input-shaft (1), the free-wheel-clutch (8) opens. The power is transferred from the input-shaft (1) to the planet carrier (7) to the planets (3) then to the ring gear (4) and then to the output-shaft (9).

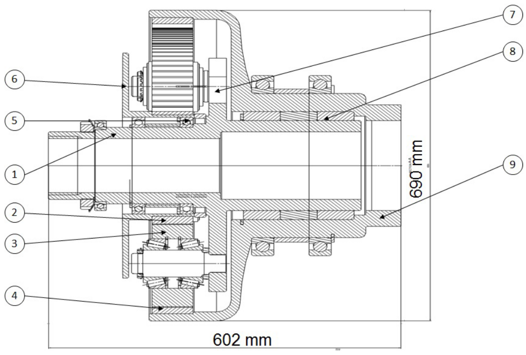

Figure 6: Siemens NX Drawing of the Moore transmission system

Two speed transmission with smooth power shift [34]: Another possibility to change the angular speed of a helicopter rotor by means of transmissions is to use epicyclic gear units, which have two rotational degrees of freedom. The speed of one element is varied while the speed of the shaft directly connected to the engine is kept constant. This causes a speed change at the third shaft, in this case the one connected to the rotor. Several patents exist, using such a mechanism.

This special transmission uses a stepped planetary gear unit with two ring gears. The sun gear is driven by the engine, the rotor is connected to the planet carrier and the angular speed of each ring gear is controlled by an electric machine, which can be operated as motor or generator, respectively a brake. The speed-changing module is intended to be operated with one ring gear stopped, i.e. with two defined gears. Only during the process of shifting from one to the other gear both electrical machines are used to enable a smooth transition. In permanent operation conditions one machine is used as generator and the other, connected with the braked ring gear, has no function.

3. RESULTS

3.1 Rotor Technology

Regarding the questions of the introduction, one rotor technology was found which enables variable rotor speed. This is the Karem Optimum Speed Rotor. By using this technology the problems of vibration are reduced and it is possible to vary the rotor speed by other means. If we interpret the question in a way like: “What rotor technology can vary the rotor tip speed?”. Then the Derschmidt-Rotor would be this technology. The technology with the variable rotor radius does not enable variable rotor speed, but it would benefit from it.

3.2 Electric Drive Train Technology

3.2.1 Full Hybrid Drive Train

Table 4 provides an overview of the weights of the components which were used in every configuration in the executed design study. Furthermore the weights of the industrial components and the corrected weight of the components are given.

Component	Weight
Generator industry	2500 kg
Generator with factor	1125 kg
Tail rotor industry	540 kg
Tail rotor with factor	270 kg
Heat exchanger	120 kg
Cable to tail rotor	18 kg
Sum	**1533 kg**

Table 4: Weights of components used in every configuration

The motor weights and the electronics weights for the different configurations are given in Table 5. These values are already corrected with the weight factor of 2. The total weight in Table 5 is the weight of the whole electric drive train. It is the sum of the values given in Table 4 plus the engine weight and the electronics weight. The heaviest configuration is the asynchronous motor version. This version has just an electric switch for the two required speeds. All other configurations can continuously vary the rotor speed.

Design	Engine weight	Electronic weight	Total weight
Torque Motor direct	1530 kg	450 kg	**3513 kg**
Torque Motor gear	1050 kg	450 kg	**3033 kg**
Six engines	1235 kg	500 kg	**3268 kg**
Synchronous engine	1205 kg	450 kg	**3188 kg**
Asynchronous engine	2005 kg	10 kg	**3548 kg**

Table 5: Weights of different investigated electric drive train configurations.

3.2.2 Superconducting Motor

Table 6 shows the weight of the components of the whole superconducting drive train and its components. The information for the electronics and its cooling is taken from the full hybrid drive train.

Component	Weight
Generators	305 kg
Main rotor engine	325 kg
Tail rotor engine	70 kg
Main rotor gearbox	120 kg
Cable to tail rotor	18 kg
Electronic	450 kg
Cooling electronic	60 kg
Cooling generator/ engine	490 kg
Sum	**1838 kg**

Table 6: Weight of the super conducting drive train and its components

3.3 Turbine Technology

Based on the research in Chapter 2.3, following turboshaft engines seems to be suitable for rotor speed variation.

- Two-shaft turboshaft engine
- Fixed geometry of the blades with an incidence tolerant blade geometry
- An additional stage for the working turbine

The power and torque characteristics and the specific fuel consumption (SFC) were analysed for this type of turboshaft engine. Figure 7 shows the torque and power curve over the relative revolution speed. Starting at the reference RPM (100%) the torque rises linearly with decreasing RPM. The power is almost constant untill 70% RPM, then it

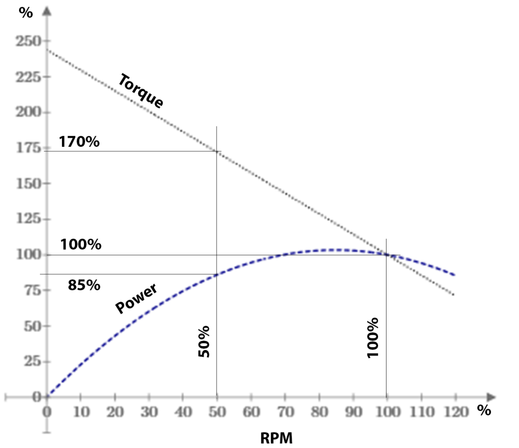

Figure 7: Relative Torque and Power curve drawn over the relative revolution speed

decreases. Ending at a relative RPM of 50% there is 85% of the reference power left with a torque of 170%. Figure 8 shows the relative specific fuel consumption (SFC) for different relative turndown operations over the relative RPM. The SFC increases with decreasing loads. By varying the RPM the SFC increases as well. The minimum SFC is at full-load operations with 100% RPM. In the range of 80% to 120% RPM at full load operation, there is almost no increase of the SFC. At turndown operations the influence of varying the RPM is higher.

An interesting fact is shown in Figure 9, the relative SFC for different relative RPM over the relative turndown operation. The minimum fuel consumption is shifting to lower RPM with decrease of the

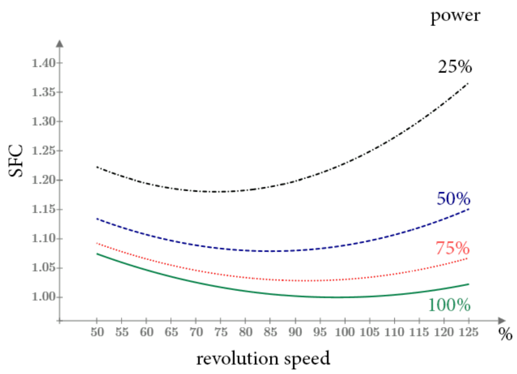

Figure 8: SFC for different relative turndown operations drawn over relative RPM

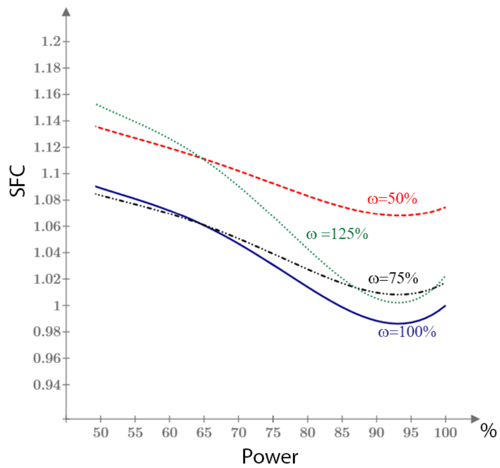

Figure 9: SFC for different relative RPM drawn over relative turndown operations

load. For 65% turndown operation the SFC is lower for 75% RPM than for 100% RPM. Furthermore the influence of the turndown operation is stronger for higher RPM than for lower RPM.

3.4 Gearbox Technology

The general advantages of the gearbox technology used in rotorcraft to vary the rotor speed are:

- a huge speed variation is possible without changing the turbine speed
- The speed variation for different rotors can be independent
- The auxiliary units, like oil pumps or generators are not influenced by the speed variation.
- It is an already accepted technology

3.4.1 Magnetic Gears

The technique of magnetic gears is under development. They have potential in the car industry for hybrid drive trains, in wind turbines, in drive trains of ships and in the space industry, especially the wobbling magnetic gears.

The advantages of magnetic gear compared to conventional gears are:

- Low maintenance
- No need for lubrication
- Overload protection (they slip in case of overload)
- Usable in a wide temperature range (-270 °C to 350 °C)
- Low vibrations
- Non-sensitive to contamination

The disadvantages are:

- Losses due to magnetic hysteresis
- Lower power and torque density
- No form fit
- Rare earth elements needed for construction
- Complex cooling for power transmissions

3.4.2 Patent study

The weights and the weight increase of the inventions are given in Table 7.

NASA Offset Compound Gear (OCG): The weight estimation showed that the designed transmission for the reference condition has a mass of about 790 kg. This would lead to a gearbox weight increase of about 120%, which is not suitable. The main reason for this increase is the single tooth meshing. The whole torque, which is very high at this position, has to be transmitted by one tooth connection and this at two meshing points. Conventional planetary gears have the advantage of load distribution to more teeth, which leads to a smaller design. Another disadvantage is the free-wheel-clutch. The NASA OCG can't be placed at this stage of the gearbox. In case of an engine failure, the tail rotor can't be driven by the main rotor because of the free-wheel-clutch.

Helicopter Rotor Transmission Systems: If this transmission system is designed, like it is given in the patent it would lead to an weight increase of about 380 kg. But in this case it is not comparable to the other inventions. This has two reasons. First, due to the used planetary configuration it is only possible to have a drive through and to speed up the output shaft. So there is a need for an additional reduction gear to lower the output speed down to the required RPM. Second the transmission range can't be so high. Between the planet carrier and the ring gear the transmission ratio is always smaller than 1/2 by fixing of the sun gear. So there is a need for two Moore transmission systems. Taken this into account, the weight increases up to 1150 kg, which means an additional weight of 175% which is definitely not suitable. The problem with the free-wheel-clutch in auto-rotation also occurs.

Two speed transmission with smooth power shift: The limiting factor for the use of this invention is the weight of the components of the electrical propulsion system, especially the electric machines. A rough estimate of the weight increase caused by adding such a module to the S-70 main gear box yielded about 650 kg, which is a weight increase of 100%. The drawback of this invention is the fact that during normal operation one electrical machine is not used at all.

Patent	Weight	Increase
NASA OCG	790 kg	120%
Helicopter Rotor Transmission Systems	380 kg (1150 kg)	58% (175%)
Two speed transmission with smooth power shift	650 kg	100%

Table 7: **Additional weights and relative weight increase of the investigated inventions when using them on a S-70 Black Hawk.**

4. DISCUSSION

Here the two questions of the Introduction should be answered.

Which technologies are possible to enable a variable rotor speed for a rotorcraft?

In our opinion there are only two technologies which have the potential to vary the rotor speed. They are the gearbox technology and the turbine technology. For sure we need a special designed rotor to enable variable rotor speed due to the vibrations, as mentioned in [1]. But this can not actively change the rotor speed. So it is not a technology in our sense of the question. The Telescoping Rotor is a good addition to enable efficient and environmental friendly rotorcraft. But it is not comparable to the variable rotor speed technology. Our model of the electric drive train is not highly sophisticated, one could ask why we used a weight factor of 2 and not of 4. We know that industry components are not designed to fly and we thought that half of the weight is a good estimation. As we found out at the ERF 2015 the factor seems to be in a good range. Our results are comparable to the ones of Mercier [20]. But even if factor 4 is taken as weight factor - the result is still the same: A full electric drive train is too heavy to be used in a rotorcraft of the CS-29 class. But it could make sense to use small electric engines to support an other speed variable technology.

What are the advantages and disadvantages of the different technologies?

One advantage of the turbine technology is the lower weight increase. A mass increase of 5% is accurate. Another advantage is the simpler gearbox. If the speed variation is done by the turbine, there is no additional gear system needed. But the weight of the gearbox itself will increase due to the torque characteristics of the turbine. An increase of the torque above the design torque causes a redesign of the gearbox. Higher torques in the gearbox mean higher mass. Another disadvantage is the loss of power by changing the revolution speed. Which also has to be taken into account is the fact that with changing the turbine speed the revolution speed of the auxiliary units also change. This could cause other problems. It is also not possible to change the rotor speeds independently, if more rotors are used.

Using a gearbox to vary the rotor speed adds an additional mass to the rotorcraft. The mass increase is in any case higher than the additional mass for the turbine itself, but don't need to be much higher than the mass increase of the turbine and the thereby linked gearbox mass increase. To enable variable transmission in a rotorcraft it is important that the part for transmission (speed) variation is not part of the main power flow (power split). A power split gearbox seems to be useful. To gain the most advantages of the gearbox technology it is necessary to place the gearbox close to the rotor. Then the auxiliaries are not influenced by the speed variation and the rotor speeds can be changed independently of each other (within the limitations of trim). Using a transmission variable gearbox the turbine can operate in the optimum operation point and there are no losses of power by changing the rotor speed.

Table 8 provides an overview of the before mentioned advantages and disadvantages of the turbine technology and the gearbox technology.

The results are used for the next step of the project "VARI-SPEED". There it should be investigated if the different technologies have varying advantages for different rotorcraft configurations.

	Advantages	Disadvantages
Turbine technology	low weight increase	possible increase of the whole gearbox weight
	simple gearbox	loss of power at of-design point operation
		change of the RPM of the auxiliaries
		no independent change of the rotor speeds
Gearbox technology	increase of the gearbox weight only with the module and the parts afterwards	high weight increase
	auxiliaries not influenced by speed variation	complex system
	independent change of rotor speeds possible	
	constant power over the whole speed range	

Table 8: Advantages and disadvantages of different technologies.

5. CONCLUSION

It could be shown that turbine technology and gearbox technology enable a variable rotor speed over the full required speed range. Rotor technology is needed to overcome the problems of vibrations and a Telescope Rotor could be an addition for environmental friendly and ecological rotorcraft. Electric propulsion is at the moment too heavy to be used in rotorcraft.

Due to the characteristic of a variable speed turbine it seems to be suitable for operations where the efficiency is the most important factor or on rotorcraft where there is a low importance of independent rotor speeds.

The gearbox technology can be used to extend the flight envelope. It can deliver maximum power over the whole speed range. Furthermore it can be used on rotorcraft configurations where independent change of rotor speeds is useful.

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HELICOPTER CONFIGURATIONS AND DRIVE TRAIN CONCEPTS FOR OPTIMAL VARIABLE ROTOR-SPEED UTILIZATION

W. Garre* [1], H. Amri**, T. Pflumm*, P. Paschinger**, M. Mileti***, M. Hajek*, M. Weigand**,
* Institute of Helicopter Technology, Technical University of Munich, D-85748 Garching, Germany
** Institute for Engineering Design and Logistics Engineering, Vienna University of Technology, AT-1060 Vienna, Austria
*** Institute of Machine Elements, Technical University of Munich, D-85748 Garching, Germany

Abstract

Recent studies [1]–[4] have shown that a variation of helicopter main rotor speed allows a significant reduction of the required power. Therefore an appropriate drive train technology is necessary to enable variable rotor speed. However, such a technology entails drawbacks such as increased weight and reduced efficiency [5]. This study provides arguments and results to enable a decision process towards a promising helicopter configuration incorporating a variable rotor speed and related applications. These are mainly obtained from mission performance calculations and additional transmission weight investigations. Benchmark missions are derived and presented while two promising drive train concepts are introduced. A continuously variable gearbox stage is shown to be especially useful for utility helicopter applications while a dual-speed, clutched stage gearbox is particularly suitable for tilt-rotor concepts. The capability to vary the main rotor speed extends the flight envelope and reduces fuel consumption. This study shows that the portfolio of missions that can be carried out efficiently and the efficiency itself is enhanced by this technology.

SYMBOLS AND ABBREVIATIONS

CVT		Continuously Var. Transmission
FVL		Future Vertical Lift
GW	[lb]	Gross Weight
IRP	[hp]	Intermediate Rated Power
ISA		Int. Standard Atmosphere
MCP	[hp]	Maximum Continuous Power
MTOW	[lb]	Maximum Take of Weight
OEI		One Engine Inoperative
SAR		Search and Rescue
SFC	[lb/hp-hr]	Specific Fuel Consumption
h	[ft]	altitude
i	[-]	transmission ratio
m	[lb]	weight
$\dot{m}_{fuel}$	[lb/hr]	fuel flow
P_{av}	[hp]	available power
P_{req}	[hp]	required power
V	[kts]	cruise speed
V_{tip}	[ft/sec]	rotor tip speed
Φ	[-]	spread of rotational speed

INTRODUCTION

One objective of the German and Austrian Aviation Research Program (LuFo V-2 and TAKE-OFF) is to promote technologies that enhance the ecological efficiency of future rotorcraft. Under ecological aspects a variable rotor speed offers the opportunity to operate the rotor at an optimal pitch to improve fuel efficiency and to reduce emissions. With a variable rotor speed, rotorcraft can therefore be developed and optimized for a whole operational design range rather than a specific design point. However, most rotorcraft are still operating at constant rotor speeds. The transnational project VARI-SPEED intends to give answers about the applicability and the determination of decision factors of such a technology. In the project it is also intended to design a rotor and transmission system for a selected configuration to investigate structural and vibrational problems encountered by a variable rotor speed. Stability and feasibility will then be studied as well as a proof of concept.

In the first study of the project the effects of a variable-speed rotor design on power savings and flight envelope are discussed for various existing helicopter configurations [4]. Calculations were

[1] w.garre@tum.de; +49 (0)89/289-16359; www.ht.mw.tum.de

performed using NDARC (NASA Design and Analysis of Rotorcraft). The aircraft chosen for the study are the UH-60A single main-rotor and tail-rotor helicopter, the CH-47D tandem helicopter, the XH-59A coaxial lift-offset helicopter and the XV-15 tiltrotor. Areas of possible power savings, ranges of rotational speed and main-rotor torque effects are presented. Depending on the aircraft, the study shows that significant power savings of up to 15% are possible at certain flight regimes within the engine limit [4].

This first investigation also shows the sensitivity of additional transmission weight relating to the possible power savings with variable rotor speed. This elucidates that a slender design area exists, where the configuration with reference rotor speed is the better choice over a variable rotor system with additional transmission weight. This non-beneficial design area enlarges with increasing empty weight of the aircraft.

Missions need to be considered in order to decide whether the variable rotor speed technology is favorable over a lighter reference configuration, because helicopters do not operate at one point of the envelope. Most missions will contain segments within the non beneficial area and segments where power can be saved. A holistic examination of a variable speed rotor system can only be made with representative missions that allows to compare the different configurations.

This study extends the research to a mission perspective, based on operator requirements, while at the same time possible variable speed gearbox architectures and weight estimations are presented. By calculating and comparing the different mentioned configurations this study expands the perceptions about the value of such a technology. The investigation is limited to ISA (International Standard Atmosphere), hover and level flight conditions. Note that both the tail rotor and engine speed are kept constant throughout the entire study.

Two current undertakings, that consider variable rotor speed, are the United States' Future Vertical Lift (FVL) program and the Europeans Clean Sky 2 - Fast Rotorcraft program. Both programs intend to extend high-speed helicopter capabilities, while still incorporating excellent hover and vertical take-off and landing (VTOL) capabilities. Future programs are foreseen to target noise reduction by variable rotor speed control [6]. The FVL comprises two Joint Multi-Role Demonstrators (JMR-TD), the Sikorsky Boeing SB>1 DEFIANT™and the Bell Helicopter, Lockheed-Martin V-280 Valor [7]. The Clean Sky 2 program aims likewise to build two demonstrators, the Airbus Helicopters' LifeRCraft and the Leonardo Helicopters' Next Generation Civil Tilt-Rotor (NextGenCTR) [6]. Each program tracks the idea of a compound helicopter competing against a tilt-rotor configuration.

Examples of existing high speed compound helicopter concepts are the Eurocopter X^3, the ABC™(Advancing Blade Concept) demonstrator XH-59A [8], Sikorsky X2 Technology™demonstrator [9] and the Sikorsky S-97 RAIDER™. The rotor speed of these examples is reduced in fast forward flight in order to avoid sonic conditions. Examples of existing tilt-rotor configurations are the Bell XV-15 demonstrator, the Bell Boeing V-22 Osprey and the Leonardo Helicopters AW609. Such configurations reduce rotor speed in fast forward flight to adjust the rotor speed towards propeller mode.

In both cases two different rotor speeds are required: a high rotor speed to meet the hover requirements and a speed reduction in fast forward flight. Concerning the considered compound configuration [10] reveals OEI hover condition as design driver. This condition also requires excellent hover efficiency to keep engine dimensions small. In this study OEI conditions are not covered within the mission calculation. Furthermore, heavy lift configurations, as examined in [10], are not considered in this study.

The Boeing A160T Hummingbird is an example of a main-/tail-rotor configuration that utilizes variable rotor speed by a dual-speed transmission, to gain advantages in ceiling and gross weight [11], [12].

A previous study was executed in the project VARI-SPEED to evaluate different possibilities for a speed variable drive train [5]. This study examined hybrid/electric drive train, variable speed turbine and variable speed gearbox concepts. Known variable drive train solutions were analyzed according to their suitability for the given problem. This was done to determine the possible range of speed variation and the thereby associated weight increase.

Mistè et al. [3] presented a methodology to determine the optimal rotational speed of a variable RPM main rotor and turboshaft engine system. The optimization goal was minimal fuel consumption. He identified that it is necessary to optimize the RPM for the rotor and the turboshaft engine independently according to each flight state of the helicopter. This means, that the optimum RPM for the rotor is not the same as for the turboshaft engine. Using a variable-speed transmission could enable to use both optima of the turboshaft engine and the rotor at the same time.

METHODOLOGY

NDARC [13], [14] is used to perform discrete performance calculations to provide grid points for subsequent mission calculations. These vary in four dimensions: flight speed, altitude, gross weight and rotor speed. In each dimension 30 discrete solutions are calculated and 50 discrete solutions in a range of $\pm$50% of the reference rotor speed respectively. This leads to $>10^6$ discrete performance solutions for each configuration. NDARC sums up the induced and profile power, interference and parasitic terms, transmission and accessory losses to determine the required power from momentum theory. In order to account for non-uniform inflow, non-ideal span loading, tip losses, swirl, blockage, stall, compressibility as well as Reynolds number corrections and other phenomena, surrogate models are added [13]. Furthermore, NDARC provides trim results, rotor states as well as engine performances. The considered helicopters are validated against flight test data.

