POSSIBLE TECHNOLOGIES FOR A VARIABLE ROTOR SPEED ROTORCRAFT DRIVE TRAIN

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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.

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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-

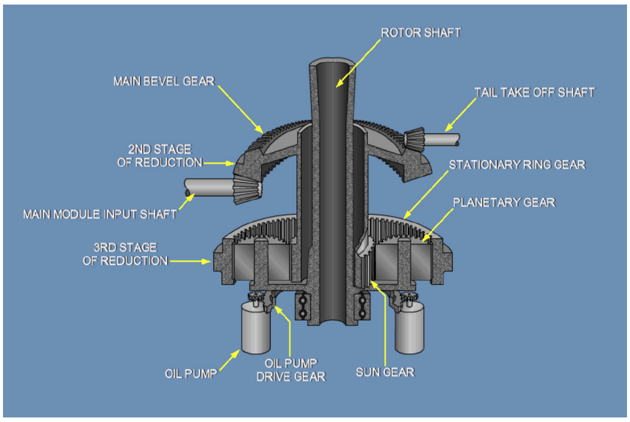

Figure 1: Components of the S-70 main gearbox [6]

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.

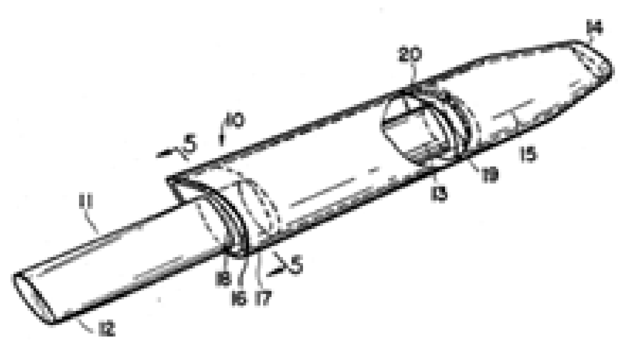

Figure 2: Telescoping rotor blade with linear twist [11]

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 Hybrid	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.

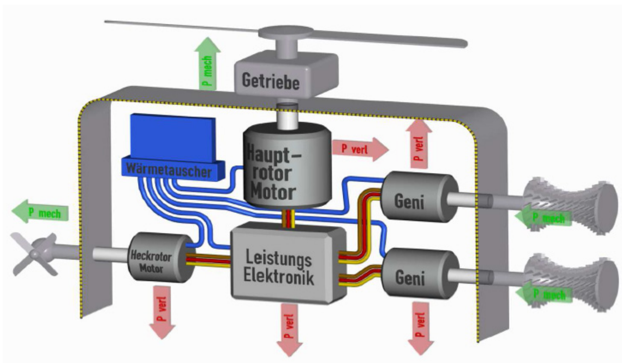

Figure 4: Schematic of the considered system

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, socalled 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-

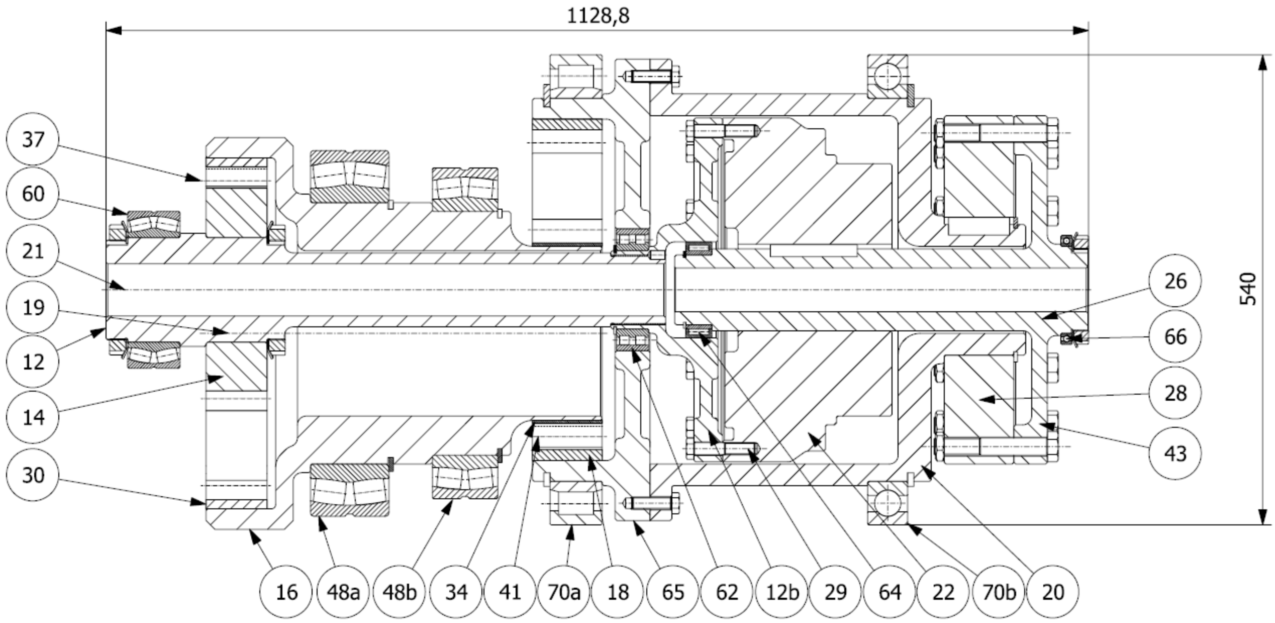

Figure 5: Siemens NX drawing of the designed NASA Offset Compound Gear

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).

