FULL ELECTRIC HELICOPTER ANTI-TORQUE

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Abstract

On the way to complete electric flight, the electrification of helicopter subsystems is an essential milestone. This paper discusses the design of an electric helicopter anti-torque system, which uses Kopter's AW09 helicopter as a platform and shall be tested in ground tests. Analysis of state of the art anti-torque devices for helicopters has helped to identify concepts, which are suitable to be combined with electric propulsion and actuation. Engineering models are used to estimate the power benefits of varied tail rotor RPM, enlarged and steerable vertical stabilizers and drag reducing devices, which cover the rotor in forward flight.

In connection with operational benefits viewed from the OEMs perspective, an architecture is proposed which consists of an electric driven shrouded tail rotor, an electric pitch actuation system and additional aerodynamic surfaces, like a steerable vertical stabilizer and a drag optimized tail rotor cover. The systems were developed according to the results of a safety analysis to meet the requirements of CS-27. The electric tail rotor drive is designed with an internal level of redundancy that allows to compensate for subsystem failures.

Acronyms and Indices

ACU	Actuator Control Unit
AW09	Helicopter Type by Kopter
CAT	Catastrophic
CCA	Common Cause Analysis
CFD	Computational Fluid Dynamics
CS	Certification Specification
DLR	German Aerospace Center
EASA	European Union Aviation Safety Agency
EDAT	Electrically Distributed Anti-Torque
EHPS	Electric / Hybrid Propulsion Systems
EMA	Electromechanical Actuator
FAA	Federal Aviation Administration
FH	Flight Hour
FHA	Functional Hazard Assessment
ICE	Internal Combustion Engine
MCU	Motor Control Unit
NPRD	Nonelectronic Parts Reliability Data
OEM	Original Equipment Manufacturer
PDE	Power Drive Elecrtonics
RBD	Reliability Block Diagram
RMT	Rule Makin Task
RPM	Revolutions per Minute
SC	Special Condition
SCU	Short Circuit Unit
STC	Supplemental Type Certificate (FAA)
TR	Tail Rotor
TUHH	Hamburg University of Technology
UAV	Unmanned Aerial Vehicle
VAST	Versatile Aeromechanics Simulation Tool
ZFL	ZF Luftfahrttechnik GmbH

1. INTRODUCTION

The quest for locally emission-free mobility sparks the use of new propulsion and powertrain concepts also for rotorcraft. Replacing state of the art combustion engines with electric propulsion systems contributes largely to that goal.

ZF Luftfahrttechnik GmbH (ZFL) in cooperation with Kopter Germany GmbH, MACCON GmbH & Co. KG, the Hamburg University of Technology (TUHH) Institute of Aircraft Systems Technology and the German Aerospace Center (DLR) Institute of Flight Systems have started the project "eTail" to investigate, develop and demonstrate suitable means to provide full electric anti torque for helicopters. The project aims to show possible benefits regarding emissions, power consumption, flight characteristics, safety, reliability, human safety and operating costs.

The AW09 helicopter acts as the platform, for which an electric anti torque device is developed.

2. EXTENDED DESIGN SPACE

2.1. State of the Art

The standard configuration for today's helicopters consists of a main rotor and a tail rotor, which counteracts the main rotor torque and controls the helicopter yaw. Besides all advantages there are and historically have been other approaches to counteract the main rotor torque. A conventional tail rotor has a direct connection to the main rotor transmission via a mechanical drive shaft. This connection prevents an independent variation of the tail rotor speed. Consequently, using distributed electric drives to replace this connection widens the scope of conceivable design options.

Both historically as well as recently, numerous patents and invention disclosures have revisited the standard tail rotor configuration. Three main ideas that appeared suitable to be realized in combination with an electric propulsion system were identified.

Already in the early 1950s ideas to vary the tail rotor orientation in flight became public like in [1]. Representative for numerous variations Figure 1 shows that two pivotable 90-degree bevel gear stages are used to power the tail rotor. This way, the rotor can be tilted in horizontal and vertical direction. The cutaway drawing shows the complexity of a complete mechanical solution, which has to integrate the power transfer into the pivoting motion. By using an electric motor, the two functions can be separated. To assess the anticipated beneficial effects of an additional lift or thrust component in hover and forward flight, thrust vectorisation is further discussed in section 2.2 of this paper.