Based on all discrete performance solutions, a multi-dimensional linear interpolation provides the function (1):

$$\begin{bmatrix} P_{req} \\ P_{av} \\ \dot{m}_{fuel} \\ SFC \\ \vdots \end{bmatrix} = \mathbf{f}\left(V, GW, h, V_{tip}\right) \qquad (1)$$

The function **f** covers the helicopter performance and efficiency in four dimensions. Thus, missions are iteratively calculated by forward time integration with equidistant time steps. This can be understood as a time-weighting of discrete solutions and its related performance gains. Fuel flow and the specific fuel consumption (SFC) are determined from the 'Referred Parameter Turboshaft Engine Model' (RPTEM) within NDARC [13]. This model provides the available power P_{av} as well as fuel flow $\dot{m}_{fuel}$ and the SFC depending on pressure altitude, air temperature and cruise speed. Thus, the successive reduction of weight by fuel burn can be considered at each time step and the speed for best range can be calculated. Segments of climb and descent are neglegted, as level flight conditions are calculated exclusively.

One time step of the integration scheme is depicted in figure 1. The mission calculation starts at time 0 and the process, exemplary illustrated for the time between j and $j+1$, is continuously repeated. During one time-step the weight, cruise speed, rotor speed, altitude and fuel burn are kept constant. In the beginning gross weight, elapsed time, range, and burned fuel are initialized. Subsequently, cruise speed, altitude, rotor speed and the tilt angle are calculated, fulfilling constraints. The constraints are either defined by specific cruise speed, altitude, rotor speed and tilt angle, or maximum range, endurance, altitude and speed. In the first case constraints can by directly applied. To maximize range and endurance the related states are determined by optimization. In case of maximum altitude and speed Lagrange Multiplier are used to account for the available power constraint. Hence, the input variables of **f** are determined and thus, performance variables and fuel consumption can be obtained. This allows to update the gross weight, elapsed time, range and burned fuel. The selected time step is always 20 seconds.

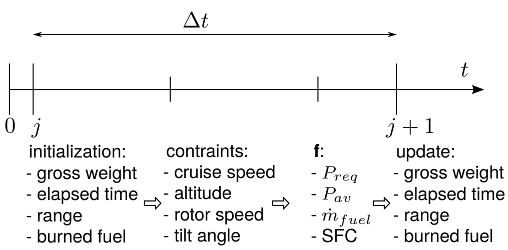

Figure 1: Illustration of one time-step of mission calculation.

To achieve a meaningful evaluation of mission advantages by variable rotor speed, the performance is compared to a constant rotor speed. The original rotor speed of each configuration is selected as reference, rather than a mission-optimized constant rotor speed. Thus, a rotor speed may exist that diminishes the mission advantages but the selection retains full hover performance, as this capability is crucial for all considered helicopters and related missions. In addition to the continuously variable and constant rotor speed the dual-speed rotor concept is investigated to draw conclusions about a two speed variable gearbox. The missions are determined individually for each configuration to consider the individual characteristics and advantages.

The maximum speed is always limited by MCP. This limit is applied to demonstrate mission performance gains with the same underlying available power and corresponding fuel flow, because the investigation focuses on efficiency. Neither a hub load limit, a aerodynamic limit nor a trim limit is applied. Speed improvements are resulting from excess power improvements that are used to increase the speed. The engine model's MCP is slightly depending on speed, but power and the related fuel burn can be treated as being approximately independent from speed.

Originally, the compound configuration was equipped with additional jet engines to overcome the power limit, in order to demonstrate aerodynamic advantages of slowed rotor speed and the Advancing Blade Concept. If distinct aerodynamic improvements are achievable beyond the MCP limit, particularly at slowed rotor speed and high cruise speed, this approach may not reveal the full potential of the technology. Besides, the models are not suitable to correctly represent physical rotor limits like compressibility, vibrational level and structural loads and they were exclusively validated against power demand.

The maximum acceptable, additional transmission weight that would cause a vanish of the achieved fuel savings is calculated for each mission. These results are compared to gearbox weight estimations. Different drive train technologies offer different range of speeds with different drawbacks in weight and efficiency. State of the art of transmission systems and gearboxes are not fulfilling the requirements of the project, as shown in [5]. A distinct shifting module is designed to be added to the UH-60 transmission system, to see if this technology is suitable for rotorcraft. The boundary conditions to the solution of the problem were set in form of input power – i.e. torque and speed –, mass and dimensions. Furthermore, one dual-speed and one Continuously Variable Transmission (CVT) solution are required. In particular, the shifting module has to change the speed of the main rotor, while other components should not to be influenced by a speed change, e.g. hydraulic pumps. Hence, only the shaft before or after the last gear stage is a plausible option, resulting in very high torques – i.e. weight. Another aspect of high relevance is represented by the fail-safe requirement of the shifting module itself. Indeed, in case of failure of a hydraulic or friction-based component, the shifting module has to continue working, allowing the rotor to rotate at nominal speed.

The possible drive train technologies which provide a variable rotor speed in connection with five different rotorcraft configurations are investigated regarding fuel savings and mission performance. A decision making process is used subsequently with the goal to find the most suitable rotorcraft configuration with a related gearbox technology for rotor speed variation.

RESULTS

A concept of a dual-speed transmission was developed in order to allow a shifting process under full load. In this case, the most appropriate gear stage is represented by an epicyclic gear stage, due to its high power density with respect to mass. Three transmission ratios can be obtained, in particular by braking or coupling in turn sun, planet carrier and ring gear. As slowing the carrier would result in a negative overall transmission ratio and as the required spread of $i_{in}/i_{out} = \Phi$=1,75 would be too small to slow the ring gear and drive off with the carrier, a double pinion epicyclic gearbox was chosen as illustrated in figure 2.

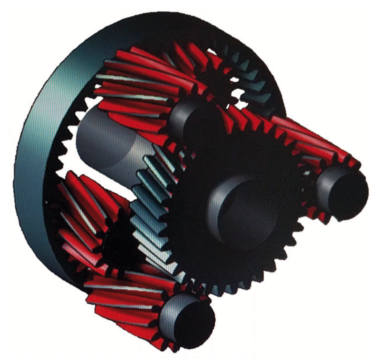

Figure 2: Double pinion epicyclic gearbox for the dual-speed approach.

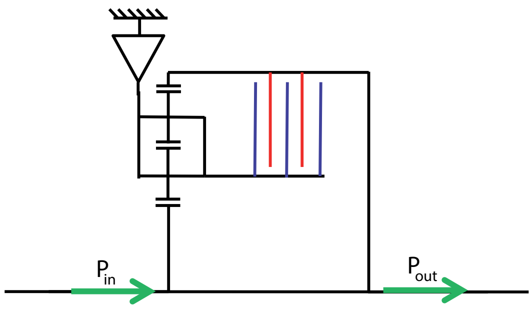

Figure 3: Schematic cross-section of double pinion epicyclic gearbox with clutch.

When the clutch is engaged, the system rotates as a block, causing no losses and having a ratio i=1. As the clutch opens, the absolute value of the carriers velocity reduces until the sprag clutch catches up giving an overall ratio i<1 and depending on the geometry of the epicyclic gearbox. A scheme is illustrated in figure 3 in principle. A concept of a self-shifting multi-disk clutch was developed combined with a dog clutch to achieve a form-locking to guarantee a fail-safe behavior of the clutch, figure 4. The overall additional weight of the module can be estimated by using a dimensioning software tool for the calculation of gears and results in m=661lb.

The weight of the gears is a very good indicator of the overall weight increase with decreasing RPM. An analysis, based exclusively on this data, has been

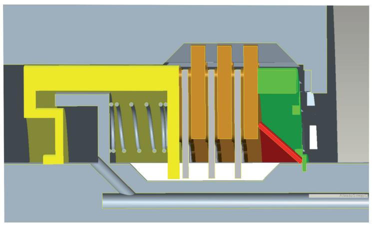

Figure 4: Principle of clutch for dual-speed approach.

performed to illustrate how placing the shifting module at an earlier stage would reduce the weight. The results, plotted in figure 5, show that an increase of velocity has significant effects on mass.

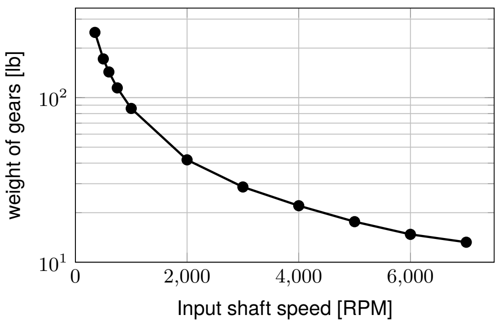

Figure 5: Weight estimation of the dual-speed shifting module depending on rotational speed.

Known CVT solutions from the automotive and industrial segment can hardly be adopted as a shifting module for a rotorcraft due to its high torque requirements. Thus, an alternative solution with a superposition of power flow seems to work best. This is schematically illustrated in figure 6. The proposed CVT shifting module consists of two coupled epicyclic gearboxes, where both ring gears are rigidly connected by a shaft. The input and output shaft are in turn connected to the sun of the first epicyclic stage and to the carrier of the second stage. The remaining carrier and sun are connected through a shaft that can be blocked or rotate, when power is superposed, at a chosen speed that determines the kinematic transmission ratio at the output.

When no power is superposed to the main flow, a ratio of i=1 is obtained. When power is added or removed from the sun-carrier shaft, every transmission ratio is theoretically achievable, getting an infinitely variable transmission. To keep the superposed power flows acceptable and unidirectional, only a maximum spread of Φ=1.75 is chosen. Using a fixed carrier train ratio of i_{12}=-2.4 the power to be superposed varies linearly

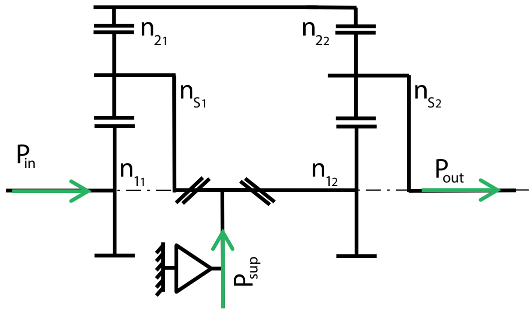

Figure 6: Schematic cross-section of CVT approach.

from 0% to 43% of the input power. For this concept and a transmission power of 2682hp (associated to the UH-60A), an additional mass for the superposition drive has to be considered with m_{SG}=243lb. The superposition drive train can be either electrical or hydraulic with an estimated weight of m_{SE}=595lb according to state of the art hydraulic components. The two stage planetary gear has an weight of m_P=485lb. So the concept has a total mass increase of m=1323lb.

In the first instance the configurations with no pusher device are investigated in a mission context. This distinctions allows to separate particular high-speed mission profiles, that still incorporate hover segments, from conventional helicopter missions. Tilt-rotor and compound configurations are designated in related research programs like Clean Sky 2 [6], FVL [7] and Russia's PSV project to perform equivalent missions. Similar programs focusing on conventional configurations (main/tail - rotor, tandem, coaxial) are rare.

Except for the considered CH-47D supply mission and the XH-59A rescue mission, mission profiles are derived from the helicopters performance. For the UH-60A a maritime SAR mission, a high altitude external transport mission and a troop transport mission are chosen. Yamakawa et. al. [15] reveal UH-60A mission requirements and Johnson [14] reveals the UH-60A performance. The maximum external cargo hook load is assumed to be 8000lb. The maximum UH-60A SAR mission radius is assumed to be 275km, while hover duration is 45min. The SAR mission is expected to require a 4 person crew. Additionally, 6 people are expected to be rescued at a maximum.

Trasana [16] contains a full CH-47D mission profile but its range is halved, because the description exceeds the considered MTOW. The second tandem mission is a high altitude external transport mission. The maximum cargo hook load is assumed as 20000lb. Additional data regarding the CH-47D is obtained from [14] likewise for the XH-59A. The passenger transport mission of the XH-59A is derived from Clean Sky 2 transport mission requirements. The XH-59A rescue mission profile was adapted from a German Federal Police rescue mission by adjusting the flight speed. Even if the XH-59A was not designed for rescue purposes, the gross weight of the helicopter matches the mission's characteristics in terms of weight. The resulting missions are illustrated in table 3.

The Future Vertical Lift (FVL) program asks for a small, agile configuration among other heavier helicopters. The related requirements are a mission radius of 424km, at a cruise speed of at least 200kts, a hover ceiling of 6000ft at 95°F and a payload capacity of 2010lb. Naturally, the configurations from the 1970's do not meet the latest mission requirements. Thus the mission requirements are diminished to enable the XV-15 and the Compound helicopter to perform the missions successfully. Especially, the hover ceiling is reduced to 4000ft/ISA. The altitude of the cruise flight segment is assumed to be 1000ft. The mission radii are resulting from maximum fuel capacity. In addition to the performance characteristics of the XH-59A Compound and XV-15 from [14] the requirements are leading to the missions illustrated in table 2.

The european Clean Sky 2 objectives regarding helicopters are a reduction of CO_2 emissions up to -17% by drag efficiency, noise reduction up to -7% (-13% until 2030) by optimized trajectories and rotor design. The european Clean Sky 2 project aims to build two demonstrators incorporating both high-speed and hover capabilities. The 'LifeRCraft' program aims to develop and built a single rotor compound configuration that is requested to perform both passenger transport and rescue operations. The main requirement of the transport mission is to fly 550km at 220kts. The rescue mission is not considered within this study.

The 'NextGenCTR' program intends to achieve a mission radius of 463km in 105min including a hover segment at a cruise speed of at least 300kts and and altitude of 25000ft [6]. These requirements and the XV-15 performance are considered within the mission definition in table 2. The mission radius is adopted and resulting from maximum fuel capacity. The payload is taken from FVL. The cruise flight altitude is slightly reduced and represents the maximum calculated altitude. The hover segment represents operations at the destination in helicopter mode.

Except for the high-speed mission profiles the missions consist of a variety of different flight conditions. This requires a permanent adaption of the optimal rotor speed. Figure 7 illustrates the progression of

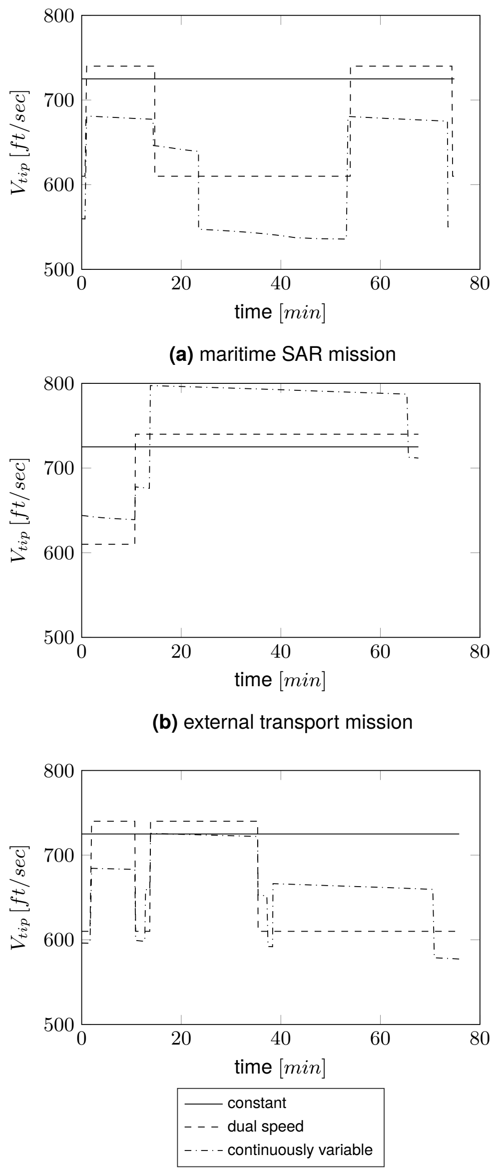

Figure 7: Optimal continuously variable UH-60A rotor speed in contrast to constant rotor speed and dual.speed approach. The missions are defined in table 3.

the UH-60A optimal rotor speed compared to the reference rotor speed and the dual-speed approach during the maritime SAR mission, the high altitude external transport mission and the troop transport mission. The optimal rotor speed shows discrete steps at the beginning of each mission segment. This results from discrete loading events and altitude steps, because climb and descent are not simulated. The continuously decrease of optimal rotor speed at each mission segment results from fuel consumption. The rotor speed of the dual-speed approach is not optimal in most cases, as figure 7 reveals, because the two rotor speeds are selected with respect to all three considered UH-60A missions.

The rotor speed approximately ranges from 535 ft/sec (-26%) to 800 ft/sec (+10%). The dual-speed approach provides the rotor speeds of 610 ft/sec (-16%) and 740 ft/sec (+2%). For each isolated mission the difference in rotor speed minimum and maximum is $\Delta V_{tip} \approx$145 ft/sec ($\pm$10%). The external transportation mission requires the highest rotor speed, the maritime SAR mission requires the lowest rotor speed. The difference between optimal and reference rotor speed is small for the troop transport mission. The mission durations are comparable. For all other configurations the main rotor speed development during the missions is illustrated in figure 9. Those reveal that the XV-15 requires the widest rotor speed reduction. Especially for the high-speed the dual-speed approach covers the optimal rotor speed well.

The mission advantages of the UH-60A using both a dual-speed approach and a continuously variable rotor speed are depicted in figure 8b. The figure is divided into three areas, representing the three calculated UH-60A missions. All other helicopters consist of two areas, related to the calculated missions. The most relevant mission performance measures are illustrated individually for each mission. The fuel improvements take into account that saving fuel, requires less initial fuel. Calculated improvements of endurance, range and payload consider an equal initial amount of fuel and the same burned fuel at the mission ending. Each measure is depicted along its own axis, six measures in total for each helicopter. The results do not consider additional transmission weight.

Regarding the UH-60A SAR mission, the hover segment endurance rather than flight speed can significantly be improved by up to 9.7% using a continuously variable rotor speed. Fuel savings of 6.3% or payload improvements of 18% are obtained during the external transport mission. Relatively, the improvements of the troop transport mission are small. The dual speed approach is always less efficient.

Equivalently, the other configurations and related mission advantages are illustrated in figure 8. Except for payload improvements during the CH-47D supply mission, the advantages of the XH-59A and CH-47D are small for both dual-speed approach and continuously variable rotor speed. As the considered passenger transport missions are equivalent for both XH-59A and the compound configurations, twice as much improvements are approximately obtained using the auxillary propeller device and a main rotor speed reduction of -8%. In both missions, the XH-59A compound is not able to maintain the FVL speed requirement of at least 200kts. However, a continuously variable rotor speed provides no additional benefits. This is true for the XV-15 as well. During the XV-15 long range transport mission range and speed improvements of 9% are obtained using the dual-speed approach and a rotor speed reduction of -43%. These are related to 8% of fuel savings. The XV-15 is able to fulfill the speed requirement from the FVL program.

In table 1 the additional empty weight for each mission is shown that compensates the achieved fuel savings by variable main rotor speed. The additional weight correlates with the fuel savings in relation to the single reference rotor speed. The UH-60A tolerates nearly 1000lb additional weight during the maritime SAR mission. But the maximum additional weight is strongly depending on the mission. The troop transport mission only allows additional 424lb. The compound and tilt-rotor configurations tolerate the most additional weight. That is due to the high fuel savings gained with respect to the constant reference rotor speed. During the long range transport mission up to 27% empty weight increase are acceptable in terms of burned fuel. In comparison, the UH-60A tolerates up to 9% addtional transmission weight during the maritime SAR mission.

DISCUSSION

Five different helicopter configurations are investigated with two different drive train concepts in the context of individual missions. The results suggest that both variable speed drive train concepts are reasonable, but one of them is typically preferable depending on the configuration. The transmission weight investigations reveal that the high-speed configurations provide acceptable margins towards additional weight.

Especially the UH-60A missions in total require a continuously variable rotor speed adjustment. That does not directly result from considering one additional mission compared to the other helicopters, but instead from the large variety of mission segments covered by all missions. As a multi-purpose helicopter, it is reasonable to improve its versatility by a continuously variable main rotor speed. The considered dual-speed approach significantly narrows the improvements. The advantages of the troop transport mission are small with respect to the other UH-60A missions, because

mission	dual speed	continuous
	UH-60A	
maritime SAR	550 lb	980 lb
external transport	315 lb	915 lb
troop transport	16 lb	424 lb
	CH-47D	
external transport	390 lb	483 lb
supply	1615 lb	1850 lb
	XH-59A	
passenger transport	313 lb	373 lb
rescue	417 lb	440 lb
	XH-59A Compound	
transport	1689 lb	1689 lb
passenger transport	1073 lb	1073 lb
	XV-15	
transport	1554 lb	1554 lb
long range transport	2688 lb	2688 lb

Table 1: Maximum additional empty weight (transmission weight) until design gets uneconomic. MTOW transgression disregarded.

the optimal rotor speed of that mission is close to the reference rotor speed as illustrated in figure 7c. Treating that mission as a standard reference mission of the UH-60A the particular advantage of a continuously variable rotor speed is elucidated. The efficiency of contrary types of missions can be improved and the portfolio of missions enhanced respectively. The maritime SAR (low payload) mission's efficiency and the external transport (high payload) mission's efficiency are distinctly improved. Using a dual-speed approach would not satisfy the large differences of all three missions. This is in contrast to the considered high speed missions, because they consist explicitly by two dominating, distinct flight regimes.

The more contrasting the mission segments and the related optimal rotor speeds considered with comparable proportions of time are, the more a continuously variable rotor speed gets interesting. If a configuration is equipped with a continuously variable rotor speed, it is capable of being adjusted towards a new specific mission. Considering only one specific mission segment narrows the advantages from variable rotor speed.

A drawback of the main-/tail-rotor configuration is the tail rotor. It needs to be driven by an additional variable gearbox, because its speed is required in contrary to the main rotor speed. Regarding this point the coaxial and tandem configurations are favorable because of no anti-torque device. Nevertheless, the XH-59A equipped with either a continuously variable gearbox or a dual-speed gearbox offers minor improvements, limiting the additional weight that can be carried in terms of overall efficiency. Equipped with an additional pusher, the improvements, for example maximum flight speed, are more than doubled. Based on this investigation, the coaxial configuration without a pusher is not a promising configuration.

The CH-47D mission advantages are low except for the payload capacity improvements of the supply mission. The high additional payload primarily results from fuel savings during the flight segments with no payload. The other mission improvements are low compared to the UH-60A.

R&D programs like Europe's Clean Sky 2 - Fast Rotorcraft program, the U.S. Future Vertical Lift program or Russia's Kamov Ka-92 focusing on high speed, usually prefer compound and tilt-rotor configurations. According to the earlier distinction, configurations featuring a propeller device or propeller mode are meant to meet fast forward flight requirements. As expected, these configurations reach the highest flight speed, while still incorporating hover capabilities. A wide rotor speed range is necessary to maintain operativeness in hover OEI conditions and to provide high speed capabilities and efficiency.

The two considered high-speed concepts approximately profit from a continuously variable rotor speed and dual-speed gearbox technology in a same way. This results from the specific mission profiles that only require a high rotor speed for excellent hover performance and a slow rotor speed for high flight speed. Whereas all high speed missions are dominated by the high speed segment. There is no justification to implement a continuously variable gearbox stage that is expected to have a higher additional weight. The XV-15 requires the widest rotor speed range of all considered configurations, besides providing the biggest range extensions of 9.5%. Fuel savings by up to 8.4% and speed improvements of 9.3% are achievable during the long range transport mission. In this case a more powerful engine should be considered to achieve even higher speeds. The most promising configuration equipped with a dual-speed gearbox stage is the tilt-rotor concept.

