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COMPOUND-SPLIT DRIVETRAINS FOR ROTORCRAFT

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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-

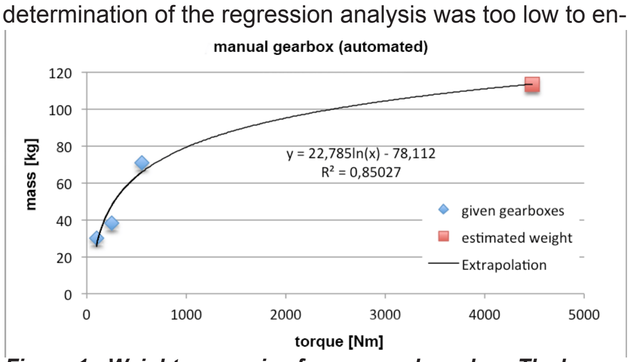

Figure 1: Weight regression for a manual gearbox. The known values are too far from the point of estimation.

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***.

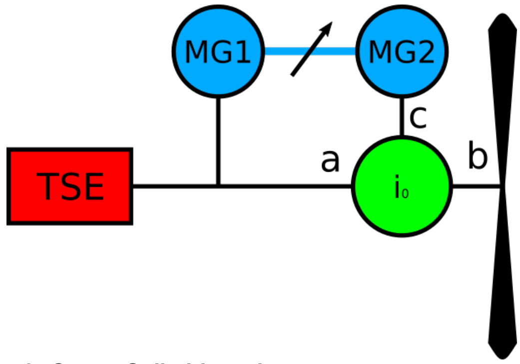

Figure 2: Output Split drivetrain

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 k_{ab} between shafts ***a*** and ***b*** as

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

wherein n_a and 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 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 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 n_b of shaft ***b*** depends on n_a and 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 T_a, T_b and 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 (P_a) can be calculated, with constant ***TSE*** Power 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 (P_c) is given as:

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

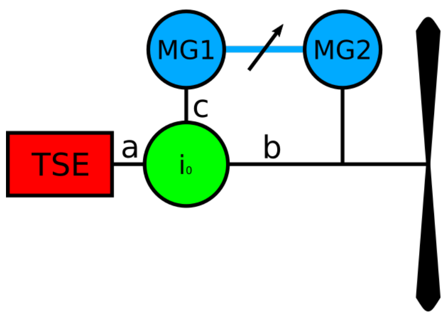

Figure 3: Input Split drivetrain

Obviously, for $k_{ab}=i_0$ 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 $k_{ab}=i_0$. Analogous to Output Split, the power at the variator path (P_c) and the power at the mechanical path (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 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 (n_a, n_c) can be chosen independently and the others are functions of these two speeds. With this con-

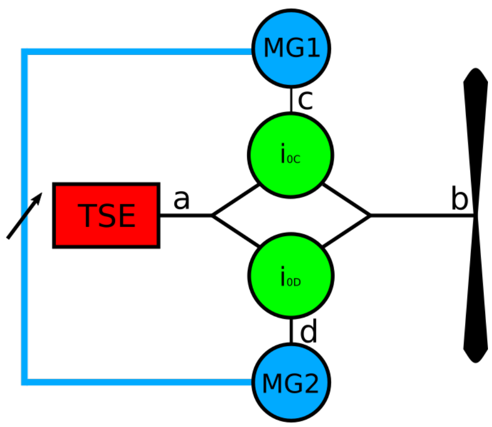

Figure 4: Compound Split drivetrain

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.

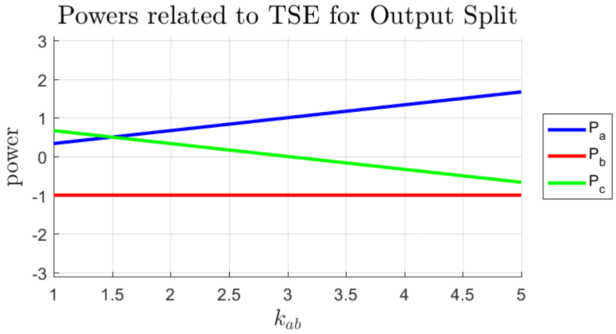

Figure 5: Shaft powers for Output Split architecture

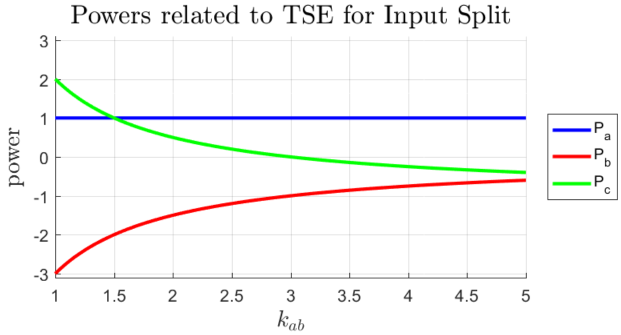

Figure 6: Shaft powers for Input Split architecture

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]).