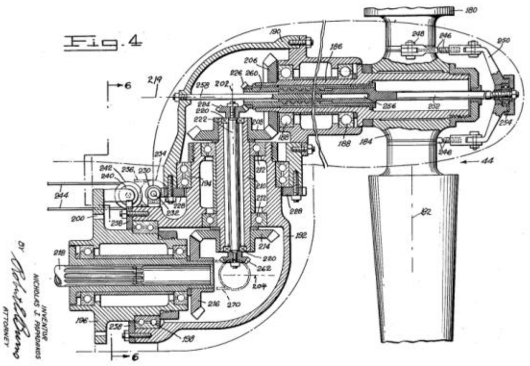

Figure 1: Cutaway drawing of patent US 2,704,128 [1]

A second approach to optimize the power consumption of anti-torque devices is substitution of the rotor by aerodynamic surfaces. In hover flight the main rotor downwash produces dynamic pressure on the tail boom. By manipulating the airflow with strakes or pressurized air blown off through slots, side forces can be produced. In forward flight the direction of the local airflow shifts to a horizontal orientation. Vertical stabilizers can then be used to help counteract the main rotor torque. In [2] and [3] the approach of covering a shrouded tail rotor in forward flight is discussed. Covering and stopping the tail rotor in forward flight disables the helicopters ability to control the movement around its vertical axis. Therefore, a rudder can be introduced to vary side forces as shown in Figure 2.

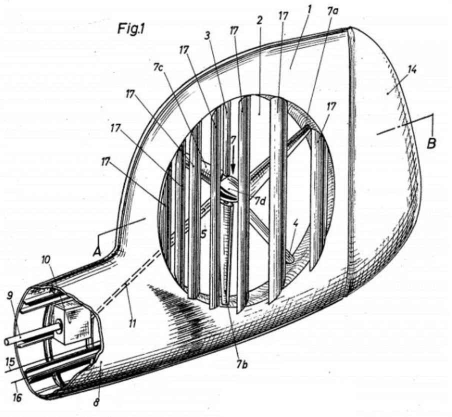

Figure 2: Shrouded tail rotor with vanes and rudder [3]

The third main aspect of electric anti torque devices is the substitution of rotor pitch by rotor RPM as a control variable. Especially modern multicopters and UAVs use RPM variations to modulate thrust. Thereby the rotors can be simplified without the need of a pitch actuation systems. For high agility around the yaw axis however, tail rotor RPM has to change at high rates. Since for electric motors the achievable torque has a big impact on weight, the rotor moment of inertia has to be reduced in order to not to add too much weight to the system. A suitable approach is to use multiple smaller rotors, arranged as an array and driven by individual motors. Bell recently used this concept with its EDAT demonstrator [4].

2.2. Investigation of Unconventional Architectures

To better understand the impact of the described design space, the German aerospace center (DLR) investigates the benefits of different variations of tail rotor and vertical fin settings with respect to power benefits. The investigations are carried out with different variants of an engineering model of the AW09 helicopter. The models are built up in VAST, the Versatile Aeromechanics Simulation Tool [5]. The structural dynamics are represented by a multibody system with rigid bodies that are connected with different types of joints. The loads of fuselage and empennage are calculated based on a comprehensive airloads model with polars based on the airfoils incorporated and considering three-dimensional flow effects.

The main rotor aerodynamics are described by a blade-element model and downwash is accounted for as usual. Since the shrouded tail rotor leads to a very complex flow field changing with operational conditions, a dedicated modeling effort is needed for this component to accurately capture its dynamic behavior. For the preliminary investigations conducted in this study, the tail rotor is treated as an open rotor. Nevertheless, two models of different complexity were investigated. In the simple version, a simple analytic tail rotor model as described e.g. by Padfield [6] is used. In a more detailed version, the aerodynamics of the tail rotor are modeled with the same sophistication as the main rotor.