The dual-speed solution is the most efficient from the weight and internal-consumption point of view. The main drawback is represented by the shifting process: in fact, torque and sliding time would be too high to result in a clutch of reasonable dimensions. As a power reduction is not a feasible solution, the only way to reduce torque – i.e. weight – is to locate the shifting module at a more convenient stage that is at higher speeds. To meet the requests in terms of ratio spread, also the design of the shifting module has to be carefully taken into account.

A continuously variable transmission has many advantages against the dual-speed solution. Among them, especially the absence of friction-based elements, such as clutches, and the ability to achieve every possible speed ratio within the limits of the system are very important. Moreover, the possibility to vary from a ratio to another smoothly and over a longer time period allows the rotor to accelerate and avoids the turbine to abruptly change its velocity. Thus, especially the CVT solution seems to be promising. Unlike the dual-speed solution, in this case an important contribution to the overall weight is given by the second epicyclic gearbox and the motor system for the power superposition. To keep components small - and thus achieving a better lightweight design -, the least power possible has to flow through the generator/motor system itself. Simulations confirm that smaller absolute values of the epicyclic transmission ratio lead to lowering superposition power. The concept also has good potentiality, as the shifting module can be merged with the epicyclic set findable as a last stage in many helicopter gearboxes. The additional weight would therefore come from one epicyclic gearbox only. Hence, a reduction of about 35% of the initially estimated weight could be achieved, which would lead to a total mass increase of m=860lb. This would be acceptable for the UH-60A. The designed gearboxes are a first approach and they are designed to be added to an already existing system. The calculated weights show that a transmission variable gearbox system could be used in rotorcraft. The additional weight of the gearbox is assumed to be smaller, if such a system is designed within a new main gearbox- and rotorcraft-design.

CONCLUSION AND OUTLOOK

Rotor speed variation technology enables an efficiency increase for any rotorcraft configuration. The variation of rotor speed with turbine technology is suitable when only a small range of speed variation is required. The limiting factor is not the turbine itself but the gearbox afterwards because of the increased torque and the attached auxiliary units which will lose power with decreasing RPM. It seems to be possible to use variable gearbox technology close to the rotor to overcome this problems. The weight increase for the speed variation unit is higher because of higher torque but it could be in an acceptable region. Dual-speed transmission systems are suitable for configurations and missions with two explicit working areas, like a tilt rotor configuration. An additional continuous speed variation in a small range done by the turbine could make sense to minimize SFC.

In the context of missions the variable rotor speed is a promising technology to enhance fuel consumption and mission performance. But the improvements are strongly depending on the diversity of mission segments notwithstanding the number of missions considered. Especially, utility and multi-purpose helicopters, in this case represented by the UH-60A, benefit from a continuously variable rotor speed. The CVT technology can also be used to operate the turbine in the optimum operation point independent of the required rotor speed. In contrast, the tilt-rotor concept especially benefits from a dual-speed gearbox stage to adjust the rotor speed according to the airplane and helicopter mode respectively.

Both, utility and tilt-rotor configurations are most promising and the high-speed configurations additionally provide an appropriate margin towards additional transmission weight and thus benefit from variable rotor speed despite related weight drawbacks. However, particular missions may not benefit from variable rotor speed, if the reference rotor speed is equivalent to the related optimal rotor speed.

By additionally taking medium speed mission segments into account, the compound helicopter may benefit from a continuously variable rotor speed, because the mission requirements are less complementary. In all cases a redesign will raise the variable rotor speed efficiency by a reasonable rotor and drive-train design. It's the aim of subsequent investigations to demonstrate the feasibility and to reinvestigate the efficiency in detail after both an appropriate rotor system and a drive train system are designed for one distinct configuration. The selection of the configuration is based on the presented results. The design gross weight will be derived from the related mission requirements, whereas the design missions itself are inferred from lessons learned. Furthermore, stability, controllability, feasibility, etc. are intended to get investigated. In the future, it should be considered to reduce the rotor speed, even beyond the power optimum, to significantly reduce noise radiation.

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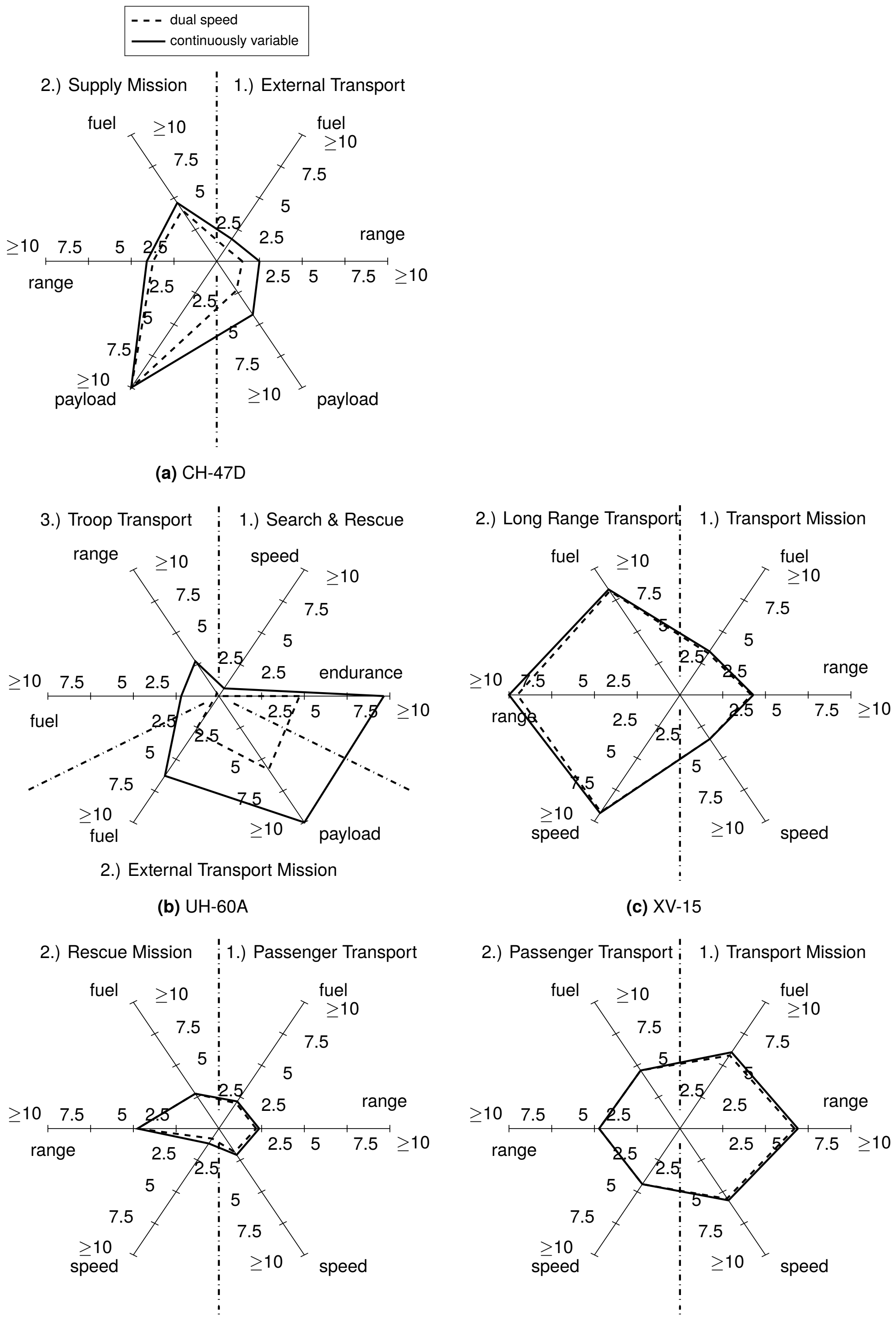
APPENDIX

segment	speed [kts]	(Δ)GW [lb]	altitude [ft]	time / range
Compound - transport and return				
1.	hover	12327	500	120 s
2.	max.	+ 0	1000	290 km
3.	hover	- 2010	4000	600 s
4.	max.	+ 0	1000	290 km
5.	hover	+ 0	500	120 s
Compound - passenger transport				
1.	hover	12327	500	120 s
2.	max.	+ 0	5000	550 km
3.	hover	+ 0	500	120 s
XV-15 - transport and return				
1.	hover	14112	500	120 s
2.	max.	+ 0	1000	210 km
3.	hover	- 2010	4000	600 s
4.	max.	+ 0	1000	210 km
5.	hover	+ 0	500	120 s
XV-15 - long range transport				
1.	hover	14112	500	120 s
2.	max.	+ 0	24000	410 km
3.	hover	- 2010	500	240 s
4.	max.	+ 0	24000	410 km
5.	hover	+ 0	500	120 s

Table 2: Mission definition for high-speed configurations with propeller device.

segment	speed [kts]	(Δ)GW [lb]	altitude [ft]	time / range
UH-60A - maritime SAR				
1.	hover	15543	50	60 s
2.	max.	+ 0	300	60 km
3.	range	+ 0	300	30 km
4.	hover	- 220	50	1800 s
5.	max.	+ 1100	300	90 km
6.	hover	+ 0	50	60 s
UH-60A - high altitude external transport				
1.	90	15065	2800	30 km
2.	hover (IRP)	+ 5500	2500	180 s
3.	75	+ 0	11000	120 km
4.	hover (IRP)	+ 0	6500	120 s
UH-60A - troop transport				
1.	hover	15685	4000	120 s
2.	110	+ 0	5000	30 km
3.	hover	+ 2915	4600	180 s
4.	120	+ 0	5000	80 km
5.	hover	- 2915	4600	180 s
6.	90	+ 0	5000	90 km
7.	hover	+ 0	4000	120 s
CH-47D - high altitude external transport				
1.	90	31683	1500	30 km
2.	hover (IRP)	+ 18000	4500	360 s
3.	80	+ 0	9000	70 km
4.	hover (IRP)	+ 0	8800	300 s
CH-47D - supply mission				
1.	70	31000	4000	65 km
2.	40	+19542	4000	74 km
3.	70	- 20458	4000	130 km
XH-59A - passenger transport				
1.	hover	12327	500	120 s
2.	max.	+ 0	5000	550 km
3.	hover	+ 0	500	120 s
XH-59A - rescue				
1.	hover (IRP)	11011	1000	120 s
2.	max.	+ 0	2969	35 km
3.	hover (IRP)	+ 176	1000	240 s
4.	max.	+ 0	2969	35 km
5.	hover (IRP)	- 176	1000	240 s
6.	range	+ 0	2969	35 km
7.	hover	+ 0	1000	120 s

Table 3: Mission definition of configurations with no propeller device.



(a) CH-47D

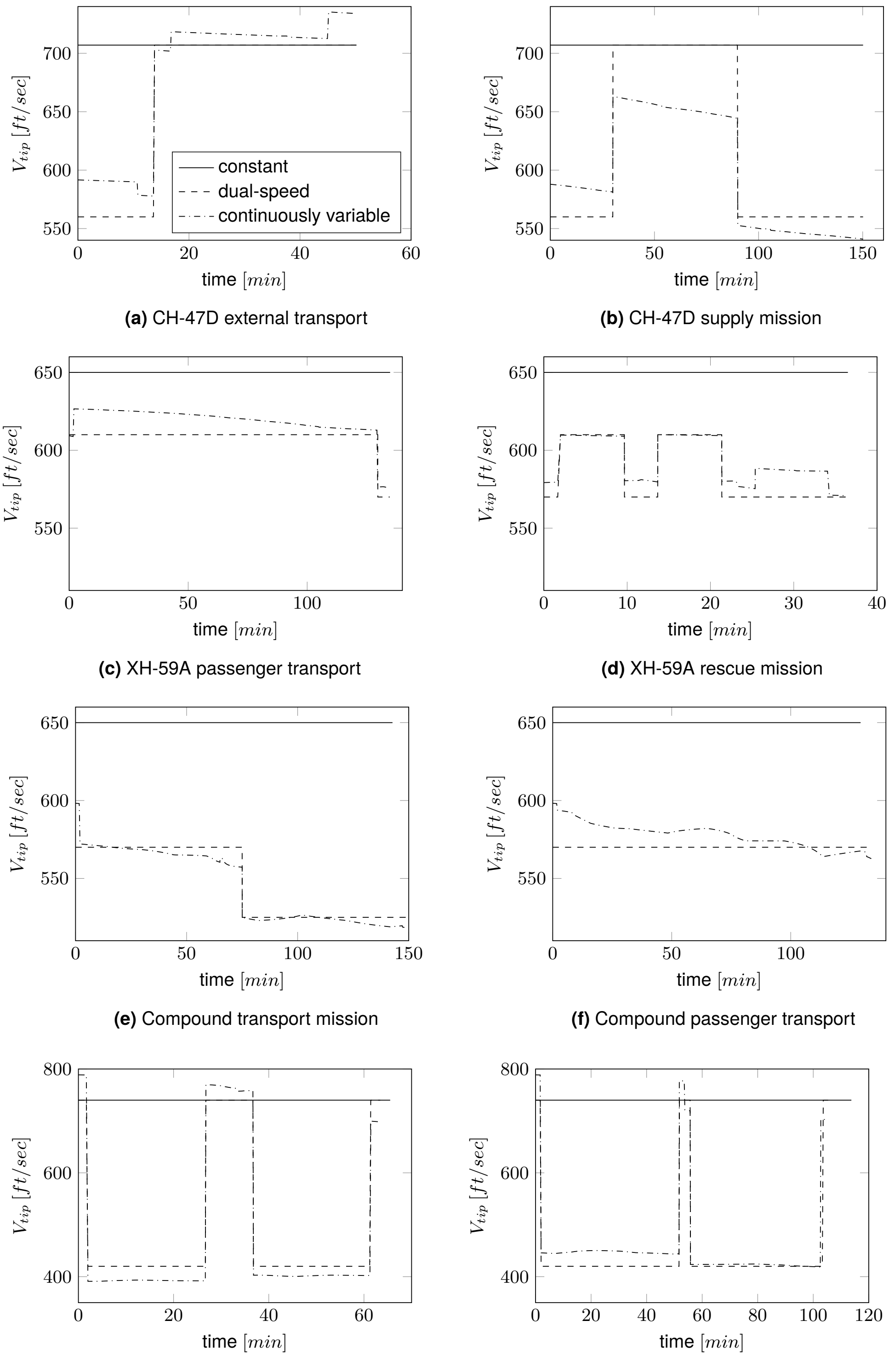
(b) UH-60A

(c) XV-15

(d) XH-59A

(e) XH-59A Compound

Figure 8: Mission advantages [%] using both continuously variable rotor speed and the dual-speed approach.



(a) CH-47D external transport

(b) CH-47D supply mission

(c) XH-59A passenger transport

(d) XH-59A rescue mission

(e) Compound transport mission

(f) Compound passenger transport

(g) XV-15 transport

(h) XV-15 long range transport

Figure 9: Optimal continuously variable rotor speed in contrast to constant rotor speed and dual-speed approach. The missions are defined in table 3 and table 2.

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COMPOUND-SPLIT DRIVETRAINS FOR ROTORCRAFT

Pierre Paschinger, pierre.paschinger@tuwien.ac.at, Zoerkler Gears GmbH & Co KG (Austria)
Hanns Amri, hanns.amri@tuwien.ac.at, TU Wien (Austria)
Katharina Hartenthaler, katharina.hartenthaler@tuwien.ac.at, TU Wien (Austria)
Prof. Michael Weigand, michael.weigand@tuwien.ac.at, TU Wien (Austria)

Keywords

variable rotor speed, transmission variable gearbox, compound split
variable speed drive train, continuously variable transmission, power split

Abstract

The investigation presented in this paper is part of the international research project VARI-SPEED with the aim to invent a speed-variable drivetrain for different rotorcraft configurations to reduce the required propulsion power, which enables a modern and ecologically efficient aviation.

The research is focused on drivetrain technologies for rotorcraft to enable a variable rotor speed. In the first part known variable transmission drivetrain technologies were listed. Evaluation parameters for usage of transmissions in rotorcraft were defined and rated with a utility analysis. The listed drivetrain technologies were evaluated according to their ability to fulfil the requirements of the evaluation parameters. It could be shown that continuously variable transmission power split gearboxes have the highest potential to be used in rotorcraft. Mechanical discrete variable transmission gearboxes may also have a potential to be used in rotorcraft but the shifting process could be a problem.

In the next step the three power split gearbox configurations – Input Split, Output Split and Compound Split – were analysed according to their power split behaviour at different transmission ratios. The more power is transferred via the mechanical path the higher the efficiency is and the lower the additional mass is. In the investigation a spread of two was assumed. This results in a maximum power flow via the variator path of 66 % for the Output Split, of 40 % for the Input Split and of 17 % for the Compound Split.

To take safety aspects and specification regulations into account, a FMEA for the Compound Split was carried out. It could be shown, that with additional measures there won't be an additional risk in the drivetrain for a rotorcraft using a Compound Split.

The findings of this research show the direction of further investigation on transmission variable gearboxes for rotorcraft. Knowing that Compound Split offers the highest potential different types can be developed and evaluated for usage.

1. INTRODUCTION

The described research is part of the international research project VARI-SPEED. The aim of the project is to invent a speed-variable drive train for different rotorcraft configurations to reduce the required propulsion power, which enables a modern and ecologically efficient aviation.

A first investigation on this topic showed that the variation of rotor speed could reduce the required power for a given flight state by up to 23 % [1]. This investigation was based on a generic CS-27 class helicopter. In this research there were also studies about different possibilities to enable rotor speed variation. Four technology categories were identified as possible candidates to enable speed variation: rotor technology, electric drive technology, turbine technology and gearbox technology. The authors concluded that further research is needed to evaluate this ideas.

W. Garre et al. [2] started an investigation about the useful range of rotor speed variation for different types of rotorcraft. The investigation was carried out for a single main rotor configuration, a tandem configuration, a coaxial configuration, a coaxial compound configuration with pusher propeller and a tilt rotor configuration. The research was based on different flight states. For every flight state in the flight envelope of each rotorcraft the optimum rotor speed was calculated. The power demand was calculated with the optimum rotor speed and was compared to the power demand at the reference rotor speed in every flight state. The results were depicted in the so called "Garre-Plot" and it could be shown that a rotor speed variation of up to 50 % is useful for almost all rotorcraft configurations. Furthermore, it could be shown that it makes sense to use the full range of speed variation. But there is always a region (some flight states) where rotor speed variation is not suitable. This is in the original design region of the rotorcraft, where the reference rotor speed is equal to the optimum rotor speed. If a mass increase is assumed to enable rotor speed variation, it is a drawback to use it in the flight states of the original design region. Whether rotor speed variation is useful or not cannot be evaluated without the knowledge of the time slice, in which the rotorcraft is operated in or out of the original design region. Therefore, rotor speed variation must be evaluated in the context of mission to show the potential of rotor speed variation.

Amri et al. [3] investigated the different possible technologies to enable a speed variation. The investigation showed that the rotor must be designed for a speed range because of the vibrations and that this could be achieved by varying mass and stiffness distribution along the blade axis [4]. Other rotor technologies, which gain similar positive effects on power demand are either not working, like “Derschmidt rotor” [5] or they mutually support each other, like the telescopic rotor [6]. Pure electric technologies are too heavy to enable main rotor speed variation. Speed variable turbines enable a speed variation in a certain range but for large speed variation the turbine efficiency decreases and the influence on other drive train components, like auxiliary units, increases. Gearbox technology with continuous or discrete variable transmission ratio could overcome this problems if it is possible to minimize the additional weight.

Further research of Garre et al. [7] was concentrated on the benefits of rotor speed variation in the context of missions by taking the drive train technologies into account. They combined the findings of [2] and [3]. Two types of transmission systems were suggested, one being a continuously variable transmission (CVT) and the other a two speed transmission system. The two speed transmission is especially useful for tilt rotor and compound rotorcraft configurations. Their missions have two important sections, one is in hover and the other is the fast forward flight. A two speed transmission system has benefits in the context of one mission. Continuously variable transmission is of interest for utility helicopters. The benefits are smaller if only one mission is taken into account. But by comparing different missions, continuously variable transmissions are most beneficial for utility rotorcraft.

The studies presented in this paper take a closer look at the transmission technologies themselves. Different drivetrain and transmission technologies which enable speed variation are investigated. Power requirements and different architectures are analysed. Also a safety analysis for the most promising solution is carried out.

2. COMPARISON OF DIFFERENT VARIABLE-TRANSMISSION DRIVETRAIN TECHNOLOGIES

Different types of transmissions for realizing various ratios already exist in several fields – like the automotive industry or plant engineering industry. The most common types are discrete and continuously variable transmissions based on positive (form) fit, friction, hydrodynamics, hydrostatics or electrics/electromagnetics. The main task of this research was to figure out the applicability of these transmissions in helicopters. To answer this question, an overview of the existing concepts is given first. Further analysis, respectively a solution finding process, for the most suitable concepts for realizing variable rotor speed was carried out.

2.1 Weight analysis of transmissions

A first attempt was a weight estimation of existing gearboxes. Weight is one of the most important parameters in the (pre-)design of a rotorcraft. Highly precise weight data are difficult to predict, because a reliable result could only be achieved with a full design model. The weight estimation was based on a regression analysis of existing gearboxes. The scaling parameter was torque transmission capability of the gearboxes. It allows an approximate weight extrapolation and should provide knowledge about the applicability in a helicopter according to the certification specification for large rotorcraft (CS-29) based on the two parameters.

The required torque transmission capability for a CS-29 rotorcraft does not lie within the range of the given data as shown in Figure 1 and therefore the fitted function has to be extrapolated. Another drawback is that the coefficient of determination of the regression analysis was too low to en-

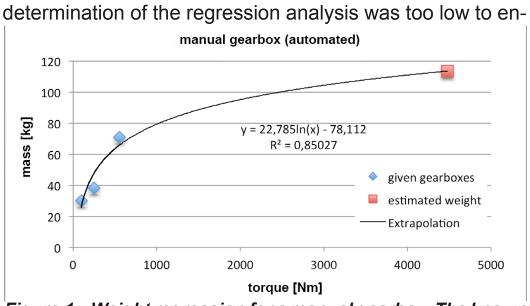

Figure 1: Weight regression for a manual gearbox. The known values are too far from the point of estimation.

able valid predictions because of the high influence of the weight to the helicopter performance. But the studies for the regression analysis showed in principle if the investigated technologies have the capability to be scaled up to the high power and torque range which is necessary for CS-29 class rotorcraft. Table 1 provides an overview of the transmission technologies and their capability for scaling.