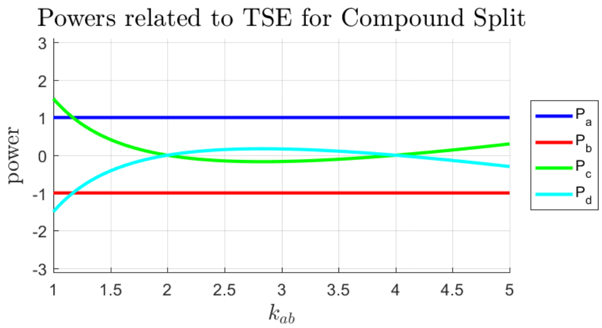

Figure 7: Shaft powers for Compound Split architecture

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]).

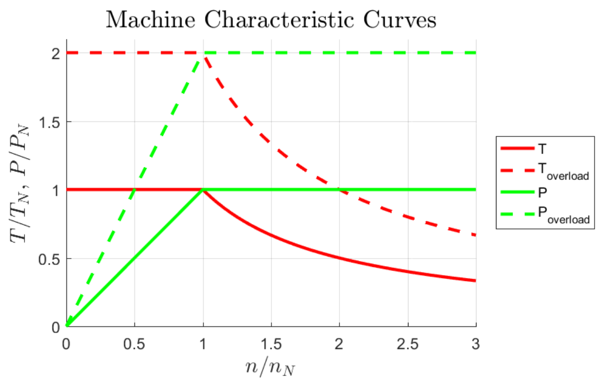

Figure 8: Characteristic curves of variator machines

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., P_{TSE}, and the required spread 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.

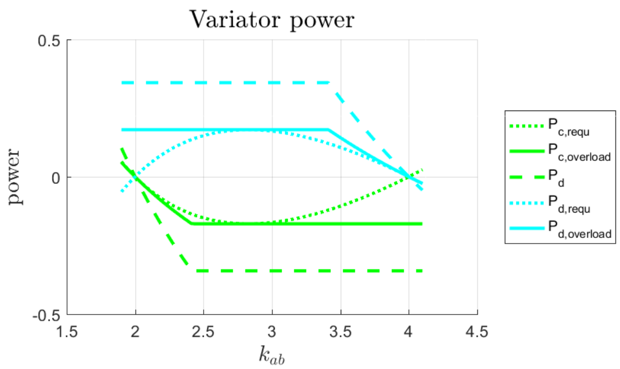

Figure 9: Available variator power compared to demand (Compound Split)

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 U_m, Current I_m and Frequency f_m into the output parameters Rotational Speed n_c and Torque T_c.
- "***Electric Generator***" (gen.)
  This function converts the input parameters Rotational Speed n_d and Torque T_d into the output parameters Voltage U_g, Current I_g and Frequency f_g.
- "***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.

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

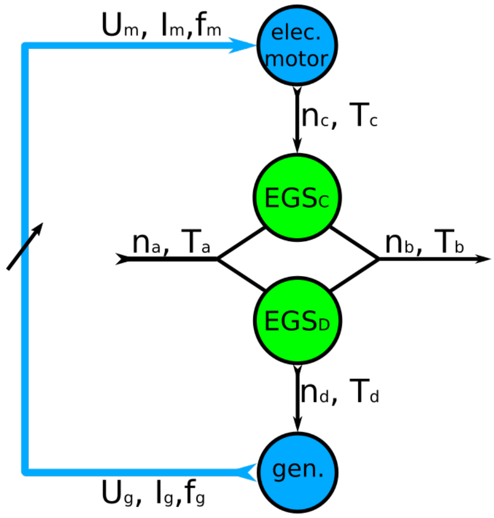

Figure 10: Functional block diagram of Compound Split drivetrain using electric variator

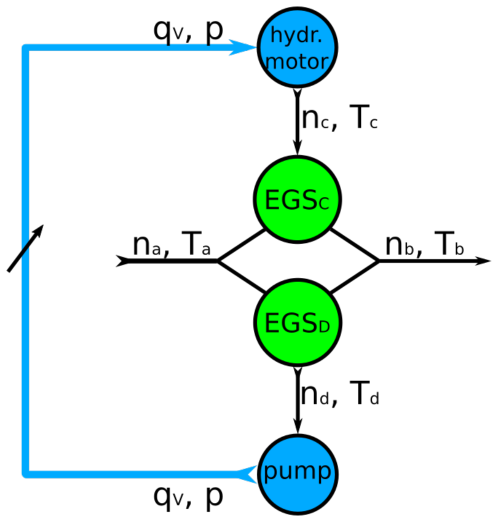

Figure 11: Functional block diagram of Compound Split drivetrain using hydrostatic variator

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
   <u>Description:</u> 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.
   <u>Occurrence:</u> 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.
   <u>Severity:</u> It is defined as a Major failure of the system.
2. no power transfer
   <u>Description:</u> 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
   <u>Occurrence:</u> 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.
   <u>Severity:</u> It is defined as a Catastrophic failure of the system.
3. no power transfer and damage on drive train
   <u>Description:</u> 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.
   <u>Occurrence:</u> This failure effect occurs only in the function Epicyclic Gear Set if the failure mode driven shaft, driving shaft or gear set gets stucked.
   <u>Severity:</u> It is defined as a Catastrophic failure of the system.
4. poor efficiency
   <u>Description:</u> This failure effect decreases the efficiency of the variator path but has no influence on the functionality of the compound split.
   <u>Occurrence:</u> 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.
   <u>Severity:</u> 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

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
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

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