First, the potential benefits of tilting the tail rotor vertically (to generate upward thrust) or horizontally (to generate forward thrust) were investigated. As shown in [7], neither of these options provides enough power benefit to justify such a complex modification of the shrouded tail rotor and the necessary changes in the flight control system. A fixed horizontal tilt was even found to be counterproductive for all forward flight conditions below maximum flight speed.

For an electrically driven tail rotor, the tail rotor speed is no longer coupled to the main rotor speed via a fixed transmission ratio. Also, with sufficient airflow as present in forward flight, a rudder can generate forces that counteract the main rotor torque. Thus, varying tail rotor speed and using the vertical fin as a rudder were investigated separately and in combination. The results showed the potential of saving more than 2% in overall power in fast forward flight. While the absolute value is small, this power saving is equal to 77 % of the power the tail rotor needs at the according flight speed of 75 m/s for the reference configuration. Even more power could be saved by shutting off the tail rotor (covered inside the closed shroud) for speeds above 50 m/s and using a steerable fin (rudder) for yaw control. Details of these investigations are found in [7].

For an electrically driven tail rotor, the thrust can not only be varied by changing the tail rotor collective control angle but also by changing the tail rotor speed. This means that the tail rotor speed instead of tail rotor collective control can be used to trim the helicopter. Figure 3 shows the comparison between the conventional trim using the tail rotor collective control angle Θ_{TR} for a fixed tail rotor speed $\Omega_{TR,ref}$ and a trim using tail rotor speed Ω_{TR} and a constant tail rotor control angle of 8.6 deg. As can be seen in the right plot, the rotational speed would get very high in low speed flight and hover with a fixed pitch. This would lead to increased noise generation and limit the ability to counteract gust loads by additional speed variations.

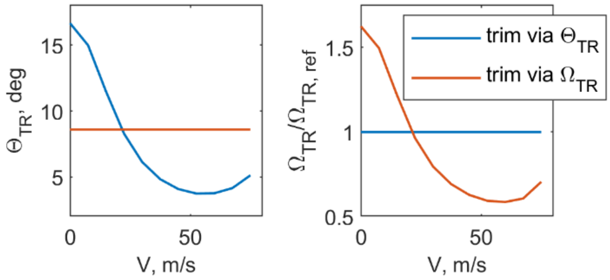

Figure 3: Trim via tail rotor collective Θ_{TR} or tail rotor speed Ω_{TR}

The left part of Figure 4 shows that the trim via tail rotor speed leads to almost 20% higher tail rotor power in hover and low speed flight, whereas the tail rotor power is reduced by 30% in cruise flight at 50 m/s. The influence on the overall power shown on the right of the figure is much smaller but shows a similar tendency. Therefore, retaining the ability to control the blade pitch in addition to varying tail rotor speed seems advisable.

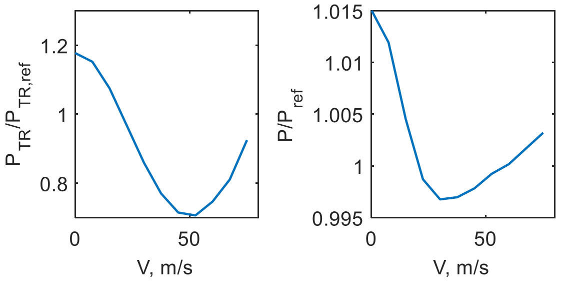

Figure 4: Change in tail rotor power and overall power for trim via tail rotor speed at fixed pitch setting

Investigations reported in [8] show that an additional aerodynamic surface the size of 2% of the main rotor area with a lever arm equivalent to the rotor radius is sufficient to fully counteract the main rotor torque in forward flight. Such an additional surface can be generated by increasing the size of the vertical tail. Therefore, the influence of an increase in fin size for the AW09 was investigated. The results show that an increase of the fin area to about 160% of its current value (corresponding to only about 1% of the rotor area) can completely unload the tail rotor in forward flight. Investigations with an increased fin area of 1 m^2 and different aspect ratios show that a slenderer fin is beneficial in forward flight whereas the influence of the aspect ratio on quartering flight is negligible. Again, more detail can be found in [7].