Transmission Technology	Scalable
Multi-step Gearbox (automated)	yes
Converter Transmission	yes
Dual Clutch Gearbox	yes
Friction Gearboxes	hardly possible
Belt Gearboxes	hardly possible
Power Split Gearboxes	yes

Table 1: Types of transmission and their scalability

2.2 Solution finding process

A further attempt to evaluate the applicability of different transmission technologies in CS-29 class rotorcraft was to summarize the properties and evaluate the most promising concept with a rating. The evaluation was based on existing data, transmission properties, advantages/disadvantages and qualified estimations. Before the technologies could be ranked, a common understanding of the evaluation parameters which represent the usage in rotorcraft is needed to be found. First different evaluation parameters were listed. Then these parameters were ranked after an evaluation based on a utility analysis which represents their importance in a rotorcraft (weighting process).

Evaluation Parameter	Value
high system reliability	9,42 %
suitable for high power demand (CS-29)	9,00 %
controllable shifting process (speed can be controlled at any time)	8,83 %
low system weight	8,42 %
possibility to transmit high torques	8,17 %
reversible power flow	7,25 %
possibility to operate at high speeds (21000 RPM)	6,58 %
high amount of gear ratios/continuously variable	6,50 %
controllability (possibility to compensate disturbances quickly)	6,50 %
form (positive) fit	6,42 %
high overall gear ratio	6,42 %
high system efficiency	6,08 %
high accuracy of gear ratio	3,25 %
low available space	3,25 %
simple structure (complexity)	2,25 %
less maintenance requirements	1,67 %

Table 2: Averaged importance of evaluating parameters as a result of the utility analysis

The utility analysis compares the parameters against each other under the aspect if one criterion is more important, equal or less important than the others. The utility analysis was done by five experts in rotorcraft transmission design. The mean outcome is given in Table 2.

The most dominating parameters which arouse out of the analysis are system reliability, applicability at high power demands and low system weight. The less dominating factors are complexity and maintenance requirements.

In the next step the evaluation of the existing transmissions was conducted. Four rating factors were defined for evaluating every gearbox technology with every evaluation parameter. It should be identified, if the gearbox technology is best (factor 1.00), good (factor 0.66), less applicable (factor 0.33) or in the worst case not suitable (factor 0.00) for the evaluation parameter.

For evaluating the power split systems it was assumed, that 10 % of the power is transmitted via the variator path. The sum of the product rating times the value of the evaluation parameter for one transmission system is compared to the other transmissions and results in a ranking. The most suitable transmissions for the application in helicopters are the electric and hydrostatic power split systems as it is given in Table 3.

	Gearbox Technology	Value
Discrete var. transmissions	Automated Manual Transmissions	72.5 %
	Double Clutch Transmissions	71.8 %
	Shiftable Planetary Gearboxes	70.4 %
Continuously Variable transmissions	Hydraulic Automatic Transmissions	66.9 %
	Belt Transmissions	52.9 %
	Link-Plate Chain Transmissions	50.2 %
	Toroidal CVT (friction based)	39.5 %
	Electric	72.0 %
	Hydrodynamic	41.0 %
	Hydrostatic	58.4 %
Power-Split transmissions	Mechanical Power Split	82.8 %
	Electrical Power Split	92.2 %
	Hydrodynamic Power Split	83.4 %
	Hydrostatic Power Split	92.2 %

Table 3: Investigated gearbox technologies with the value of usability in rotorcraft according to the evaluation parameters in Table 2.

2.3 Results of the comparison

With the results of the solution finding process, the weight investigation and some previously executed research in [3] the following conclusion can be made.

1. ***Power split transmissions*** seem to ***have the highest potential to be used in rotorcraft.*** The use of an electric or hydrostatic engine as variator seems to be more promising than a mechanical or a hydrodynamical variator. But further research is needed to validate this result.
2. Pure friction based transmissions are not usable in rotorcraft. Most of them are not scalable to high torques or weight and dimension would increase too much.
3. As shown in [3] pure electric transmissions are too heavy to be used it in rotorcraft.
4. Pure hydraulic based CVTs are not usable. In case of loss of lubrication the whole torque transmission capability is lost. This is highly risky and not consistent with the certification specifications.
5. Multi-step transmissions have the capability to transmit high power and torque but some problems might occur during the shifting process. These are mainly caused by the energy that has to be dissipated in the clutch to compensate the different levels of momentum and kinetic energy between two gear-steps. Furthermore the rotor speed can not be controlled during the shifting operation.

3. POWER SPLIT TRANSMISSIONS IN ROTORCRAFT

Fixed-ratio mechanical transmissions have high efficiencies, whilst other types of drivetrains – like electric or hydrostatic transmissions – offer the opportunity of continuously variable output speed control. By using epicyclic gear sets and split the power provided by the main (thermal) engine into a mechanical path and a variator – i.e., electrical or hydrostatic – path, a CVT with satisfactory efficiency can be obtained. This is possible because an epicyclic gear set has two kinematic degrees of freedom, i.e., the rotational speeds of two shafts can be varied independently, and the third one is determined by them.

Every power split transmission of this kind has at least one mechanical point (MP) which denotes a transmission ratio at which the total propulsion power is transmitted via the mechanical path. Therefore, this is a highly efficient operation condition. A transmission ratio apart from the MP requires a power flow in the variator path. The portion of power transmitted by each of the two paths depends on the desired transmission ratio of the drivetrain. Operation apart the MP decreases the efficiency of the power split transmission, because the variator is less efficient than the mechanical path. So it is important to minimize the required power in the variator path to reach a defined offset of the MP.

There are different possible configurations for those types of power split transmissions. The three basic configurations are described hereafter. There is a special attention paid to the behaviour during changing the transmission ratio and the power demand to figure out which type is most suitable for the application in rotorcraft.

3.1 Output Split transmission

In Figure 2 a schematic sketch of a so-called Output Split drivetrain is depicted. Propulsion power is provided by a turbo-shaft- engine (***TSE***, red) and transferred by shaft ***a*** with constant rotational speed. A portion of power is taken off (e.g., via a fixed-ratio gearbox) and then converted into electric or hydrostatic power by a motor/generator or pump unit (***MG1***, blue) and transmitted to another motor/generator or pump unit (***MG2***, blue), where it is re-converted to mechanical power and supplied to the epicyclic gear set (***EGS***, green). This path is called the variator. The other portion of power remains on the mechanical path shaft ***a*** and is also supplied to the ***EGS***.

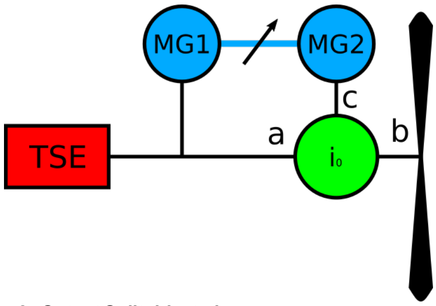

Figure 2: Output Split drivetrain

Since the rotational speed of ***MG2*** is independent of the one of the ***TSE***, it can be varied by the variator in order to control the rotor speed via the ***EGS***. It should be pointed out, that no storage device for the variator energy, such as a battery or a pressure accumulator, is needed.

For simplicity, additional fixed-ratio gear stages, rotors and turboshaft engines were neglected in the sketch and the description above. Generally, every mechanical connection (black lines) could contain several gear stages and rotors/ engines/auxiliary units can be connected to the shafts. But these units won't change the described behaviour of the system.

As the variator power depends on the transmission ratio, we first define the transmission ratio $\boldsymbol{k_{ab}}$ between shafts ***a*** and ***b*** as

(1) $$k_{ab} := \frac{n_a}{n_b} ,$$

wherein $\boldsymbol{n_a}$ and $\boldsymbol{n_b}$ denote the rotational speeds of shafts ***a*** and ***b***. An Output Split transmission has one mechanical point, which corresponds to the epicyclic gear ratio $\boldsymbol{i_0}$

(2) $$i_0 := \frac{n_a}{n_b}\Big|_{n_c=0}$$

of the ***EGS***. At this transmission ratio, shaft ***c*** has no rotational speed $\boldsymbol{n_c}$ and therefore no power is transmitted via the variator path. This mechanical point is defined by the characteristics of the epicyclic gear set, i.e., the tooth ratio. The epicyclic gear ratio is a constructive value of an epicyclic gear set. By taking the epicyclic gear ratio into account, the rotational speed $\boldsymbol{n_b}$ of shaft ***b*** depends on $\boldsymbol{n_a}$ and $\boldsymbol{n_c}$ as follows:

(3) $$n_b = \frac{n_a + n_c \cdot (i_0 - 1)}{i_0} .$$

For stationary operation conditions, the ratio between the torques $\boldsymbol{T_a}$, $\boldsymbol{T_b}$ and $\boldsymbol{T_c}$ at shafts ***a***, ***b*** and ***c*** is constant and defined by the epicyclic gear ratio:

(4) $$T_a : T_b : T_c = 1 : -i_0 : (i_0 - 1) .$$

As a consequence, the power on the mechanical path ($\boldsymbol{P_a}$) can be calculated, with constant ***TSE*** Power $\boldsymbol{P_{TSE}}$, in relation to the defined epicyclic ratio and the desired transmission ratio:

(5) $$P_a = \frac{k_{ab}}{i_0} \cdot P_{TSE} .$$

The power at the variator path ($\boldsymbol{P_c}$) is given as:

(6) $$P_c = \left(-\frac{k_{ab}}{i_0} + 1 \right) \cdot P_{TSE} .$$

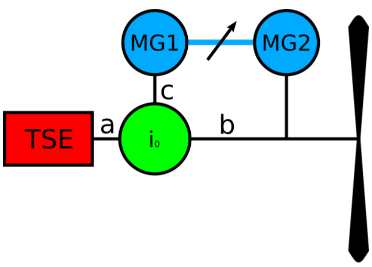

Figure 3: Input Split drivetrain

Obviously, for $\boldsymbol{k_{ab} = i_0}$ no power is transmitted via the variator path and the Output Split operates at the mechanical point.

3.2 Input Split transmission

The architecture of an Input Split drivetrain is similar to the one of an Output Split, but the position of the ***EGS*** is changed (cf. Figure 3). Input Split drivetrains also have one mechanical point at $\boldsymbol{k_{ab} = i_0}$. Analogous to Output Split, the power at the variator path ($\boldsymbol{P_c}$) and the power at the mechanical path ($\boldsymbol{P_b}$) are:

(7) $$P_b = -\frac{i_0}{k_{ab}} \cdot P_{TSE}$$

and

(8) $$P_c = \left(\frac{i_0}{k_{ab}} - 1 \right) \cdot P_{TSE} .$$

The formula for the rotor speed $\boldsymbol{n_b}$ at the rotor shaft ***b*** is identical to the Output Split:

(9) $$n_b = \frac{n_a + n_c \cdot (i_0 - 1)}{i_0} .$$

3.3 Compound Split transmission

Another possibility of arranging the variator units is the so-called Compound Split as depicted in Figure 4 (cf., for example, [14], [15]). In a sense, it is a combination of Output and Input Split. The basic configuration uses two epicyclic gear sets with two common (or positively connected) shafts. Again, there is no storage device for the variator energy, so that the power transformed at ***MG1*** is equal to the power at ***MG2*** (efficiencies neglected). In this configuration there are two mechanical points due to the two epicyclic gear sets. Because of the connection of shafts ***a*** and ***b***, the kinematic degree of freedom of a Compound Split drivetrain is two – as well as for Output and Input Split. This means that two rotational speeds ($\boldsymbol{n_a}$, $\boldsymbol{n_c}$) can be chosen independently and the others are functions of these two speeds. With this con-

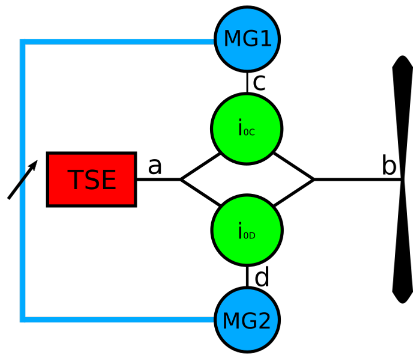

Figure 4: Compound Split drivetrain

straints, constant torque ratios (stationary condition without losses) and equivalence of motor/generator powers, we obtain the following relations for the power in the variator path (P_c and P_d):

$$P_c = P_{TSE} \cdot \left(\frac{i_{0C}}{k_{ab}} - 1 \right) \cdot \frac{k_{ab} - i_{0D}}{i_{0C} - i_{0D}} \tag{10}$$

$$P_d = P_{TSE} \cdot \left(\frac{i_{0D}}{k_{ab}} - 1 \right) \cdot \frac{i_{0C} - k_{ab}}{i_{0C} - i_{0D}} , \tag{11}$$

wherein i_{0D} and i_{0C} are the epicyclic ratios in the mechanical points of the epicyclic gear sets. The rotational speed of the rotor is calculated as a function of the ***TSE*** speed (n_a) and the speed of one variator engine (n_c):

$$n_b = \frac{n_a + n_c \cdot (i_{0c} - 1)}{i_{0c}} . \tag{12}$$

The rotational speed of the second variator engine (n_d) is then calculated as

$$n_d = \frac{n_a - i_{0D} \cdot n_b}{1 - i_{0D}} . \tag{13}$$

3.4 Comparison of the power flow in the variator path of the configurations

Now the behaviour of the power of the different power split architectures can be calculated. Therefore the following assumptions are made:

- The power of the ***TSE*** is normalized to one ($P_{TSE} = 1$)
- The power of the ***TSE*** is constant in all operation conditions
- The power demand of the rotor is constant in all operation conditions and is equal to minus one
- The investigated range of transmission ratios between ***TSE*** and rotor is from two to four ($k_{ab} = 2...4$)
- Therefore the mechanical point for the Input Split and Output Split is chosen at $k_{ab} = 3$
- One mechanical point of the Compound Split is defined at $k_{ab} = 2$ and the other at $k_{ab} = 4$

3.4.1 Output Split transmission

The power of shaft ***b*** is constant in every operation condition because it is directly connected to the rotor. The power of the ***TSE*** is split into shaft ***a***, the mechanical path, and shaft ***c***, the variator path, depending on the considered transmission ratio. At the mechanical point $k_{ab} = i_0 = 3$, no power flows across the variator path. For transmission ratios greater than i_0, the power on the shaft ***a*** (P_a) exceeds the input power and the power in the variator path P_c becomes negative, i.e., ***MG2*** works as generator whilst ***MG1*** takes the part of the motor. In this operation conditions, reactive power circulates between the mechanical and variator path. Because this does not contribute to driving the rotors, but causes losses and reduces efficiency, this transmission ratios should be avoided. The maximum positive power in the variator path is 33 % of the total power and the maximum negative power is -33 %. The power characteristics over the transmission ratio is depicted in Figure 5.

To avoid reactive power circulations the mechanical point must be set to the maximum transmission ratio. Then the maximum power flow in the variator path is 66 % of the total power.

3.4.2 Input Split transmission

Here the power of the shaft ***a*** is constant in every operation condition because it is directly connected to the ***TSE***. The power flow to the rotor is then divided into the mechanical path P_b and the variator path P_c. As for the Output Split, at the mechanical point $k_{ab} = i_0 = 3$ no power flows across the variator path. For smaller transmission ratios, reactive power flow occurs. The maximum positive power in the variator path is 50 % of the total power and the maximum negative power is -25 %. The power characteristics over the transmission ratio is depicted in Figure 6. To avoid reactive power circulations the mechanical point must be set to the maximum transmission ratio. Then the maximum power flow in the variator path is -40 % of the total power.

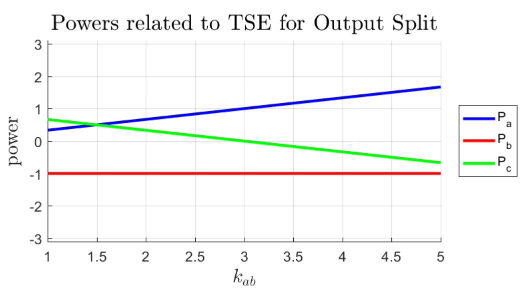

Figure 5: Shaft powers for Output Split architecture

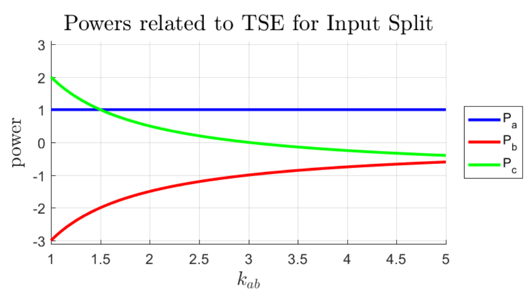

Figure 6: Shaft powers for Input Split architecture

3.4.3 Compound Split transmission

The input power P_a and the output power P_b are constant due to the reason that the input shafts ***a*** are directly connected to the ***TSE*** and the output shafts ***b*** are directly connected to the rotor. (Figure 7) At the two mechanical points at $k_{ab} = 2$ and $k_{ab} = 4$ there is no power flow via the variator path. Between these points one variator engine works always as motor and the other always as generator. There is no reactive power circulation. The maximum power flow via the variator path is 17 % of the total power and appears at a transmission ratio of $k_{ab} = 2.83$, the geometrical mean between the two mechanical points (cf. [14]).

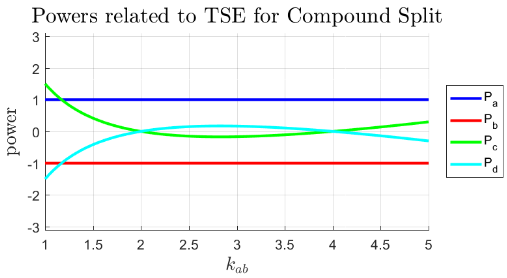

Figure 7: Shaft powers for Compound Split architecture

3.4.4 Comparison

In Table 4 the maximum values of the power flow in the variator path are given. The input power split configuration is the worst and the compound power split configuration is by far the best.

Power Split Configuration	max. Variator power
Input Power Split	75 %
Output Power Split	66 %
Compound Power Split	17 %

Table 4: Comparison of the maximum power in the variator path by avoiding reactive power flow.

It should be noted, that the maximum variator power for all Power Split architectures is independent of the absolute values of the transmission ratio i_0 resp. i_{0C} and i_{0D} and only depends on the required spread ***R***

$$R := \frac{i_{max}}{i_{min}} = \frac{k_{ab,max}}{k_{ab,min}} \tag{14}$$

only (cf. [14]). For Compound Split architectures the maximum variator power can be calculated as:

$$P_{var,max} = |P_c(\sqrt{i_{0c} \cdot i_{0D}})| = \left| \frac{\sqrt{R} - 1}{\sqrt{R} + 1} \cdot P_{TSE} \right| . \tag{15}$$

3.5 Variator technologies

In principle, every machine or pair of machines able to convert mechanical input power with given rotational speed to mechanical output power with continuously variable speed is qualified as variator. For this study we restrict to the two most promising solutions, the electric and the hydrostatic variator. As the power flow in the variator path is known, the next question to be answered is, if there are electric or hydrostatic engines available which can deliver the required power characteristic.

For basic estimation and assessment of drivetrain properties, the characteristics of a wide range of electric and hydrostatic machines can be approximated by the curves depicted in Figure 8 (cf. [11], [12], [13]).

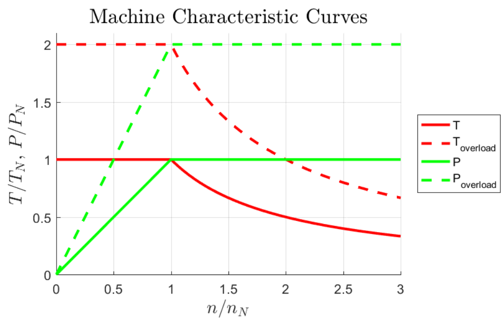

Figure 8: Characteristic curves of variator machines

The deliverable torque as a function of machine speed is plotted as red solid line. For rotational speeds lower than a characteristic nominal speed n_N, the maximum continuous torque is constant. Consequently, the available power (green solid line) increases linear from $n=0$ to $n=n_N$. Above the nominal speed, machine power remains constant and therefore torque follows a hyperbolic functionality in ***n***. The dashed lines in Figure 8 represent overload torque (red) and overload power (green), assuming an overload factor of 2. This assumption applies rather for electric machines than hydrostatic machines, latter having much less overload capacities (≈1.125).

Most variator machines considered in this paper can be operated in all four-quadrants, i.e., the characteristic curve depicted in Figure 8 can be extended to negative rotational speeds, torques and powers by mirroring around the coordinate axes resp. the origin. Depending on the sign of power, the operation mode of the machine, i.e., motor or generator/pump, is different between two quadrants.

Since the maximum of variator power just depends on the overall propulsion power, i.e., $\boldsymbol{P_{TSE}}$, and the required spread $\boldsymbol{R}$, these two parameters determine the maximum continuous power of the electric/hydrostatic machines.

With this knowledge the characteristic curve of the required machines can be fitted into the power plot of a Compound Split transmission (Figure 7). The main criteria is the gradient of the power increase of the machines. The gradient has to be higher than the gradient of the required power. This can be enabled by a additional transmission between the variator engine and the epicyclic gear set of the Compound Split. Then the maximum available power of the engines should be as close as possible to the maximum required power to minimize the additional weight. Figure 9 gives an example of a variator characteristic fitted into the power requirement of the Compound Split. The required power is depicted as a dotted line, whilst the available variator power is a solid line. The overload power (dashed line) can be used for dynamic loads in the system, like acceleration.

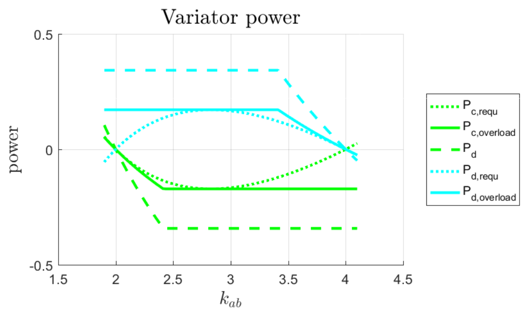

Figure 9: Available variator power compared to demand (Compound Split)

4. FMEA AND CERTIFICATION ASPECTS (SAFETY ASSESSMENT)

The introduction of a new technology, especially in drivetrain applications, affects many other parts of the rotorcraft and the specific impacts have to be investigated in detail. A major topic in aerospace applications is safety and the certification of such changes. In this chapter some important aspects of certifying large rotorcraft using a Compound Split drivetrain according the European standard CS-29 [8] and safety considerations based on a ***Failure Mode and Effects Analysis*** (FMEA) acc. to SAE ARP4761 [9] are discussed.

4.1 Safety Assessment

Despite of the benefits which Compound Split drivetrains offer to rotorcraft, they also involve specific risks which have to be rated. The aim of this resarch is to find the possible failures of the compound split system, to define their criticality and their effects on the rotorcraft as well as to find solutions to minimize the effects on the rotorcraft.