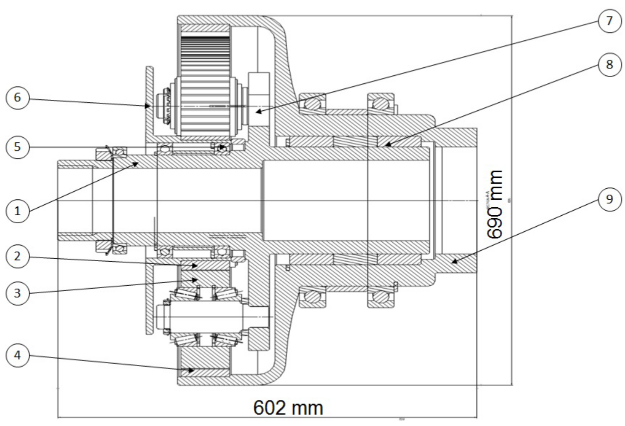

Figure 6: Siemens NX Drawing of the Moore transmission system

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

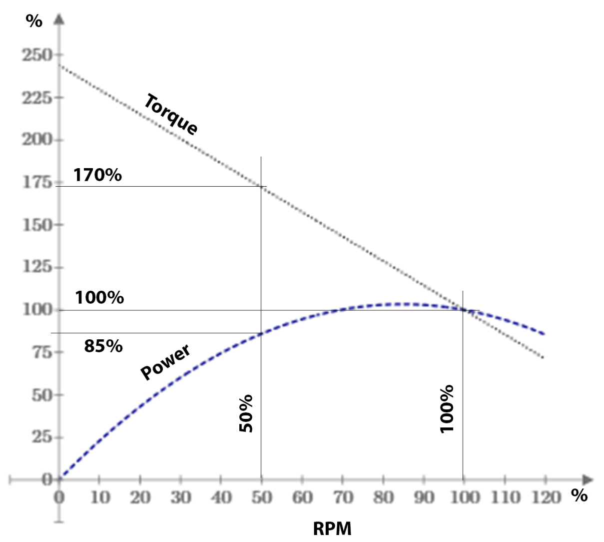

Figure 7: Relative Torque and Power curve drawn over the relative revolution speed

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

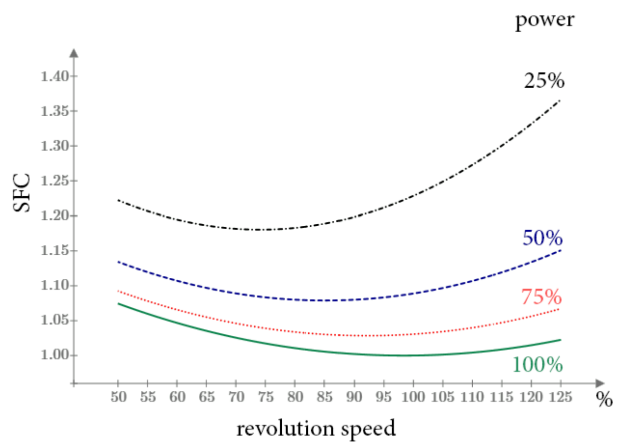

Figure 8: SFC for different relative turndown operations drawn over relative RPM

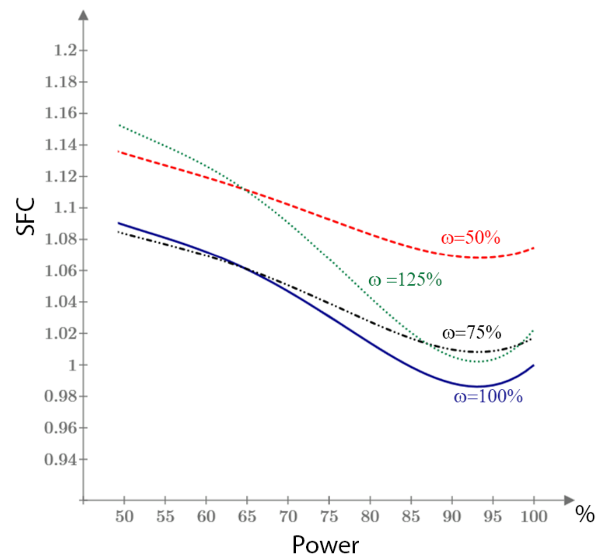

Figure 9: SFC for different relative RPM drawn over relative turndown operations

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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