In addition to the investigations described so far, CFD simulations are used to investigate different variants of tail rotor coverings.

First, the impact of vanes with different angles inside the airflow is analysed. The calculated loss of thrust corresponds to wind tunnel test results published in [9]. Depending on vane position and number, the thrust is reduced by 7-13 % for 90 deg opened vanes on both rotor sides in hover. If the vanes on both sides are closed to 60 deg relative to the tail rotor plane, the thrust reduction rises to ~45 %. Based on these results, thrust vectoring through vanes does not appear profitable so that a suitable system does only need to drive the cover flaps either completely opened or closed.

Next, the orientation of added flaps is investigated. The majority of documented concepts which consider a closing mechanism use vertical vanes as shown in Figure 2.

Over a forward flight velocity of 0, 15 and 30 m/s both drag and produced side force for a flight with open vanes and spinning tail rotor was investigated.

For hover flight both horizontal and vertical vanes reduce the produced side force as discussed before. During the transition to forward flight for a horizontal vane orientation that effect remains almost constant whereas the side force, which can be produced with vertical vanes, is 20% lower than the reference clean tail rotor as shown in Figure 5.

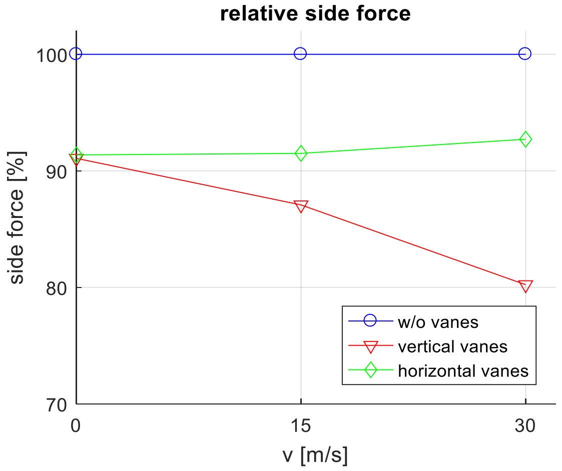

Figure 5: Relative side force of tail rotor without, with vertical and horizontal vanes for 0, 15 and 30 m/s forward flight

This effect can be explained by a bigger drag area of the vertically orientated vanes, which disturb the tail rotor inflow in forward flight. Moreover, it can be shown that the increased surface produces more drag. Compared to a tail rotor without vanes, horizontal vanes create a ~50 % higher drag coefficient whereas vertical vanes increase the drag coefficient by almost 600 % for an airspeed of 30 m/s.

Finally, the impact of different closing methods for the tail rotor were analysed. Therefore, the configuration in Figure 6 was simulated with an open tail rotor, a tail rotor closed on both sides, a tail rotor closed on either the suction or pressure side at a time and a rotor which blocks airflow through the rotor plane (Dirichlet v=0).

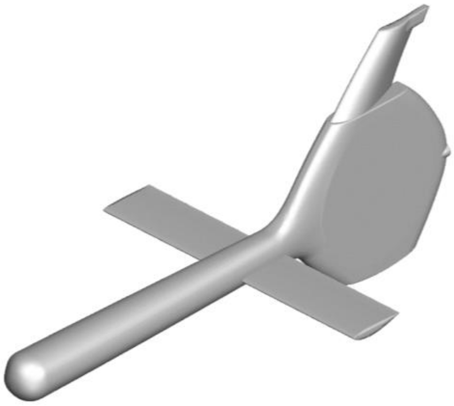

Figure 6: Investigated tail rotor configuration (with closed rotor)

As it can be seen in Figure 7, closing the tail rotor reduces drag and it is most effective to cover both sides. Nonetheless, closing only one side also reduces the drag compared to an open rotor. To cover only the suction side for this configuration is more effective than covering only the pressure side. Particular design aspects of the AW09 configuration like the struts that support the tail rotor gearbox tend to support this choice.