FMEA poses a suitable method for determining low level failures and their influence on higher system levels. For the analysis in this paper the standard SAE ARP4761 [9], primarily intended for showing compliance with FAR/JAR 25.1309 [10], was used as a systematic basis. It offers methodology for conducting a comprehensive safety analysis for aircraft and airborne equipment, comprising Failure Hazard Analysis (FHA), Preliminary System Safety Assessment (PSSA) and System Safety Assessment (SSA). Due to the early design stage, there is little information on details of the drivetrain, so that conducting a full safety assessment is not practical or even possible. For the purpose of getting an overview of failures and risks added to a helicopter drivetrain by implementing Compound Split transmission, we concentrate on FMEA as a method used in SSA.

4.1.1 Defining Functions

Starting point of the FMEA is the definition of the system level to be analysed. A functional FMEA is most suitable for the aim of this study. The focus of a functional FMEA is on the conversion of a given input to an output, i.e., a function in a mathematical sense, without considering how the conversion is done. For example a function transfers oil pressure and oil volume flow into rotational speed and torque. The functional FMEA asks about the consequences when this function is not working any more. The main functions which make up a Compound Split drivetrain were identified and pictured in Figure 10 (electric variator) and Figure 11 (hydrostatic variator).

Four types of functions are distinguished for the Compound Split drivetrain using ***electric*** variator:

- "***Electric Motor***" (eletr. motor)
  This function converts the input parameters Voltage $\boldsymbol{U_m}$, Current $\boldsymbol{I_m}$ and Frequency $\boldsymbol{f_m}$ into the output parameters Rotational Speed $\boldsymbol{n_c}$ and Torque $\boldsymbol{T_c}$.
- "***Electric Generator***" (gen.)
  This function converts the input parameters Rotational Speed $\boldsymbol{n_d}$ and Torque $\boldsymbol{T_d}$ into the output parameters Voltage $\boldsymbol{U_g}$, Current $\boldsymbol{I_g}$ and Frequency $\boldsymbol{f_g}$.
- "***Epicyclic Gear Set 1***" (EGS C)
  This function converts the input parameters Torque $\boldsymbol{T_a}$ and $\boldsymbol{T_c}$ and Rotational Speed $\boldsymbol{n_a}$ and $\boldsymbol{n_c}$ into the output parameters Torque $\boldsymbol{T_b}$ and Rotational Speed $\boldsymbol{n_b}$.

- "***Epicyclic Gear Set 2***" (EGS D)
  This function converts the input parameters Torque T_a and Rotational Speed n_a into the output parameters Torque T_b and T_d and Rotational Speed n_b and n_d.

Four types of functions are distinguished for the Compound Split drivetrain using ***hydrostatic*** variator:

- "***Hydraulic Motor***" (hydr. motor)
  This function converts the input parameters Pressure p and Volume Flow q_v into the output parameters Rotational Speed n_c and Torque T_c.
- "***Pump***" (pump)
  This function converts the input parameters Rotational Speed n_d and Torque T_d into the output parameters ressure p and Volume Flow q_v.
- "***Epicyclic Gear Set 1***" (EGS C)
  This function converts the input parameters Torque T_a and T_c and Rotational Speed n_a and n_c into the output parameters Torque T_b and Rotational Speed n_b.
- "***Epicyclic Gear Set 2***" (EGS D)
  This function converts the input parameters Torque T_a and Rotational Speed n_a into the output parameters Torque T_b and T_d and Rotational Speed n_b and n_d.

In the electric variator there is a "true" variator in the power line, a frequency converter. Therefore the input parameters of the electric motor are not the same as the output parameters of the electric generator. But in a hydrostatic variator the output of the pump is the input of the hydraulic motor. This is because the variation achieved by changing the piston stroke of the pump and/or the hydraulic motor.

The functions of the epicyclic gear sets are not described precisely. There is only a part of the torque T_a converted into a part of the torque T_b . The amount depends on the current transmission ratio k_{ab}. But this is not important for the FMEA. Furthermore it can be seen that the epicyclic gear set functions are the same in the hydraulic variation and in the electric variator. So they can be reduced in the FMEA. The function of an epicyclic gear set is the same for two input shafts and one output shaft as for one input shaft and two output shafts. Therefore the remaining two epicyclic gear set functions can be reduced to one for the FMEA. Finally the following five functions are distinguished for the FMEA:

- Electric Motor
- Generator
- Hydraulic Motor
- Pump
- Epicyclic Gear Set

It shall be mentioned that the functions cannot be identified as the related devices directly, since the function is to provide the defined output for given input whereas in real devices the output influences the input.

4.1.2 Executing FMEA

The worksheet used for the functional FMEA is based on a template provided in [9] but several modifications were made to meet the requirements of the study. Most notably, the column for quantitative specification of the probability of each failure mode was removed, since no valid data is available at the moment. The structure of the FMEA worksheet is defined as follows.

- The first column contains the function name
- Next are the failure modes identified for each function.
- Every mode is categorized by its influence on the next

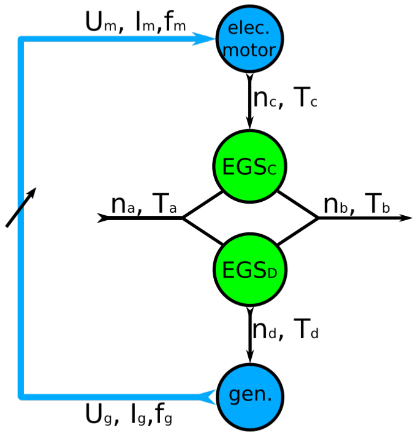

Figure 10: Functional block diagram of Compound Split drivetrain using electric variator

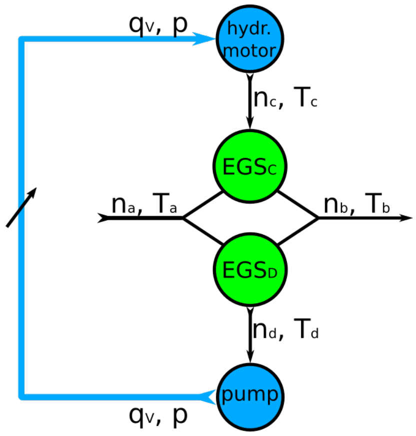

Figure 11: Functional block diagram of Compound Split drivetrain using hydrostatic variator

higher system level, in this special case the drivetrain respectively the entire rotorcraft. This failure effect and a related effect category are entered in columns three and four.
- The following two columns contain failure detection methods and possible causes of each failure mode.
- A core part of each FMEA is the assessment of severity of a failure mode. The US certification standard AC 29-2C [8] provides a system for assigning qualitative severity grades as well as qualitative and quantitative allowable probabilities to failure modes. The severity classes are described in Table 5. For this information three columns are provided.
- The last two columns of the FMEA worksheet describe possible counter measures in case of a failure and the assessed severity of the failure in case this compensating actions operate effectively.

4.2 Results

The results of the FMEA are summarized in the appendix in Table 6 (electric machines), Table 7 (hydrostatic machines) and Table 8 (epicyclic gear sets). In the following there is a description of failure modes, failure effects and compensating actions.

Failure modes

In Table 6 and Table 7 there are six failure modes for each of the four functions: Electric Motor, Generator, Hydraulic Motor and Pump, in total 24. The six failure modes are valid for two output parameters, e.g. Voltage and Current, hence three failure modes for each output parameter.

All 24 failure modes can be reduced therefore to one of the three following failure cases:
- total loss of an output quantity
- low value of an output quantity
- high value of an output quantity

The cases are now independent from the particular output parameters and the failure effects and compensating actions can be directly described according to the failure cases.

In Table 8 five failure modes for the function Epicyclic Gear Set are listed:
- driving shaft gets stucked
- driven shaft gets stucked
- variator shaft gets stucked
- breakage of any shaft
- gear set gets stucked

Failure effects

In Table 6, Table 7 and Table 8 the following failure effects are identified:
1. limited power transfer
   Description: In this failure effect the power transfer in the variator path is limited. The transmission ratio can be changed only in a certain region due to the lack of power. But the rotorcraft can still be operated as the main power flow is on the mechanical path.
   Occurrence: This failure effect occurs in the failure case low output parameter and in the failure mode high rotational speed of the functions Electric Motor and Hydraulic Motor.
   Severity: It is defined as a Major failure of the system.
2. no power transfer
   Description: In this failure effect there is a cut-off of the power transfer from the turboshaft engine to the rotor. The main rotor can rotate free and there is no torque transfer in the system
   Occurrence: This failure effect occurs in the failure case no output parameter except in the failure mode no rotational speed of the functions Electric Motor and Hydraulic Motor. Also for the failure mode breaking of any shaft of the function Epicyclic Gear Set this failure effect occurs.
   Severity: It is defined as a Catastrophic failure of the system.
3. no power transfer and damage on drive train
   Description: In this failure effect there is a cut-off of the power transfer from the turboshaft engine to the rotor. But in this case there is no transfer of rotational speed possible. The main rotor and the turboshaft engine can not rotate freely which leads to an additional damage in the drivetrain.
   Occurrence: This failure effect occurs only in the function Epicyclic Gear Set if the failure mode driven shaft, driving shaft or gear set gets stucked.
   Severity: It is defined as a Catastrophic failure of the system.
4. poor efficiency
   Description: This failure effect decreases the efficiency of the variator path but has no influence on the functionality of the compound split.
   Occurrence: This failure effect occurs in the failure case high output parameter except in the failure mode high rotational speed of the functions Electric Motor and Hydraulic Motor.
   Severity: It is defined as a Minor failure of the system.

5. fixed transmission ratio
   Description: In this failure effect the Compound Split looses its ability to change the transmission ratio from the turboshaft engine to the rotor. So the system is working like a transmission system with fixed transmission ratio.
   Occurrence: This failure effect occurs in the failure mode no rotational speed of the functions Electric Motor and Hydraulic Motor. Also the failure mode variator shaft gets stucked of the function Epicyclic gear set leads to this failure effect.
   Severity: It is defined as a Major failure of the system.

Compensation actions

1. overrunning clutch
   An overrunning clutch enables the transmission of rotational speed in one rotation direction. In the other direction it locks. The clutch is positioned in the shaft between the epicyclic gear set and the variator path. It enables a power transmission from or to the variator path but in the case of no torque from the variator path at the shaft the overrunning clutch locks the shaft and the power flow from the turboshaft engine to the rotor is possible with fixed transmission ratio.
   This compensation action can be used for the failure affects “no power transfer” and “fixed transmission ratio” as a back up.
2. clutch system
   The clutch system enables the separation of one epicyclic gear set from the main power flow. In this case the whole power is transferred via the other epicyclic gear set with a constant transmission ratio. This compensation action can be used for the failure effect “no power transfer and damage on drive train”. It can also increase the safety of a rotorcraft without speed variation technology. In such a rotorcraft a failure of the gearbox would end up in a catastrophic failure.
3. adjustment of drivetrain management
   This is an adaptation of the control system of Compound Split system. If there is not enough power in the variator path the controller sets the Compound Split into a save region for example in one mechanical point. Then the rotorcraft can continue the operation.

5. DISCUSSION

The utility analysis of the evaluation parameters showed that transmission systems for rotorcraft should have a high system reliability, the ability to transfer high power and torque as well as a low additional weight increase and the controllability of the speed variation.

Pure continuously variable transmissions – e.g. fluid or friction based systems – have a good controllability but are not highly reliable and can not transfer hight torque or power. Therefore they are not considered to be usable in rotorcraft.

Discrete variable transmission systems based on gears have the ability to transfer high power and torque, have a high power to mass ratio and are highly reliable. But during the transition from one gear to another, the rotor speed can not be controlled.

Description	Severity of failure effect
“Failure conditions which would not significantly reduce rotorcraft safety, and which involve crew actions that are well within the crew capabilities. Minor failure conditions may include, for example, a slight reduction in safety margins or functional capabilities, a slight increase in crew workload, such as routine flight plan changes, or some inconvenience to occupants.” (AC 29-2C, p. C-47)	Minor
“Failure conditions which would reduce the capability of the rotorcraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew work load or in conditions impairing crew efficiency, or discomfort to occupants, possibly including injuries.” (AC 29-2C, p. C-47)	Major
“Failure conditions which would reduce the capability of the rotorcraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be -- (i) A large reduction in safety margins or functional capabilities. (ii)Physical distress or higher workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely. (iii) Serious or fatal injury to a relatively small number of the occupants. (iv) Loss of ability to continue safe flight to a suitable landing site.” (AC 29-2C, p. C-47)	Hazardous
“Failure conditions which would prevent a safe landing.” (AC 29-2C, p. C-47)	Catastrophic

Table 5: Failure severity classes acc. to AC 29-2C [8]

Power Split transmission systems can combine the advantages of continuously variable transmissions and discrete variable transmission systems. There is one mechanical path for the power transmission and one variator path to control the transmission ratio. Therefore this transmission system is the best for usage in rotorcraft.

Three basic types of Power Split transmission are possible: Input Split, Output Split and Compound Split. These types are different in their reactions on changes of the transmission ratio. A comparison of the power flow via the variator path for a spread of 2 showed that the maximum power flow for the Output Split is 66 %, for the Input Split 40% and for the Compound Split 17%. So the Compound Split is the most promising solution.

A FMEA for a Compound Split showed that there are additional sources of failures. But it could be shown that the risks of this new failures are low and that there are countermeasures to negate those risks.

6. CONCLUSION

The investigation could show that continuously variable transmission for rotorcraft can be realised with the Compound Split gearbox configuration. Compound Split offers a high efficiency because of the low power flow via the variator path. Using Compound Split architectures in rotorcraft is an additional risk. But with some additional effort it could also increase the safety compared to state of the art drivetrains.

7. ACKNOWLEDGMENTS

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APPENDIX

FUNCTION NAME	FAILURE MODE	FAILURE EFFECT	FAILURE EFFECT CATEGORY	DETECTION METHOD	POSSIBLE CAUSE	SEVERITY OF FAILURE EFFECTS (AC 29-2C)	ALLOWABLE QUALITATIVE PROBABILITY (AC 29-2C)	ALLOWABLE QUANTITATIVE PROBABILITY (AC 29-2C)	COMPENSATING ACTIONS	Serverty of failure after compensation action
Electric generator	loss of voltage	no power transfer, undefined transmission ratio	2	voltmeter	e.g., failure in V/f control	Catastrophic	Extremely Improbable	< 1.0 E-9	overrunning clutch between shaft and housing	Minor
	low voltage	limited power transfer, limited range of transmission ratios, poor efficiency	1	voltmeter	e.g., failure in V/f control	Major	Remote	1.0E-5 to 1.0E-7	adjustment of drivetrain management, operation with limited transmission ratio	Minor
	high voltage	poor efficiency, increase of temperature	4	voltmeter	e.g., failure in V/f control	Minor	Reasonably probable	1.0E-3 to 1.0E-5	adjustment of drivetrain management, operation with limited transmission ratio	No effect
	no current	no power transfer, undefined transmission ratio	2	ammeter	e.g., failure in V/f control	Catastrophic	Extremely Improbable	< 1.0 E-9	overrunning clutch between shaft and housing	Minor
	low current	limited power transfer, limited range of transmission ratios, poor efficiency	1	ammeter	e.g., failure in V/f control	Major	Remote	1.0E-5 to 1.0E-7	adjustment of drivetrain management, operation with limited transmission ratio	Minor
	high current	poor efficiency, increase of temperature	4	ammeter	e.g., failure in V/f control	Minor	Reasonably probable	1.0E-3 to 1.0E-5	adjustment of drivetrain management, operation with limited transmission ratio	No effect
Electric motor	no rotational speed (stucked)	fixed transmission ratio	5	RPM counter	e.g., seizure, bearing damage	Major	Remote	1.0E-5 to 1.0E-7	defined breaking point, overrunning clutch between shaft and housing	Minor
	low rotational speed	limited power transfer, limited range of transmission ratios, poor efficiency	1	RPM counter	e.g., failure in V/f control	Major	Remote	1.0E-5 to 1.0E-7	adjustment of drivetrain management, operation with limited transmission ratio	Minor
	high rotational speed	limited power transfer, limited range of transmission ratios, poor efficiency	1	RPM counter	e.g., failure in V/f control	Major	Remote	1.0E-5 to 1.0E-7	adjustment of drivetrain management, operation with limited transmission ratio	Minor
	no torque	no power transfer, undefined transmission ratio	2	torque meter	e.g., cable break, failure in V/f control	Catastrophic	Extremely Improbable	< 1.0 E-9	overrunning clutch between shaft and housing	Minor
	low torque	limited power transfer, limited range of transmission ratios, poor efficiency	1	torque meter	e.g., failure in V/f control	Major	Remote	1.0E-5 to 1.0E-7	adjustment of drivetrain management, operation with limited transmission ratio	Minor
	high torque	poor efficiency, increase of temperature	4	torque meter	e.g., failure in V/f control	Minor	Reasonably probable	1.0E-3 to 1.0E-5	adjustment of drivetrain management, operation with limited transmission ratio	No effect

Table 6: FMEA of electric variator functions

FUNCTION NAME	FAILURE MODE	FAILURE EFFECT	FAILURE EFFECT CATEGORY	DETECTION METHOD	POSSIBLE CAUSE	SEVERITY OF FAILURE EFFECTS (AC 29-2C)	ALLOWABLE QUALITATIVE PROBABILITY (AC 29-2C)	ALLOWABLE QUANTITATIVE PROBABILITY (AC 29-2C)	COMPENSATING ACTIONS	Serverty of failure after compensation action
Hydrostatic pump	loss of pressure	no power transfer, undefined transmission ratio	2	pressure indicator	e.g., leakage	Catastrophic	Extremely Improbable	< 1.0 E-9	overrunning clutch between shaft and housing or energy storage	Minor
	low pressure	limited power transfer, limited range of transmission ratios, poor efficiency	1	pressure indicator	e.g., leakage	Major	Remote	1.0E-5 to 1.0E-7	adjustment of drivetrain management, operation with limited transmission ratio	Minor
	high pressure	poor efficiency, increase of temperature	4	pressure indicator	e.g., failure of displacement control	Minor	Reasonably probable	1.0E-3 to 1.0E-5	adjustment of drivetrain management, operation with limited transmission ratio, pressure valve	No effect
	no flow rate	no power transfer, undefined transmission ratio	2	flow display	e.g., failure of displacement control, leakage	Catastrophic	Extremely Improbable	< 1.0 E-9	overrunning clutch between shaft and housing	Minor
	low flow rate	limited power transfer, limited range of transmission ratios, poor efficiency	1	flow display	e.g., failure of displacement control	Major	Remote	1.0E-5 to 1.0E-7	adjustment of drivetrain management, operation with limited transmission ratio	Minor
	high flow rate	poor efficiency, increase of temperature	4	flow display	e.g., failure of displacement control	Minor	Reasonably probable	1.0E-3 to 1.0E-5	adjustment of drivetrain management, operation with limited transmission ratio, valve	No effect
Hydrostatic motor	no rotational speed (stucked)	fixed transmission ratio	5	RPM counter	e.g., seizure, bearing damage	Major	Remote	1.0E-5 to 1.0E-7	overrunning clutch between shaft and housing and pressure valve	Minor
	low rotational speed	limited power transfer, limited range of transmission ratios, poor efficiency	1	RPM counter	e.g., failure of displacement control	Major	Remote	1.0E-5 to 1.0E-7	overrunning clutch	Minor
	high rotational speed	limited power transfer, limited range of transmission ratios, poor efficiency	1	RPM counter	e.g., failure of displacement control	Major	Remote	1.0E-5 to 1.0E-7	overrunning clutch	Minor
	no torque	no power transfer, undefined transmission ratio	2	torque meter	e.g., failure of displacement control, shaft broken	Catastrophic	Extremely Improbable	< 1.0 E-9	overrunning clutch between shaft and housing or energy storage	Minor
	low torque	limited power transfer, limited range of transmission ratios, poor efficiency	1	torque meter	e.g., failure of displacement control	Major	Remote	1.0E-5 to 1.0E-7	adjustment of drivetrain management, operation with limited transmission ratio	Minor
	high torque	poor efficiency, increase of temperature	4	torque meter	e.g., failure of displacement control	Minor	Reasonably probable	1.0E-3 to 1.0E-5	adjustment of drivetrain management, operation with limited transmission ratio	No effect

Table 7: FMEA of hydrostatic variator functions

FUNCTION NAME	FAILURE MODE	FAILURE EFFECT	FAILURE EFFECT CATEGORY	DETECTION METHOD	POSSIBLE CAUSE	SEVERITY OF FAILURE EFFECTS (AC 29-2C)	ALLOWABLE QUALITATIVE PROBABILITY (AC 29-2C)	ALLOWABLE QUANTITATIVE PROBABILITY (AC 29-2C)	COMPENSATING ACTIONS	Serverty of failure after compensation action
Epicyclic gear set	driving shaft gets stucked	no power transfer from TSE to rotor, consequential damages to drivetrain	3	RPM counter	e.g., seizure, bearing damage	Catastrophic	Extremely Improbable	< 1.0 E-9	clutch system	Major
	driven shaft gets stucked	no power transfer from TSE to rotor, consequential damages to drivetrain	3	RPM counter	e.g., seizure, bearing damage	Catastrophic	Extremely Improbable	< 1.0 E-9	clutch system	Major
	variator shaft gets stucked	fixed transmission ratio	5	RPM counter	e.g., seizure, bearing damage	Major	Remote	1.0E-5 to 1.0E-7	overrunning clutch between shaft and housing	Minor
	gear set gets stucked	no power transfer from TSE to rotor, consequential damages to drivetrain	3	RPM counter	e.g., tooth break, bearing damage	Catastrophic	Extremely Improbable	< 1.0 E-9	clutch system	Major
	breakage of any shaft	no power transfer, undefined transmission ratio	2	RPM counter, torque meter	shaft breakage	Catastrophic	Extremely Improbable	< 1.0 E-9	clutch system	Major

Table 8: FMEA of epicyclic gear set in three-shaft operation

Mass and Kinematic Analysis of Compound Split with Simulation of the Shifting Process for Variable Rotor Speed

Hanns Amri	Katharina Hartenthaler	Michael Weigand
Dipl.- Ing.	Dipl.- Ing.	Univ. Prof.
Vienna University of Technology	Vienna University of Technology	Vienna University of Technology
Vienna, Austria	Vienna, Austria	Vienna, Austria

ABSTRACT

The investigation presented in this paper is part of the project VARI-SPEED which aims to invent a speed variable drivetrain for different rotorcraft configurations. A kinematic and a mass analysis of compound split transmissions (CS) variations and a rotorcraft drivetrain simulation model to analyze the dynamic behavior during rotor speed change were performed. All solutions have the same power flow in the variator path but different fixed carrier transmission ratios of the planetary gears, which lead to a difference in mass. CS can be used as two speed transmissions and as continuous variable transmissions (CVT). As a two speed transmission less torque and friction energy is induced in the clutches than in a double clutch transmission, but CVT enable a smooth transition with no friction losses. CS offer the opportunity to vary rotor speed which decreases the overall power demand and lead to a more ecologically efficient rotorcraft aviation.

NOTATION

SYMBOL	DESCRIPTION
a	polynomial coefficient
C	clutch
c_D	drag coefficient
c_L	lift coefficient
CS	Compound Split Transmissions
CVT	Continuous Variable Transmissions
DCT	Double Clutch Transmissions
FMEA	Failure Mode Effect Analysis
FVL	Future Vertical Lift
i	transmission ratio $[-]$
i_0	fixed carrier ratio (planetary gearbox) $[-]$
i_B	basic transmission ratio (compound split) $[-]$
M	torque $[N \cdot m]$
MP	mechanical point (compound split)
m_{PG}	mass of a planetary gear set $[kg]$
N	stationary transmission ratio (planetary gearbox) $[-]$
OP	operation point
P	power $[W]$
PGS	planetary gear set
RPM	Revolutions per Minute
TSE	turboshaft engine
VTOL	Vertical Take Off and Landing

SYMBOL	DESCRIPTION
α	angle of attack $[°]$
φ	variation range$[-]$
ω	rotational speed $[rad/s]$
ω_S	rotational speed of sun gear $[rad/s]$
ω_R	rotational speed of ring gear $[rad/s]$
ω_C	rotational speed of planet carrier $[rad/s]$
1...4	shaft number (compound split)
1...3	stage number (simulation model)
1...2	number of clutch (simulation model)
I	first planetary gear set
II	second planetary gear set
in	input (from turboshaft engine)
out	output (to rotor)
T	turboshaft engine
V	variator

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INTRODUCTION

Current research and development in the US as well as in Europe and in Russia indicates the necessity for variable speed rotor technologies in future rotorcraft. Rotor speed variation is used for two reasons. On one hand rotor speed variation increases the efficiency and reduces the noise of a rotorcraft. On the other hand it is possible to overcome the divergent requirements to the rotor speed in hover and fast forward flight with rotor speed variation.

The National Aeronautic and Space Administration (NASA) *Heavy Lift Rotorcraft System Investigation* (Ref. 13) is a research project which shows the possibility of rotor speed variation to increase the efficiency of the rotorcraft. Three different rotorcraft configurations for passenger transport in short and middle range flights were investigated. A tilt-rotor concept was identified with the highest potential to be economically competitive. The so called *Large Civil Tilt-Rotor Concept* has a transport capacity of 90 passengers in a range of 1850 km (1000 nm) with 155 m/s (300 knots). A variable rotor with a speed variation range of 50% (hover: 200 m/s (650 ft/s); cruise flight: 105 m/s (350 ft/s) (Ref. 6) is required to reach the economical competitiveness of the concept.

Boeings *A160 Hummingbird* is an other good example for improved rotorcraft efficiency due to rotor speed variation. This unmanned aerial vehicle (UAV) set a new record in endurance flight in its class in May 2008. The vehicle was airborne for 18.7 hours (Ref. 16). This was possible due to a two stage transmission gearbox. The rotor and the blades were designed according to the invention, called *Optimum Speed Rotor Technology*, proposed by Karem (Ref. 14).

Airbus Helicopters invented a so-called VARTOMS (Variable Rotor Speed and Torque Matching System) for the H 145 with the goal to reduce noise especially in urban areas and to improve handling qualities. A speed range of 96.5% to 103.5% of the nominal RPM is possible (Ref. 7). A similar system is also used in the Mi-8 class helicopter and its modifications (Ref. 5).

Currently there are two major rotorcraft research programs: the United States "Future Vertical Lift" (FVL) program and the European "Clean Sky 2 - Fast Rotorcraft" program. Both programs intend to develop high speed rotorcraft with excellent hover and vertical take-off and landing (VTOL) capabilities. These two requirements lead to opposite requirements for the rotor speed. Fast forward flight requires a lower rotor speed than hover. Therefore rotor speed variation is beneficial. Future programs are foreseen to focus on noise reduction with variable rotor speed control (Ref. 12). The FVL intends to build two Joint Multi-Role Demonstrators (JMR-TD). One is the Sikorsky Boeing SB-1 DEFIANT and the other is the Bell Helicopter Lockheed-Martin V-280 Valor (Ref. 4). The Clean Sky 2 program comprises to build two demonstrators, the Airbus Helicopters' LifeRCraft and the Leonardo Helicopters' Next Generation Civil Tilt-Rotor (NextGenCTR) (Ref. 12).

H. Amri et. al. (Ref. 2) investigated possible benefits of rotor speed variation and conceivable technical approaches to enable rotor speed variation. A calculation of the required rotor power showed that a power reduction of 23% is possible for a given flight state. The results were achieved with a CAMRAD II simulation model of a CS-27 class helicopter. Furthermore four technology categories were identified as possible candidates to enable rotor speed variation: rotor technology, electric drive technology, turbine technology and gearbox technology.

W. Garre et. al. (Ref. 10) analyzed the possible efficiency increase and enhancement of the flight envelope with rotor speed variation for five different rotorcraft configuration: a single main rotor, a coaxial rotor, a coaxial compound, a tandem and a tilt-rotor configuration. The research was based on different flight states. For every flight state in the flight envelope of each rotorcraft the optimum rotor speed was calculated and the power demand was compared with the power demand at the reference rotor speed. The results were presented in the so called "Garre-Plot" (Ref. 10) and it could be shown that a rotor speed variation of up to 50% is useful for almost all rotorcraft configurations and that it makes sense to use the full range of speed variation. Power savings up to 40% are possible with rotor speed variation. But there are always some flight states where rotor speed variation is not suitable. This is in the original design region of the rotorcraft, where the reference rotor speed is equal to the optimum rotor speed. Therefore rotor speed variation must be evaluated in the context of missions and additional weight to show the potential of rotor speed variation.

H. Amri et. al. (Ref. 3) explored possible technologies for rotor speed variation according to the defined categories in (Ref. 2). Karems optimum speed rotor technology (Ref. 14) seems to be a promising solution for occurring vibrations. The telescopic rotor technology can also reduce required power, but it is more efficient in combination with a rotor speed variation executed with a gearbox or TSE. To use an electric drivetrain is not suitable. A conceptual investigation of serial hybrid systems showed that the mass increase is too high for the usage in a helicopter. Speed variable turbines enable a speed variation in a certain range but for large speed variations the turbine efficiency decreases. The torque loading increases on the whole drivetrain with a decrease of the turbine speed. This leads to a higher gearbox weight. Also the auxiliary units have to be designed for the lower RPM to enable the full functionality at lower speeds, which leads to additional weight. Transmission variable gearboxes could overcome those problems if they are placed close to the main rotor shaft. Then the rest of the drivetrain is not influenced of the speed variation but the weight increase must be within certain limits.

To prove the feasibility of rotor speed variation and to show the effects of different drivetrain technologies on the performance, W. Garre et. al. (Ref. 9) analyzed the rotor speed variation in the context of missions. A two speed transmission and a continuous variable transmission (CVT) were suggested. The results showed that for tilt-rotor and compound rotorcraft a two speed transmission is useful. Their missions have two important sections, one is in hover and the other is fast forward flight. These two types of rotorcraft have the highest increase of efficiency with a speed variable rotor of all investigated types. A CVT system could not increase the efficiency further on. By comparing different missions, continuously variable transmissions are most beneficial for utility rotorcraft.

P. Paschinger et. al. (Ref. 15) explored different gearbox technologies to enable rotor speed variation. Three technology groups were defined: discrete variable gearboxes, pure CVT gearboxes and power split gearboxes. These technologies were evaluated according to their usability in rotorcraft. It could be shown that CVT power split gearboxes have the highest potential to be used in rotorcraft. The analysis of the three basic principles of power split, the input split, the output split and the compound split, showed that compound split have the lowest power flow via the variator path. This is an indicator for the efficiency and the weight. The higher the power flow via the variator path the higher is the weight and the lower the efficiency. The research concluded that compound split transmissions are most suitable for rotor speed variation. A Failure Mode Effect Analysis (FMEA) of the compound split indicated no additional risks in the drivetrain for a rotorcraft which could not be negated with additional measures.

The research described in this paper focuses on the applicability of compound split transmission and its possible design variations. A classification of the different constructive solutions with a kinematic modeling method and a mass estimation model is presented. The shifting process of a compound split and its effects on the drivetrain is simulated and compared to a double clutch transmission and a CVT.

COMPOUND SPLIT INVESTIGATION

Kinematic analysis

At the beginning a short definition of epicyclic gearboxes, also called planetary gearboxes, is given for a better understanding of the compound split variations. Then a kinematic description of a compound split is given and its boundary conditions are defined for the usage in rotorcraft.

Planetary gear definitions: A planetary gearbox, as shown in Figure 1, consists of three shafts. The sun shaft is connected with the sun gear (S), the ring shaft is connected with the ring gear (R) and the planets (P) are rotatable mounted on the planet carrier (C) shaft and mesh with the sun gear and the ring gear.

The planetary gear set has two rotational degrees of freedom and one torsional degree of freedom. The fixed carrier ratio i_0 of a planetary gear set is defined as the ratio between the rotational speed of the sun gear ω_S and the ring gear ω_R with a non rotating planet carrier $\omega_C = 0$ (Equation 1).

$$i_0 = \left.\frac{\omega_S}{\omega_R}\right|_{\omega_C=0} = \frac{\omega_S - \omega_C}{\omega_R - \omega_C} = -11.3... - 1.4 \qquad (1)$$

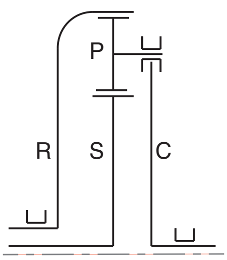


Fig. 1. Scheme of a planetary gearbox: S sun gear, R ring gear, P Planet, C planet carrier

Assignment	Conversion	Range of N
$N = \left.\frac{\omega_S}{\omega_R}\right\|_{\omega_C=0}$	$i_0 = N$	$-11.3 < N < -1.4$
$N = \left.\frac{\omega_R}{\omega_S}\right\|_{\omega_C=0}$	$i_0 = \frac{1}{N}$	$-0.71 < N < -0.09$
$N = \left.\frac{\omega_C}{\omega_S}\right\|_{\omega_R=0}$	$i_0 = 1 - \frac{1}{N}$	$0.08 < N < 0.42$
$N = \left.\frac{\omega_C}{\omega_R}\right\|_{\omega_S=0}$	$i_0 = \frac{N}{N-1}$	$0.58 < N < 0.92$
$N = \left.\frac{\omega_R}{\omega_C}\right\|_{\omega_S=0}$	$i_0 = \frac{1}{1-N}$	$1.09 < N < 1.7$
$N = \left.\frac{\omega_S}{\omega_C}\right\|_{\omega_R=0}$	$i_0 = 1 - N$	$2.4 < N < 12.3$

Table 1. Relationship between fixed carrier ratio i_0 and stationary transmission ratio N

The fixed carrier ratio defines all ratios in the planetary gear set and hence all kinematic characteristics. Due to constructive reasons the fixed carrier ratio i_0 can be between -1.4 and -11.3. The negative sign indicates a change in the direction of rotation. The higher the fixed carrier ratio i_0 is, i.e. close to -1.4, the more planets can be used and the *PGS* is smaller and less heavy.

For the kinematic analysis the scheme of the planetary gearbox as given in Figure 2 was used. The shafts A, B and C can be either the sun shaft, the ring shaft or the planet carrier shaft. N is the transmission ratio from shaft A to shaft B when shaft C is not rotating. N is called stationary transmission ratio.

The assignment of shaft A, B and C to the constructive elements of the planetary gear set (sun gear, planet carrier, ring gear) depends on the value of the stationary transmission ratio N. According to Table 1, N can have values between $N_{min} = -11.3$ and $N_{max} = 12.3$ depending on the arrangements of the shafts. There are some areas in this range where no constructive solutions are possible. In total there are six constructive cases within this range. The relationship between the stationary transmission ratio N and the fixed carrier ratio i_0 as well as the assignment of the shafts is given in Table 1.

Planetary gears are often used in continuous variable transmissions (CVT). With a planetary gear set it is possible to operate the power source at constant speed and simultaneously change the speed of the driven machine with a variator on the third shaft, due to the two rotational degrees of freedom. The

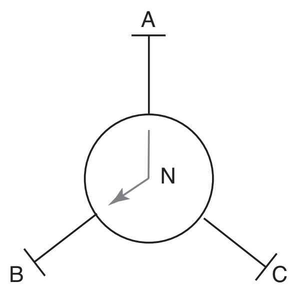


Fig. 2. kinematic scheme of an epicyclic gearbox

variator changes its speed due to power transformation (e.g. converting mechanical power to electric power and back). If a planetary gear set is used as CVT, it has one mechanical point (MP). A mechanical point is defined as a transmission ratio where no power transformation occurs hence the power is only transfered mechanically. Power transformation is always related to a lower efficiency than a direct mechanical transmission. Therefore the mechanical point is important in case of efficiency.

Kinematic description: The structure of a compound split is given in Figure 3 according to the defined scheme of a planetary gear set in Figure 2. A compound split gearbox consists of two planetary gear sets (I and II). Two shafts of the planetary gear sets are connected to each other ($A_I - A_{II}$ and $B_I - B_{II}$). There are two rotational degrees of freedom and two torsional degrees of freedom. The compound split has four shafts to connect (1-4). A random arrangement of the shafts to the boundary conditions (e.g. position of TSE) enables eight kinematic design possibilities of a compound split. Four design possibilities are independent of each other (variant A, B, C, D). The other four possibilities are the exchange of PGS_I and PGS_{II} (variant 1, variant 2). Due to the explained kinematic scheme, it is possible to analyze also the constructive assignment of the shafts of the planetary gear sets without changing the mathematical system.

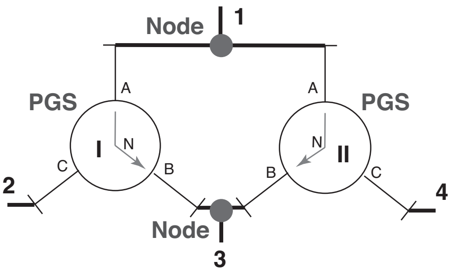


Fig. 3. Scheme of a compound split gearbox

A compound split has four kinematic elements, according to Figure 3. These are two nodes (Node 1 and 3) each with three shafts (e.g. 1, A_I, A_{II}) and two planetary gear sets (PGS I and II) also with three shafts (A, B, C) each. At the nodes the sum of the torque must be zero (Equation 2 for node 1 and Equation 3 for node 3) and the speed of the shafts must be equal (Equation 4 for node 1 and Equation for 5 node 3).

$$M_1 + M_{I_A} + M_{II_A} = 0 \quad (2)$$

$$M_3 + M_{I_B} + M_{II_B} = 0 \quad (3)$$

$$\omega_1 = \omega_{I_A} = \omega_{II_A} \quad (4)$$

$$\omega_3 = \omega_{I_B} = \omega_{II_B} \quad (5)$$

N defines the relationship of the rotational speed (Equation 6) and the relationship of the torques (Equation 8) under the consideration of the torque equilibrium (Equation 7) in a planetary gear set. The equations are valid for both planetary gear sets.

$$N = \frac{\omega_A - \omega_C}{\omega_B - \omega_C} \quad (6)$$

$$M_C + M_A + M_B = 0 \quad (7)$$

$$-N = \frac{M_B}{M_A} \quad (8)$$

Boundary conditions: The following boundary results using the compound split in a rotorcraft for rotor speed variation conditions. One shaft, called input shaft (in), is connected with the turboshaft engine (TSE), another shaft, called output shaft (out), is connected with the rotor, the third shaft is connected with the variator generator (V) and the fourth shaft is connected with the variator motor (V). As the variator generator and the variator motor are part of the compound split, there is no power transfer in and out of the compound split besides the power of turboshaft engine (P_{in}) and the rotor (P_{out}). Power losses would not change the characteristic and therefore they are neglected. The power on the input shaft P_{in} must be the same as on the output shaft P_{out} (Equation 9) and the power which is taken from the variator generator must be equal to the power which is provided by the variator motor (Equation 10).

$$P_{in} = P_{out} \quad (9)$$

$$P_{V_I} = P_{V_{II}} \quad (10)$$

A definition of the operation conditions is needed to enable a comparison of the compound split variations. The basic task of the compound split is to reduce the rotational speed from the input shaft to the output shaft and to vary this reduction. The lowest reduction, or transmission ratio, is called basic transmission ratio i_B. If this transmission ratio is applied, the rotor rotates at highest speed. The ratio between the highest rotor speed and the lowest rotor speed is called variation range φ. P. Paschinger et. al. (Ref. 15) explained that a compound split can vary the transmission ratio between its mechanical points. This means that one mechanical point enables the transmission ratio of i_B (Equation 11), and the other mechanical point has the transmission ratio of $i_B \cdot \varphi$ (Equation 12).

$$MP_I : \frac{\omega_{in}}{\omega_{out}} = i_B \quad (11)$$

$$MP_{II} : \frac{\omega_{in}}{\omega_{out}} = i_B \cdot \varphi \quad (12)$$

Results Compound Split Investigation

The power flow in the variator path and the stationary transmission ratio were investigated with the defined kinematic model of the compound split.

Variator power: The power transmission in the variator path is an important indicator, because it is related to the efficiency of the whole compound split and has a certain impact on the mass. The variator power (Equation 13) for the first engine is calculated under the consideration of Equations 2-10. It shows that the power flow in the variator path depends on the actual transmission ratio i, the basic transmission ratio i_B and the variation range φ. The variator power only depends on the boundary conditions and they are the same for all variations.

$$\frac{P_{V_I}}{P_{in}} = \frac{(i - i_B \cdot \varphi) \cdot (i_B - i)}{i \cdot i_B \cdot (\varphi - 1)} \tag{13}$$

The compound split variations can not be distinguished by the variator power and variator size. A possibility to distinguish the compound split variations can be the planetary gear sets. Therefore a closer investigation of each variant is done.

Variant A: The first variant is shown in Figure 4. The input shaft is shaft 1. The input speed is equal to the speed of shaft 1 (Equation 14) and the torque on shaft 1 depends on the turboshaft engine (Equation 16). The rotor is connected to shaft 3, therefore the output speed is equal to the speed of shaft 3 (Equation 15).

$$\omega_{in} = \omega_1 \tag{14}$$

$$\omega_{out} = \omega_3 \tag{15}$$

$$M_1 = \frac{P_{in}}{\omega_{in}} \tag{16}$$

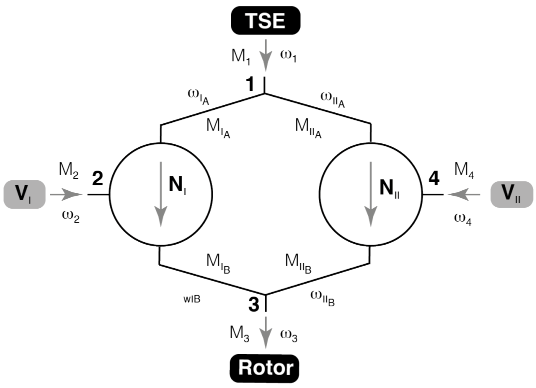


Fig. 4. Compound Split Variant A1

The mechanical points are on the boundaries of the speed range with no variator power. Therefore the mechanical points MP can be defined according to Equation 17 and 18.

$$\begin{aligned} MP(A1)_I &: \left.\frac{\omega_1}{\omega_3}\right|_{\omega_2=0} = i_B \\ MP(A2)_I &: \left.\frac{\omega_1}{\omega_3}\right|_{\omega_4=0} = i_B \end{aligned} \tag{17}$$

$$\begin{aligned} MP(A1)_{II} &: \left.\frac{\omega_1}{\omega_3}\right|_{\omega_4=0} = i_B \cdot \varphi \\ MP(A2)_{II} &: \left.\frac{\omega_1}{\omega_3}\right|_{\omega_2=0} = i_B \cdot \varphi \end{aligned} \tag{18}$$

Computing the Equations 2-10 shows that the stationary transmission ratios are equal to the mechanical points for variant A1 and A2 (Equations 19 and 20).

$$N(A1)_I = N(A2)_{II} = i_B \tag{19}$$

$$N(A1)_{II} = N(A2)_I = i_B \cdot \varphi \tag{20}$$

For variant A1 it can be seen that the maximum input torque of a PGS is equal to the input torque of the compound split and that it occurs in each of the mechanical points. So the whole power is transfered via PGS_I at $MP(A1)_I$ ($i = i_B$, Equation 21). The slower the rotor speed the more power is transfered via PGS_{II} until the lowest rotor speed is reached at $MP(A1)_{II}$ and all power is transfered via PGS_{II} ($i = i_B \cdot \varphi$, Equation 22). The maximum input torque on each planetary gear set (M_{I_A} and M_{II_A}) is the input torque M_1.

$$\frac{M_{I_A}}{M_1} = -\frac{i - i_B \cdot \varphi}{i_B \cdot (\varphi - 1)} \tag{21}$$

$$\frac{M_{II_A}}{M_1} = -\frac{i_B - i}{i_B \cdot (\varphi - 1)} \tag{22}$$

Taking a closer look at the results of Equations 19 and 20) leads to the following realization: Variant A1 and A2 are identical. The change of the arrangement of the PGS has no influence on the kinematic behavior.