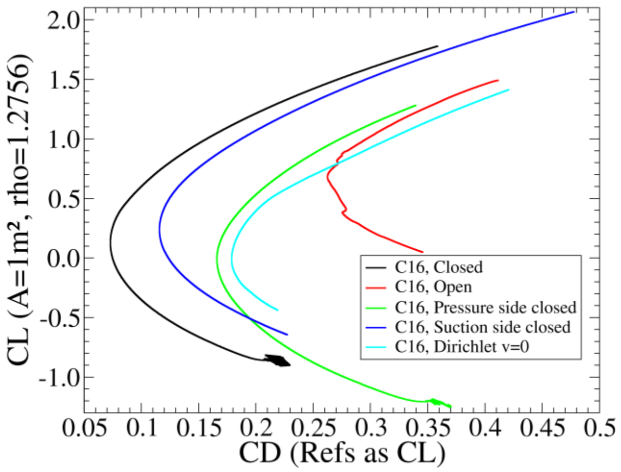

Figure 7: Lift over drag for different tail rotor covering methods at 60 m/s

Considering increasing weight and complexity of a completely closed tail rotor compared to a one-sided coverage, the closure of only the suction side is assessed as preferable for this project. Therefore, horizontal vanes on this side will be used.

3. OEM EXPECTATIONS

Since customer requirements are at least as important as flight mechanical improvements, the OEMs perspective has to be considered to make sustainable design decisions.

As mentioned before, an electrically driven tail rotor provides the additional degree of freedom of rotor RPM. The expectation considering this degree of freedom is to save energy for example by reducing the RPM during cruise flight and thereby reduce the emission of carbon dioxide. Depending on the architecture, another advantage of such a system can be a reduced maintenance effort due to fewer mechanical parts. Despite all the advantages, it is important to satisfy the customers' expectations. One of the main concerns of customers is payload. To minimize the penalty on payload, the system weight of such an innovative configuration must be as low as possible.

3.1. The future of propulsion

The continuing development of electric propulsion systems and especially the storage of energy may lead to a full electric rotorcraft in the future. In the meantime, a partial electrification of the drive train will enable the collection of data required for the selection of the most suitable architecture for rotorcraft. Figure 8 shows a concept for increasing the electrification of the AW09. The intention in this case is to combine the electric tail rotor with a hybrid drive train in general, which requires a source of electric energy for both propulsive elements, the main rotor drive and the anti-torque device. Such a configuration may allow a smaller internal combustion engine (ICE) and is thus further capable of fulfilling the challenging customer demand for a high payload.

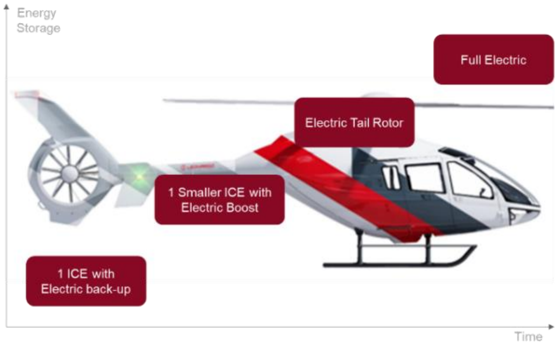

Figure 8: Electrification schedule for the AW09

Despite those positive factors, such a system will likely not be available as a retrofit. As shown in Figure 9, considering only the electric anti-torque system itself, there are already interfaces to complex systems like the gas turbine. This setup is necessary to provide the electric energy required, but it definitely needs a lot of effort to realize those interfaces in the existing conventional rotorcraft.

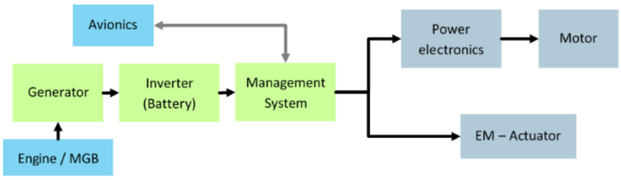

Figure 9: Concept for electric energy supply

Despite the effort, components like the generator attached to the engine or the main transmission require a configuration with new power take-off stages and thus a different gearbox design. This change requires at least a new supplemental type certificate (STC). This additional expense for the manufacturer will inevitably lead to an increase in the purchase price. In order to compensate for the higher price of this configuration, there have to be advantages in daily operation for the customer.