Variant B: The next considered variant B is shown in Figure 5. In this variant the variator engines are at the combined shafts 1 and 3 and the rotor and turboshaft engine are connected to shaft 2 and 4. The boundary conditions are given in Equations 23 to 25. The definitions of the mechanical points of variant B are given in the Equations 26 and 27.

$$\omega_{in} = \omega_2 \tag{23}$$

$$\omega_{out} = \omega_4 \tag{24}$$

$$M_2 = \frac{P_{in}}{\omega_2} \tag{25}$$

$$\begin{aligned} MP(B1)_I &: \left.\frac{\omega_2}{\omega_4}\right|_{\omega_3=0} = i_B \\ MP(B2)_I &: \left.\frac{\omega_2}{\omega_4}\right|_{\omega_1=0} = i_B \end{aligned} \tag{26}$$

$$\begin{aligned} MP(B1)_{II} &: \left.\frac{\omega_2}{\omega_4}\right|_{\omega_1=0} = i_B \cdot \varphi \\ MP(B2)_{II} &: \left.\frac{\omega_2}{\omega_4}\right|_{\omega_3=0} = i_B \cdot \varphi \end{aligned} \tag{27}$$

Computing variant B leads to the results for the stationary transmission ratios as given in Equation 28 and 29. The stationary transmission ratios are only depending on the mechanical points, but not as directly as in variant A.

$$\begin{aligned} N(B1)_I &= \frac{\varphi \cdot (i_B - 1)}{i_B \cdot \varphi - 1} \\ N(B2)_I &= \frac{i_B \cdot \varphi - 1}{\varphi \cdot (i_B - 1)} \end{aligned} \tag{28}$$

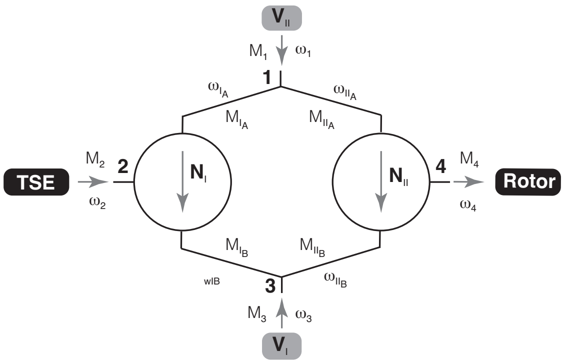


Fig. 5. Compound Split Variant B1

$$N(B1)_{II} = \frac{i_B - 1}{i_B \cdot \varphi - 1}$$
$$N(B2)_{II} = \frac{i_B \cdot \varphi - 1}{i_B - 1} \quad (29)$$

The comparable torque for variant B1 to variant A1 on the planetary gear sets are given in Equations 30 and 31. It can be seen that the torque on the first planetary gear set (PGS_I) is independent of the actual transmission ratio i. The input torque on the planetary gear set is always the input torque M_2 (Equation 25). The input torque on the second planetary gear set (PGS_{II}) depends on the actual transmission i and is higher than the input torque M_2 if $N(B)_I > 1$.

$$\frac{M_{I_A}}{M_2} = -\frac{i_B \cdot \varphi - 1}{\varphi - 1} \quad (30)$$

$$\frac{M_{II_A}}{M_2} = \frac{i \cdot (i_B \cdot \varphi - 1)}{i_B \cdot (\varphi - 1)} \quad (31)$$

Variant C: Figure 6 shows the kinematic scheme of variant C. The turboshaft engine and one variator engine are connected to the combined shafts 1 and 3. The rotor and the other variator engine are connected to the shafts 2 and 4. The boundary conditions are given in Equations 32 to 34. The mechanical points are defined in Equations 35 and 36.

$$\omega_{in} = \omega_1 \quad (32)$$

$$\omega_{out} = \omega_2 \quad (33)$$

$$M_1 = \frac{P_{in}}{\omega_1} \quad (34)$$

$$MP(C1)_I : \left.\frac{\omega_1}{\omega_2}\right|_{\omega_3=0} = i_B$$
$$MP(C2)_I : \left.\frac{\omega_1}{\omega_2}\right|_{\omega_4=0} = i_B \quad (35)$$

$$MP(C1)_{II} : \left.\frac{\omega_1}{\omega_2}\right|_{\omega_4=0} = i_B \cdot \varphi$$
$$MP(C2)_{II} : \left.\frac{\omega_1}{\omega_2}\right|_{\omega_3=0} = i_B \cdot \varphi \quad (36)$$

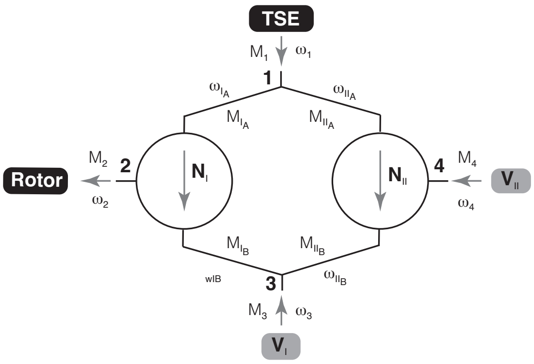


Fig. 6. Compound Split Variant C1

The stationary transmission ratios are given in Equations 37 and 38. Computing the first stationary transmission ratio from the TSE to the rotor with $N(C1_{AC})_I = i_B$ and $N(C2_{AC})_I = i_B \cdot \varphi$ results in the mechanical points. C2 has a higher transmission ratio and therefore a higher mass.

$$N(C1)_I = 1 - i_B$$
$$N(C2)_I = 1 - i_B \cdot \varphi \quad (37)$$

$$N(C1)_{II} = \frac{i_B - 1}{i_B \cdot \varphi - 1}$$
$$N(C2)_{II} = \frac{i_B \cdot \varphi - 1}{\varphi - 1} \quad (38)$$

The comparable torque for C1 to variant A for PGS_I is given in Equation 39. It depends on the actual transmission as in variant A. In the first mechanical point ($MP(C1)_I$; $i = i_B$) the input torque on the planetary gear set is equal to the input torque M_1. In the second mechanical point ($MP(C1)_{II}$; $i = i_B \cdot \varphi$) the input torque on the planetary gear set is the input torque times the variation range ($M_{I_A} = \varphi \cdot M_1|_{i=i_B \cdot \varphi}$), which is not zero as for variant A. As the variation range is always higher than one it means that there is more torque than delivered by the turboshaft engine. Idle power occurs! The comparable torque to variant A for PGS_{II} is given in Equation 40. It is zero for the first mechanical point ($MP(C1)_I$) and for the second mechanical point ($MP(C1)_{II}$) it depends on the transmission variation ratio ($M_{II_A} = M_1 \cdot (\varphi - 1)|_{i=i_B \cdot \varphi}$).

$$\frac{M_{I_A}}{M_1} = \frac{i - 2 \cdot i_B \cdot \varphi + i \cdot \varphi}{i_B - 2 \cdot i + i_B \cdot \varphi} \quad (39)$$

$$\frac{M_{II_A}}{M_1} = \frac{(i_B - i) \cdot (\varphi - 1)}{i_B - 2 \cdot i + i_B \cdot \varphi} \quad (40)$$

Variant D: Figure 7 shows variant D. The turboshaft engine and one variator engine are connected to the shafts 2 and 4 and the rotor and the other variator engine are connected to the combined shafts 3 and 1. The boundary conditions are given in Equations 41 to 43. The mechanical points are defined in Equations 44 and 45.

$$\omega_{in} = \omega_2 \tag{41}$$

$$\omega_{out} = \omega_3 \tag{42}$$

$$M_2 = \frac{P_{in}}{\omega_2} \tag{43}$$

$$\begin{aligned} MP(D1)_I: \ \frac{\omega_2}{\omega_3}\bigg|_{\omega_1=0} &= i_B \\ MP(D2)_I: \ \frac{\omega_2}{\omega_3}\bigg|_{\omega_4=0} &= i_B \end{aligned} \tag{44}$$

$$\begin{aligned} MP(D1)_{II}: \ \frac{\omega_2}{\omega_3}\bigg|_{\omega_4=0} &= i_B \cdot \varphi \\ MP(D2)_{II}: \ \frac{\omega_2}{\omega_3}\bigg|_{\omega_1=0} &= i_B \cdot \varphi \end{aligned} \tag{45}$$

The stationary transmission ratios are given in Equations 46 and 47. Computing the first stationary transmission ratio from the TSE to the rotor indicates that the transmission ratio is equal to the mechanical point. ($N(D1_{CB})_I = i_B$). $N(D2)_I$ has a higher transmission ratio. The second stationary transmission ratio is equal to the first stationary transmission ratio times a function of the variation ratio ($N(D)_{II} = N(D)_I \cdot (1-\varphi)$.

$$\begin{aligned} N(D1)_I &= \frac{i_B}{i_B - 1} \\ N(D2)_I &= \frac{i_B \cdot \varphi}{i_B \cdot \varphi - 1} \end{aligned} \tag{46}$$

$$\begin{aligned} N(D1)_{II} &= \frac{i_B - i_B \cdot \varphi}{i_B - 1} \\ N(D2)_{II} &= \frac{i_B \cdot (\varphi - 1)}{i_B \cdot \varphi - 1} \end{aligned} \tag{47}$$

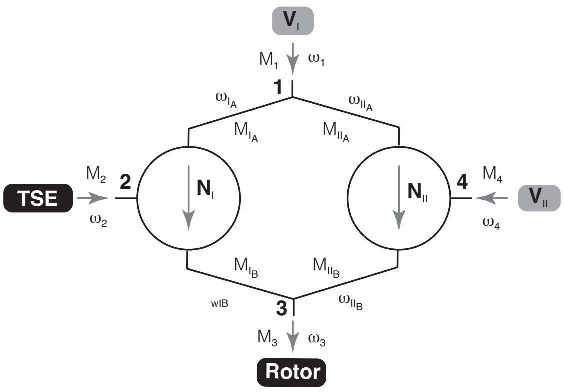


Fig. 7. Compound Split Variant D1

The comparable torque of D1 to variant A for PGS_I is given in Equation 48. It is independent of the actual transmission ratio i and the input torque of PGS_I is equal to the input torque M_2 as in variant B. The comparable torque to variant A for PGS_I is given in Equation 48. The comparable torque to variant A for PGS_{II} is given in Equation 49. It is zero for the first mechanical point ($MP(C1)_I$) and for the second mechanical point ($MP(C1)_{II}$) it depends on the basic transmission ratio ($M_{II_A} = M_1 \cdot (i_B - 1)|_{i=i_B \cdot \varphi}$).

$$\frac{M_{I_A}}{M_2} = i_B - 1 \tag{48}$$

$$\frac{M_{II_A}}{M_2} = -\frac{(i_B - i) \cdot (i_B - 1)}{i_B - 2 \cdot i + i_B \cdot \varphi} \tag{49}$$

GEARBOX MASS ESTIMATION

Mass calculation according to ISO 6336

The compound split variations can be distinguished by the stationary transmission ratio of the planetary gear sets and hence by the fixed carrier ratio of the planetary gear sets. It is difficult to make a decision which variation is the best for rotorcraft based on the fixed carrier ratio. A good decision factor is the mass of the compound split variant based on the basic transmission ratio and the transmission range. The gears of a planetary gear set can be designed according to ISO 6336 (Ref. 8) based on the torque of the sun and the fixed carrier ratio. Therefore the following assumptions were made (ISO 6336-1):

- The maximum number of planets in a planetary gear set is always used.
- The application factor is set to one ($K_A = 1$), because the application is equal for all variants.
- The internal dynamic factor is set to one ($K_V = 1$), because only low RPM occur.
- The face load factor ($K_\beta = 1$) and the transverse load factors ($K_\alpha = 1$) are set to one, because this factors are depending on the construction of the planetary gear set.
- Pressure angle is set to 20 degrees ($\alpha_n = 20°$), as usual for helical gears and the helix angle is set to zero ($\beta = 0°$).
- There is no profile shift ($x = 0$).
- The minimum number of teeth of the gears is set to $z_{min} = 17$.
- The face width is defined as 88% of the diameter of the smallest gear. This factor is usual for case hardened gears.

Computing the gear geometry and the mass according to ISO 6336 with this assumptions in dependency of the fixed carrier ratio and the input torque leads to a very complex equation which is not given here. But it was possible to solve the problem analytically by executing the following steps:

- Calculating the tooth load as a function of the number of planets, number of teeth of the smallest gear, the module and the torque.
- Calculating the number of planets as a function of the fixed carrier ratio.
- Transforming the safety of surface durability (ISO 6336-2) and the safety of tooth bending strength (ISO 6336-3) as a function of the module, the torque, number of teeth of the smallest gear and the fixed carrier ratio.
- Transforming the two equations to the module and finding the two real solutions for the module, one for the durability and one for the tooth bending strength.
- Using z_{min} for the number of teeth of the smallest gear, the safety of tooth bending is set to 1.2 and the safety of surface durability to 1.0. Then the module is only a function of the fixed carrier ratio and the torque.
- The gears were estimated as cylinders. With the density of steel $7850\,{}^{kg}/_{m^3}$ the mass could be calculated.

As a result, it can be seen that the torque increases the mass of a planetary gear set linearly and the fixed carrier ratio up to the power of two. A polynomial function was calculated based on the result of the ISO 6336 calculation. The polynomial function with its coefficients is given in Equation 50.

$$m_{PG} = (a_0 + a_1 \cdot i_0 + a_2 \cdot i_0^2) \cdot M \quad (50)$$

$$a_0 = -0.0004038177188$$

$$a_1 = -0.0004165768445$$

$$a_2 = 0.0001785895452$$

A comparison of the polynomial function and the results of the ISO 6336 calculation is given in Figure 8. The dotted line represents the polynomial function and the solid line the ISO 6336 calculation. The polynomial function fits quite well to the calculation. The highest error is 0.00026 $kg/N \cdot m$ at $i_0 = -5.5$. This is an error of 2%.

The torque on the sun is always the smallest and the torque on the planet carrier is always the highest on a planetary gear set. The torque on a planetary gear set can be identified by computing Equations 6 to 8. Due to this relationships the fixed carrier ratio can be computed with the torque according to Equation 51.

$$i_0 = 1 + \frac{M_C}{M_S} \quad (51)$$

Gearbox Mass Estimation Results

Figure 17 in the appendix shows the mass of the compound split variations plotted over the basic transmission ratio i_B and the variation range φ. In every plot are all six combinations of shaft connections for the planetary gear sets considered.

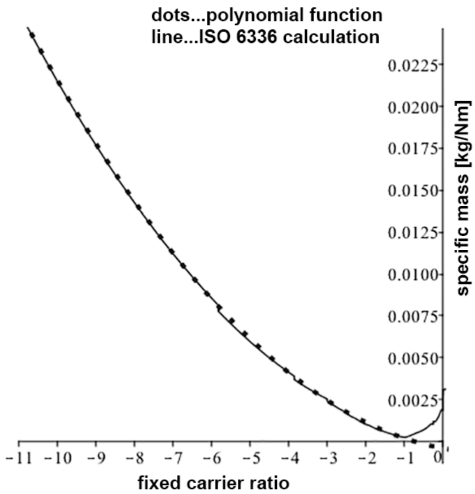


Fig. 8. Comparison between polynomial function and ISO 6336-1 calculation of the planetary gear set mass

The variants A, C2 and D2 enable a high basic transmission ratio combined with a low variation range. Their maximum weight is lower compared to the variants B, C1 and D1. The variants B, C1 and D1 enable a high basic transmission ratio combined with a high variation range. Only D1 also enables a high basic transmission ratio combined with a low variation range and therefore a low mass.

Figure 17 shows the maximal variation range for the compound split, whereas the whole range is not applicable for rotorcraft. Rotorcraft need a speed variation range of about $\varphi \sim 1.5$ according to W. Garre (Ref. 9). The absolute value of the basic transmission ratio should be higher than one $|i_B| > 1$ because the turbine speed is higher than the rotor speed. An additional transmission stage is necessary if the basic transmission ratio is smaller than one. For all variations it can be seen (Figure 17) that the negative basic transmission ratio i_B leads to a higher mass than the positive counter part. Figure 9 combines all variants. It shows which variant has the minimum mass in the area of interest. D1 is the dominating variant, but there is an area in which A and C2 are better than D1.

Figure 10 is a cross section through the area at a variation range of 1.5 to illustrate how the mass behaves. C2 is the first possible variant at a basic transmission ratio of 2.25 and the mass is increasing with an increasing basic transmission ratio. Variant A starts at a basic transmission ratio of 2.4 but it is heavier than C2 till 2.8. Its mass is also increasing with an increasing basic transmission. At a basic transmission ratio of 3.3 variant D1 is possible. Its weight is far less than from A and C2 at this point. The mass is more or less equal than from C2 at 2.25. As a higher transmission ratio is more suitable for rotorcraft transmissions. D1 is the preferable variant at a basic transmission ratio of 3.5. Higher basic transmission ratios for D1 adds no additional benefits because an ordinary planetary

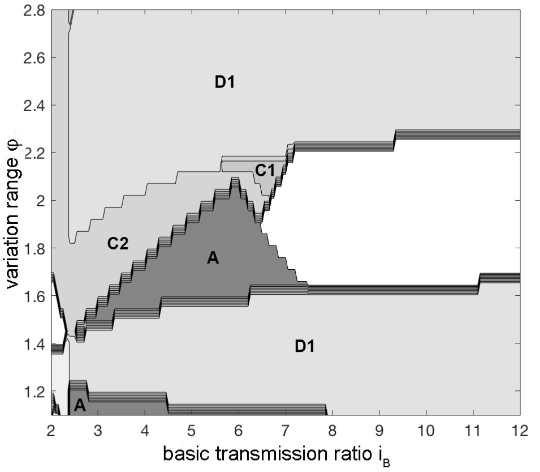


Fig. 9. Comparison of the minimum mass in the area of interest

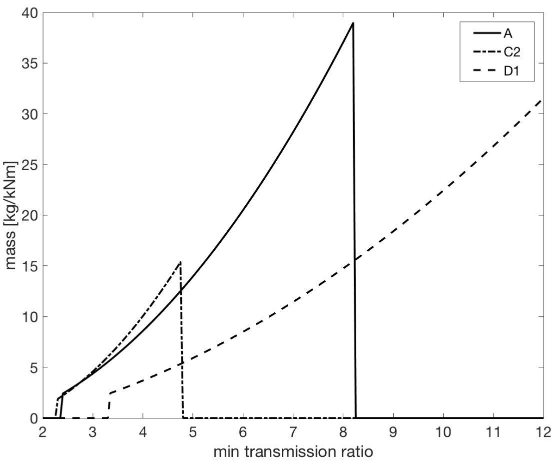


Fig. 10. Mass of A, C2 and D1 at a variation range of 1.5

gear stage has a better mass to torque ratio than any compound split.

SHIFTING PROCESS

A first approach to evaluate the applicability of variable speed transmissions in helicopters was to analyze the behavior of the shifting process.

Model description

Various shiftable transmissions were selected and integrated in a helicopter drive train simulation model. The main purpose was to prove the feasibility of the shifting concepts. Furthermore the results are supposed to show how the components turbine, transmission and rotor interact and influence each other during the transition. Therefore a basic model of the helicopter drive train was built in Matlab Simulink. The rotor should be operated at two different rotor speeds.

- The rotor RPM for hover (higher RPM) is defined with 285 $^1/_{\text{min}}$ (29.85 $^{\text{rad}}/_{\text{s}}$).
- After the shifting process the rotor RPM for forward flight (lower RPM) is decreased to 190 $^1/_{\text{min}}$ (19.89 $^{\text{rad}}/_{\text{s}}$).

For the simulation the shifting duration, the simulation time and the timing for up- and downshift were stated as:

- The whole simulation time was set to 3000 s.
- After 1000 s simulation time the first transition starts (downshift).
- After 2000 s simulation time the second (reverse, upshift) process starts.

Figure 11 shows the principle of the basic drive train which was set up in Matlab. The model consists of a turbine model, a reduction stage i_T, a variable speed gearbox, another reduction stage i_3 and the main rotor.

Fig. 11. Principle of the basic helicopter drivetrain

Turbine: In (Ref. 3) the power and torque characteristics of a two-shaft turboshaft engine were evaluated. Between 100% and 70% RPM the power remains nearly constant. The torque rises constantly when RPM is decreased. At approximately 70% RPM the power is decreasing. Ending at a relative RPM of 50% there is 85% of the reference power left with a torque of 170%. Based on this characteristic the model was set up to simulate the turbine behavior. For the simulation of the turbine the following input data according to a CS-29 helicopter were used:

- The angular velocity of the turboshaft engine is in its operation point 2188 $^{\text{rad}}/_{\text{s}}$
- with a maximum power of both turboshaft engines, which are combined to one, of 2110 kW.
- The inertia of mass for the turboshaft engine was assumed with 8 $kg \cdot m^2$.

The turbine loop integrates a controller, which automatically responds to the change in RPM, by in- or decreasing power. The influence of the approximated mass of inertia was also taken into account.

TSE reduction stage: The first reduction stage i_T reduces the turbine speed to an acceptable input speed for the following variable speed gearbox. This paper focuses on a Double Clutch Transmission (DCT), a general Continuously Variable Transmission (CVT) and the above explained Compound Split Transmission as a two speed transmission (CS). The gearbox placeholder in Figure 11 can be substituted with these gearbox configurations.

Double Clutch Transmission: The Double Clutch Transmission (Figure 12) simulation model switches between two mechanical paths with different transmission ratios i_1 and i_2. For this simulation model the given transmission ratios are used:

- The input gearbox transmission ratio is $i_T = 30.5415$.
- The transmission ratio is $i_1 = 1$ for higher rotor speed.
- The transmission ratio is $i_2 = 1.5$ for lower rotor speed.
- The reduction stage which is designed as an planetary gearbox has the fixed carrier ratio of $i_3 = i_{03} = -1.4$.
- The transition time (i.e. locking/unlocking clutches) $0.04\,s$.

The engaging and disengaging of the paths is realized with two clutches C_1 and C_2. At the beginning C_1 is engaged while C_2 remains unlocked. The rotor operates at high RPM with the transmission ratio i_1. When the shifting process starts, C_1 is disengaging while C_2 is engaging. Now the rotor is operating at low speed under the consideration of i_2. The reverse shifting process (from i_2 to i_1) happens inversely. In the model the friction work which is induced in the clutches during the shifting process is visualized and evaluated.

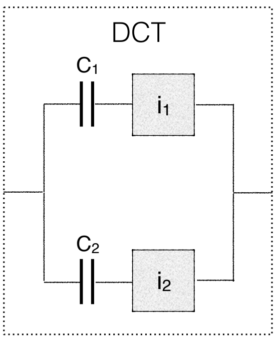


Fig. 12. Double Clutch Transmission

In the model idealized clutches were used with a kinematic friction coefficient of 0.5 and the engagement pressure of Clutch 1 was set to $10\,bar$ and of Clutch 2 to $5\,bar$.

Continuously Variable Transmission: The second simulated gearbox was the Continuously Variable Transmission (Figure 13). The CVT can continuously provide every required speed between i_{CVT1} and i_{CVT2} for different mission requirements. Between these ratios a smooth transition occurs.

- the input gearbox transmission i_T was set to 8.72547
- the transmission ratio for higher speed is $i_{CVT1} = 1$
- after the continuous variation of the transmission ratio for the lower rotor speed is $i_{CVT2} = 1.5$
- the simple reduction stage i_3 has a transmission ratio of 8.40067
- the transition time between i_{CVT1} and i_{CVT2} is $100s$

In the simulation the CVT was idealized. It causes no losses and the dynamic of transmission compliance was unattended.

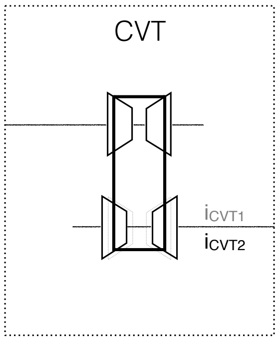


Fig. 13. Continuous Variable Transmission

Compound Split Transmission D1: The Compound Split Transmission (Figure 14) Variant D1, which resulted from the concept finding and the weight estimation process, was simulated in the basic drive train model. The model consists of two epicyclic gearboxes (PGS) with the fixed carrier ratios i_{01}, and i_{02}. Following transmission ratios were defined for the simulation:

- the fixed carrier ratio i_{01} for the first PGS is -2.5, which results in a lower rotor speed
- the fixed carrier ratio i_{02} for the second PGS is -1.43, for the higher rotor speed
- The reduction stage which is designed as an planetary gearbox has the fixed carrier ratio of $i_3 = i_{03} = -1.4$.
- the input gearbox transmission ratio i_T is equal to the CVT with 8.72547
- transition time (i.e. locking/unlocking clutches) $0.04\,s$

The input is connected with the sun gear at the first stage. Both ring gears of the first and second stage are are connected with each other. The carrier of the first PGS is connected with the sun gear of the second stage and to the reduction stage $i_0 3$ To enable speed variation two couplings are mounted. The clutches are alternating engaging and disengaging which causes a change in gear ratio. Clutch 1 (C_1) is mounted between the two ring gears and the second clutch (C_2) at the carrier of the second PGS. The activation of the clutches for the DCT and CS is similar. At the beginning C_1 is locked and C_2 unlocked. The rotor is operating at higher speed. When the shifting process starts, C_1 unlocks while C_2 is engaging. Due to the change in transmission ratio the rotor now operates at lower RPM. The reverse process is performed when C_2 is disengaging and C_1 is engaging. Then the rotor accelerates again.