3.2. Operational benefits

Many rotorcraft operate in the emergency medical service sector. This operational field often relates to congested areas and the work of crewmembers and medical personnel close to the tail rotor. To improve safety in this area, there are technical solutions like shrouded tail rotors and systems with a rotor turning inside the structure pushing air through the tailboom. The disadvantages of the latter solution are the technical complexity and the inefficiency in terms of directional control of the aircraft, while a shrouded concept still has the turning rotor blades that endanger personnel working close to it.

The electric propulsion of the tail rotor has the ability to improve the way of torque balancing. Despite the improbable availability of a retrofit solution, this brings advantages to the customer that can definitely lead to a safer, more efficient and less noisy operation of the rotorcraft. This may be achieved by a combination of the modifications investigated in section 2.2. The lower noise level in level flight promises an improved acceptance of flight operations in urban areas, while rapidly stopping the tail rotor on ground is also possible. The latter solves the safety issue of the turning blades, at the same time keeping the aerodynamic efficiency of a conventional tail rotor solution.

4. DESIGN DECISIVE REQUIREMENTS

Inherent to an electric tail rotor drive is its independence from the main rotor RPM. Since a non-rotating rotor cannot develop thrust and the loss of tail rotor thrust might be a catastrophic event, the tail rotor drive has to be developed with a high level of reliability. The approach that is chosen in this project is presented in section 6.

Despite the challenges to achieve that reliability, the option to vary tail rotor RPM offers new possibilities for configuration and reconfiguration in case of malfunction or detected failure.

To produce a specific tail rotor thrust there is a strong interdependence between rotor RPM and rotor pitch. Broadly speaking a higher tail rotor RPM needs a lower pitch setting to develop the same thrust and vice versa. This relationship leads to the two main advantages of an electrically driven tail rotor.

First, the tail rotor can be adapted to operate more economically or with less emissions. Since every blade geometry is optimized to a specific operating point, every deviation throughout the envelope is a loss of efficiency. By introducing a second input variable to the tail rotor, a finer tuning to the designated design optimum is achievable for all operating conditions, compare section 2.2.

Second, for some failure modes of the pitch actuation system and the tail rotor drive, the other system can compensate the failure to maintain at least degraded level of tail rotor thrust variation. For example, the event of a jammed pitch actuation system can be compensated by changing the tail rotor RPM within its defined boundaries. That allows the pilot to trim the helicopter to a desired flight condition and thus offers more margin to execute corresponding emergency procedures.

Inversely, if the tail rotor drive cannot maintain its desired RPM, the pitch actuation system can be used to still achieve the demanded thrust. Nonetheless, a complete loss of tail rotor RPM consequently leads to a complete loss of tail rotor thrust.

As discussed in section 2.2, power benefits can be achieved by introducing steerable aerodynamic surfaces which counteract main rotor torque in forward flight. Regarding the possibilities for reconfiguration during system failures, the articulated surfaces can be used to vary side forces as a function of the flight condition. Compared to fixed vertical stabilizers, which can counteract the main rotor torque at one specific flight condition with one specific yaw angle, if the airspeed is high enough, the proposed rudder also widens the options for pilots to execute emergency procedures.

The combination of all systems is anticipated to achieve power benefits in forward flight conditions, operational benefits like RPM optimization to comply with noise regulations or minimize contact risks on the ground as well as the described possibilities for reconfiguration that increase the survivability in case of an emergency.

5. SYSTEM ARCHITECTURE

Based on the investigation results of the extended design space the team decided to investigate a modular solution. The basic design uses the current AW09s tail rotor components. An electric motor is implemented inside the tail boom to drive the tail rotor. In addition, the pitch actuation system is electrified. An electromechanical actuator is located inside the tail boom and connected mechanically to the tail rotor blades for pitch adjustment.

Based on this concept, an enlarged vertical stabilizer with an electrically actuated rudder is added to unload the tail rotor in forward flight.

As a third and more extensively modified solution compared to the basic design, an adjustable cover of the tail rotor is envisioned.

The following section describes how the system architecture for the eTail project was developed in with regard to the safety regulations.

5.1. Safety regulations

The certification norm of the considered helicopter is the CS-27 [10]. For the purpose of simplicity just the tail boom of the helicopter is considered and specifically the used propulsion method. Further, EASA published the Special Condition E-19 [11] Electric-/Hybrid propulsion system (EHPS). This special condition outlines how an electric propulsion system can be certified in an aircraft. The EHPS was developed in close exchange with the aircraft manufacturers. The SC E-19 gives guidance in design and construction of systems and equipment and the compliance substantiation. These are considered in the process of developing the system.

The EASA also announced the Notice of Proposed Amendment 2021-11: Enhancement of the safety assessment processes for rotorcraft designs, RMT.0712 [12], which would decrease the required safety requirements for the system. In this notice, the safety requirements for the considered helicopter, the Leonardo AW09, would be decreased. The catastrophic failures are classified with a failure rate of $10^{-8}\frac{1}{FH}$ instead of $10^{-9}\frac{1}{FH}$. This results in a decrease of the development assurance level from A to B. This amendment is not accepted yet, but because the FAA has taken a similar approach, it will be taken into account for the following work.

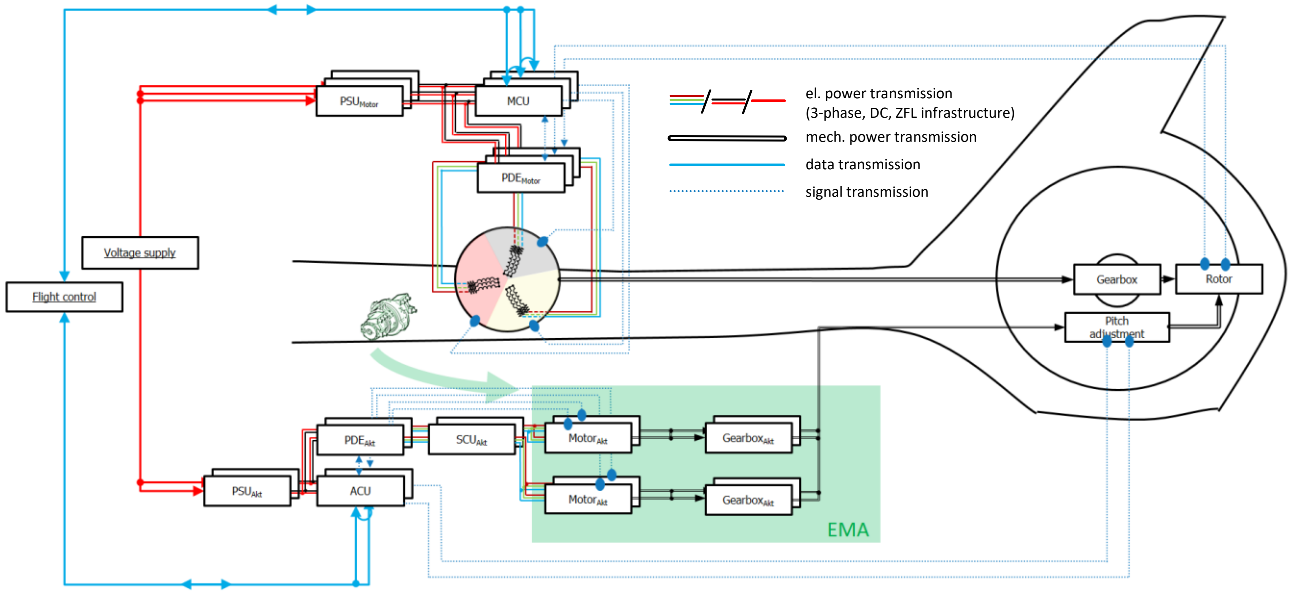

Figure 10: Functional System Architecture with Redundancy

5.2. Required redundancy of the system

To synthesize the architecture of the system, a safety analysis is conducted. From the functional requirements an initial layout is derived. After defining the basic architecture, which fulfils the required functions, a preliminary system safety analysis is performed. It consists of a functional hazard assessment (FHA) and a common cause analysis (CCA). By the FHA it is recognized, that a catastrophic (CAT) failure is possible and therefore a failure rate of $10^{-8}\frac{1}{FH}$ or smaller is required for the whole system.