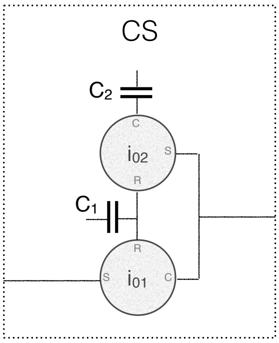


Fig. 14. Compound Split Transmission (R Ring Gear, S Sun Gear, C Carrier, 1 first stage, 2 second stage, C_1 Clutch 1, C_2 Clutch 2)

Rotor: After the following reduction stage i_3 the reduced RPM is used to calculate the rotor behavior in the simulation model. The rotor model is based on the blade-element theory. Therefore a known aerodynamic characteristic of an airfoil based on NACA 23012 (Ref. 1) was used. For the rotor

- 4 blades with an
- blade area of $4.5\,m^2$
- and a mean blade radius of $4\,m$
- under the consideration of an approximated inertia of mass of $8000\,kg \cdot m^2$

were assumed. Data points from the lift and drag coefficient charts were determined. To enable a variation of the coefficients depending on the angle of attack a curve fitting function was calculated. For the lift coefficient c_l the linear function (Equation 52) was used.

$$c_l(\alpha) = 0.105\alpha + 0.1124 \tag{52}$$

Under the consideration of a Reynolds number of $3.0 \cdot 10^6$ the drag coefficient c_d was approximated with the polynomial function in Equation 53.

$$c_d(\alpha) = 0.0008\alpha^2 - 0.0006\alpha + 0.0624 \tag{53}$$

The required lift of $37840.91\,N$ is specified for a hovering condition. Based on this required lift, which should remain constant during the shifting process, the angle of attack is adapted due to the variation of rotor speed. The variation of the angle of attack is limited between 15 and -10 degree. With the current RPM and the angle of attack the lift and drag is calculated for each state of the system. The torque which results from the drag is applied to the drive train as rotor load torque. This torque and the rotor mass inertia influence the turbine behavior.

Simulation Results

The simulation results for the used gearboxes are described in this section. Figure 15a describes the turbine power and Figure15b the provided turbine torque over the angular velocity of the turbine. Figure 15c shows the angular velocity of the turbine over the simulation time. The depicted figures represent the results for the compound split transmission with partial load with the given lift. To demonstrate the behavior of the drive train the maximum lift isn't used. At the beginning of the simulation, the turbine runs up to speed by increasing power and accelerates the drive train (0>2) until the maximum turbine power (1) is reached. The turbine controller slowly reacts to the exceedance of the operational point (2>3) with a decrease of turbine power which reduces RPM until the operational point (OP) is reached (3>4). Until the gear transition (4>4', OP1) the rotor rotates with constant speed (29.85 1/s). After 1000 s simulation time the first shifting process (4') starts to a lower rotor speed. The transmission ratio changes and due to the mass inertia of the rotor the rotor speed can't change abruptly. Hence the turbine has to adapt instantly to the new conditions. The turbines angular velocity increases (4'>5) while the rotor starts to decelerate. The loop controller reacts to the higher turbine speed and reduces the turbine power (4>6) by decreasing fuel feed. Passing nominal speed (6) the turbine needs to balance the reaction moment by increasing power while the turbine is still lowering (6>7). Now the turbine provides enough power (7) to accelerate the system to nominal speed. The turbine increases the power as long as the rotor reaches its operating torque (7>8). Now the rotor operates at nominal speed (8>8', OP2) according to the predefined ratio (19.89 1/s). The reverse process occurs during the shift to the higher rotor speed, which starts after 2000 s simulation time (8'). In this case the rotor has to be accelerated. At the beginning the turbine speed decreases (8'>9) rapidly due to the rotor mass inertia. The loop controller attempts to increase power (8'>10) to accelerate the rotor. The turbine has enough torque due to its characteristic to accelerate the system and reaches the operating point again (10). This methodology for the turbine and rotor behavior is equal for the DCT and the CVT. There are only differences if the transition time during the shifting process varies. For comparison the turbine angular velocity over time for the DCT at 0.04 s (Figure 16a) and the CVT (Figure 16b) at 100 s transition time are presented. As it can be seen in Figure 16b the longer transition time results in a faster and more uniform transition. The drivetrain has more time to adapt to changes in speed, power and torque. The shorter the transition time the more the turbine slips. A main issue of the CS and DCT concept to enable the gear transition are the implemented clutches. Both concepts are basically quite similar in regard to the gear transition. The DCT uses simple spur gears whereas the CS concept is based on planetary gear sets. The torque which has to be transmitted in the clutches for the CS is less than for the DCT. Due to the average lower torque less friction work is induced in the clutches in the CS concept. The results for the friction work and transmitted torque of clutch 1 and 2 of both concepts are summarized in Table 2.

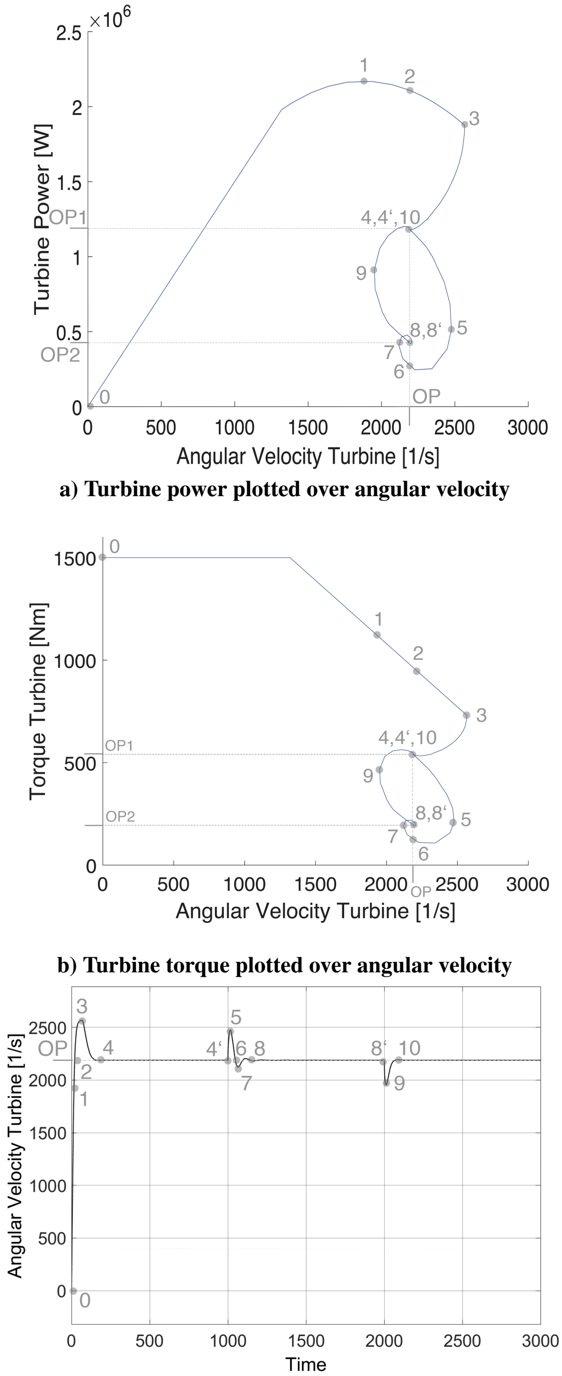
Concerning the clutches the induced friction work has to be dissipated as heat. For this reason the clutches are a main construction part to ensure the functionality (failure safety). Disregarding the dimensioning of the clutches, it can be shown, that the gear transition with a compound split concept, a continuous variable and a double clutch transmission is in principle possible. Comparing those concepts, the CVT offers the best transition behavior, because no friction occurs and the shifting is continuous. The compound split offers less induced friction work than the DCT in the clutches, which leads to smaller clutches with less weight. Hence there are further weight benefits for the applicability of the compound split in a helicopter.

DISCUSSION

The kinematic analysis of variant A shows that it can be used at low variation range with high or low basic transmission ratio. PSG_I has the basic transmission ratio at the stationary transmission ratio $N_I = i_B$. This enables a light weight design. The stationary transmission ratio of PGS_{II} is the highest transmission ratio of the CS $N_{II} = i_B \cdot \varphi$. PGS_{II} PGS_{II} is the limiting factor in CS-A and leads to a high mass increase. The advantage of CS-A is that both *PGS* can be constructed with the sun shaft as input shaft and the carrier shaft as output shaft. This enables the highest transmission ratio in a given *PGS*. The maximum input torque for both *PGS* is equal to the input torque of the *CS*. Both *PGS* have to transmit the total input torque.

In variant B always both *PGS* are in use at every transmission ratio. This enables a high basic transmission ratio i_B combined with a high transmission range φ, but a low transmission range is not possible. The input torque on PSG_I is equal to the input torque of CS at every transmission ratio. The input torque on PSG_{II} is always higher than the input torque of the CS. This leads to a higher mass increase. Variant B is not applicable for rotorcraft.

In variant C an idle power flow occurs. This causes efficiency losses and increases the load on the *PGS*. Therefore CS-C is not applicable.



a) Turbine power plotted over angular velocity

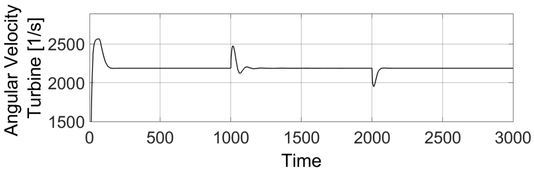
b) Turbine torque plotted over angular velocity

c) Turbine angular velocity plotted over time

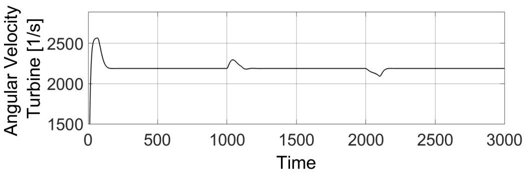
Fig. 15. Compound split simulation results

		Torque		Friction Work (accumulated)	
simulation time		1000 s	2000 s	1000 s	2000 s
CS	Clutch 1	$1.18 \cdot 10^4 N \cdot m$	$0 N \cdot m$	$15.51 J$	$5.16 \cdot 10^5 J$
	Clutch 2	$0 N \cdot m$	$7.29 \cdot 10^3 N \cdot m$	$1.74 \cdot 10^5 J$	$1.74 \cdot 10^5 J$
DCT	Clutch 1	$1.65 \cdot 10^4 N \cdot m$	$0 N \cdot m$	$24.59 J$	$6.54 \cdot 10^5 J$
	Clutch 2	$0 N \cdot m$	$6.01 \cdot 10^3 N \cdot m$	$1.91 \cdot 10^5 J$	$1.91 \cdot 10^5 J$

Table 2. Comparison of compound split (CS) and double clutch (DCT) transmission in terms of torque and friction work in the clutch



a) Turbine angular velocity over time for the DCT at 0.04 s transition time



b) Turbine angular velocity over time for the CVT at 100 s transition time

Fig. 16. Comparison shifting time

Variant D enables a high and low basic transmission ratios combined with high and low transmission ranges. The difference between CS-D1 and CS-D2 is the stationary transmission ratio of PSG_I. The stationary transmission ratio of CS-D1 is the basic transmission ratio $N_I = i_B$ and for $CS-D2$ the stationary transmission ratio the basic transmission ratio times the variation range $N_{II} = i_B \cdot \varphi$ from the TSE to the rotor. Therefore CS-D1 is the preferable variant.

For rotorcraft variant D1 seems to be the most suitable one and if this variant is not possible also variant A could be used. The compound split transmission can be used as CVT and as DCT.

The simulation of the shifting process showed that a CVT solution has the smallest impact on the drivetrain. No friction energy occurs and a smooth transition between the different rotor speeds is possible. Using the CS-D1 as a two speed transmission enables less friction work during the shifting process compared to a DCT. Also the torques on the clutches are lower in the CS solution than in the DCT. This enables a smaller design of the clutches and so a reduction of the mass of the drivetrain.

CONCLUSION

1. All eight compound split variations have the same power flow via the variator path and the power flow depends only on the variation range φ.
2. Compound split variations can be distinguished by the fixed carrier ratio of its planetary gear sets and this has an influence on the mass.
3. Every compound split configuration can have the best mass to torque ratio depending on the basic transmission ratio and the variation range.
4. The variant D1 seems to be the best to be used in rotorcraft for speed variation.
5. A compound split can be used as continuous variable transmission or as two speed transmission.
6. The simulation of the shifting process of a two speed transmission showed a shifting process is possible during rotorcraft operation.
7. Less torque and less friction work occur at the clutches of a compound split transmission than on a comparable double clutch transmission.
8. CVT systems have no friction work and enable a smooth transition between different rotor speeds.

Author contact: Hanns Amri: hanns.amri@tuwien.ac.at; Getreidemarkt 9 / E307-3; 1060 Vienna; AUSTRIA

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APPENDIX

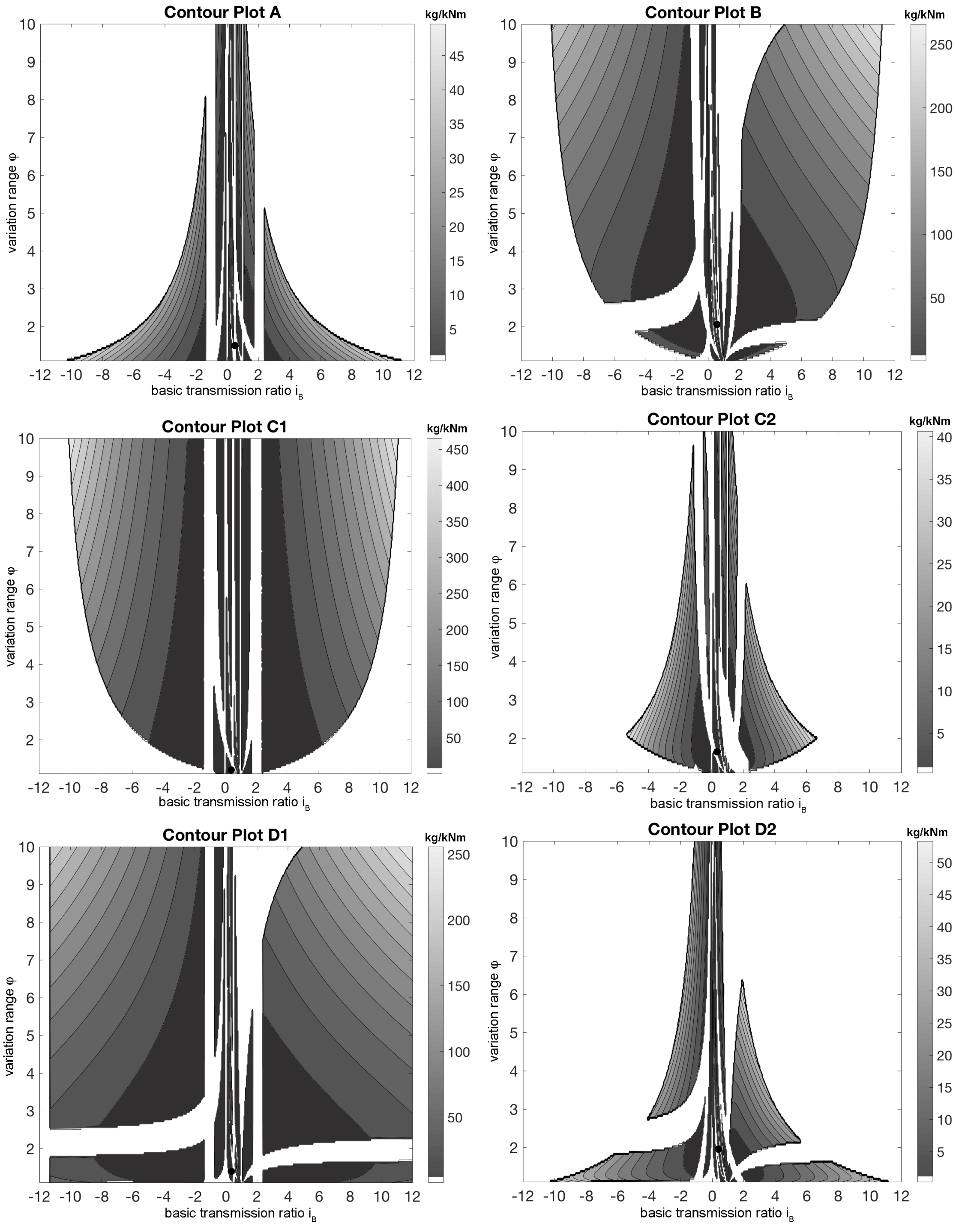

Fig. 17. Mass of compound split variations plotted over basic transmission and variation ratio

Lebenslauf

Persönliche Daten

Name	Hanns AMRI
Adresse	Untere Hauptstraße 1
	2424 Zurndorf
Telefon	+43 676 8822 8785
E-Mail	hanns.amri@icloud.com
Geburtsdatum	18. August 1984 in Wien
Familienstand	verheiratet

Universitäre Arbeitserfahrung

seit 07 / 2016 **Karl Landsteiner Privatuniversität**
Universität für Gesundheitswissenschaften

Tätigkeiten: Lektor in den Gegenständen Mechanik, Mathematik und Informatik

seit 03 / 2013 **Technische Universität Wien**
Fakultät für Maschinenwesen und Betriebswissenschaften
Institut für Konstruktionswissenschaften

seit 03/2013 Universitäts- / Projektassistent in Forschung und Lehre

Lehrtätigkeiten:
Eigenständige Abhaltung von:

- Konstruktionsübungen (in Bachelor und Master)
- Laborübungen (im Master)
- Rechenübungen (im Master)
- Projektarbeiten (im Master)
- Betreuung von Bachelor- und Diplomarbeiten
- Organisation von Gastlehrveranstaltungen

Unterstützung von Vorlesungen und Vorlesungsprüfungen

seit 07 / 2015 Projektleiter des FFG geförderten Forschungsprojektes „VARI-SPEED“ und Doktorand im Forschungsprojekt „VARI-SPEED“
Tätigkeiten:

- Projektantragserstellung / Projektmanagement / Leitung des Projektes
- Koordination der Forschungstätigkeiten innerhalb des Teams
- Koordination mit Unterauftragnehmer und Partner national und international
- Entwicklung und Bewertung eines drehzahlvariablen Antriebsstranges für Hubschrauber

Arbeitserfahrung

von 03 / 2011 bis 02 / 2013 — **Liebherr Transportation Systems GmbH**
Hersteller von Klimaanlagen für Schienenfahrzeuge

Tätigkeiten: Entwicklungsingenieur von Klimaanlagen für Schienenfahrzeuge
Technische Betreuung eines Projektes von der Angebotserstellung bis zur technischen Abnahme, Verantwortung für die Systemtechnik-Schnittstelle für Regelungstechnik und Einkauf, Leitung der Konstruktion

seit 01 / 2012 — **Eigene Landwirtschaft im Nebenerwerb**

Schul- und Berufsbildung

seit 07 / 2015 — **Technische Universität Wien**

Doktorratsstudium im Beriech von Antriebssträngen von Hubschrauber

von 10 / 2004 bis 11 / 2010 — **Technische Universität Wien**

Studienzweig: **Maschinenbau**;
Vertiefung: Transporttechnik und Logistik;
Diplomarbeit aus dem Fachgebiet Regelungstechnik- Titel: „*Simulation der Energieeffizienz einer Heizungs- und Lüftungsanlage bei Schienenfahrzeugen mit bedarfsabhängiger Regelung der Lüftung*“
Während des Studiums folgende Praktika absolviert:
- Siemens Transportation Systems GmbH 2009
- MUS MAX Landmaschinenbau Urch GmbH 2006

von 01 / 2012 bis 07 / 2012 — **Norwegische Universität für Technik und Naturwissenschaften (NTNU)**

Auslandssemester

von 09 / 1998 bis 07 / 2003 — **Höhere Landwirtschaftliche Bundeslehranstalt „Francisco Josephinum“** -Fachrichtung: Landtechnik

Während des Studiums folgende Praktika absolviert:
- TBW Büro für Maschinenbau DI Weintögl 2002
- Azienda Agricola Attilo Cagliani (IT) 2001 - Landwirtschaftlicher Betrieb
- Szigeti OEG 2000 - Schmiede und Schlosserei

Weitere Ausbildung

seit 2003 **Österreichisches Bundesheer**

Ausbildung zum Milizoffizier:
- Derzeit im Militärkommando Salzburg als Verbindungsoffizier
- bis 2016 Kommandofunktion in der Luftraumüberwachung
- Diverse Führungs- / Organisations- / Rethoriklehrgänge
- bis 2004 Einjährig Freiwilligen Ausbildung

seit 2000 **Freiwillige Feuerwehr Zurndorf**

- Ausbildung zum Zugkommandanten
- Ausbildung zum Ausbildner in der Feuerwehr

Technische Fähigkeiten

Computerkenntnisse

★★★★★	MS Office und iWorks (Verschiedene Versionen)
★★★★•	Matlab und Simulink
★★★••	Maple und Maple Sim
★★★••	Mehrkörpersimulation SIMPACK
★★★★•	CAD - NX, Catia, Creo
★★•••	FEM - Nastran
★★★★★	KISSSOFT - Maschinenelemente Berechnungsprogramm
★••••	MDesign - Maschinenelemente Berechnungsprogramm
★••••	Workbench - Maschinenelemente Berechnungsprogramm

Ausbildungen

KISSSOFT Schulungen (Vertiefung, Planetengetriebe)

Sprengbefugter

Kältetechnik Schulung

Anforderungsmanagement: SMART (Fa. Synergio)

Schweißprüfung nach ÖNORM EN 287-1 135 P BW 1.1 S t10 PA bs

Persönliche Fähigkeiten

Sprachen Muttersprache: Deutsch

Englisch in Wort und Schrift

Grundkenntnisse in Italienisch

Führerscheine **A, B, C, E zu C, (F, G)**

Veröffentlichungen

AHS 2018 H. Amri, K. Hartenthaler, M. Weigand: *"Mass and Kinematic Analysis of Compound Split with Simulation of the Shifting Process for Variable Rotor Speed";* Vortrag: AHS International 74th Annual Forum & Technology Display, Phoenix, Arizona, USA, May 14–17, 2018; in AHS International 74th Annual Forum, (2018), AHS_214.

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