To determine the level of redundancy, values for the failure rate of the involved components have to be assumed. For this purpose, the values from NPRD-2016 [13] are used, since the empirical data is a suitable substitution for the actual reliability values which still have to be determined.

The functional architecture is transferred into a reliability block diagram (RBD) and the failure rate is calculated based on it. With the given components and their respective failure rates, a simplex architecture is not suited to achieve the required over-all failure rate. For the functional part of the RPM control a failure rate of $7.29 \times 10^{-5}\frac{1}{FH}$ and for the pitch adjustment $1.40 \times 10^{-4}\frac{1}{FH}$ is obtained. The easiest way to get a better result for the failure rate is using redundancy. In Figure 10 the functional system architecture with the chosen redundancy is depicted. The number of blocks for one component is equal to the level of redundancy used.

In a prior project ZFL developed an actuator, which has a very low failure rate. Within the framework of eTail this actuator was chosen to be used. It features a dual-duplex concept, which is shown in the green EMA block in Figure 10. Theoretically, one half of the actuator would be enough to provide the required control performance, but the whole is needed to satisfy the required safety requirements. The failure rate of the whole actuator without power electronics is $10^{-12}\frac{1}{FH}$ and therefore well below the required value. The components with the main contribution to the failure rate are the power electronics. One solution for the power electronics is a duplex variant, where two lanes of power electronics are operating in parallel. When conducting a sensitivity analysis, it became apparent that the ACU has the biggest impact on the failure rate in the power electronics. Therefore, one solution would be to use component-wise redundancy for the ACU. This variation would result in a more complex architecture, but would also approximately half the failure rate. In comparison, the pitch adjustment subsystem would have a failure rate of $9.16 \times 10^{-9}\frac{1}{FH}$ in the pure lane wise redundancy.

For the RPM control, a duplex architecture for the power electronics and the motor is chosen as a first design choice. With this setup a failure rate of $2.89 \times 10^{-9}\frac{1}{FH}$ is achieved. If one adds the failure rate of the pitch adjustment one gets a total failure rate for the whole system of $1.20 \times 10^{-8}\frac{1}{FH}$.

This is above the required failure rate, but just slightly. Because the failure rates used are empirical, this could be a reasonable architecture variant to proceed. Furthermore, if the component-wise redundancy is used as described for the pitch adjustment, a failure rate below $10^{-8}\frac{1}{FH}$ is achieved.

From parallel research by MACCON it was discovered that a duplex architecture for the motor was not sufficient to overcome braking torque in some failure modes. So, a triplex architecture for the motor is used and because the usage of asymmetrical power electronics is not preferred, a triplex architecture is used there as well.

6. TECHNICAL REALIZATION

As the safety analysis of the tail rotor drive has shown, the tail rotor drive and pitch actuation systems require a high level of reliability. Especially for the electric motor, which powers the tail rotor, the objective is the development of a compact solution with internally redundant systems to minimize its geometrical footprint. Even though the safety analysis has shown that a dual redundant system in theory meets the safety requirements, technically a dual system might not be the most suitable solution.

A widespread opinion is that the concept of redundant winding systems is already sufficient to design a motor with a fail-safe structure. But to avoid an undisturbed motor operation by switching over to the faultless redundant system is only a valid measure if the fault can be continuously neutralized in the faulty system. Besides that, the further influence on the overall system has to be confined, so that an emergency operation can be maintained. To guarantee this, internal winding short-circuits are particularly critical, as they cause permanent damping braking torque in the faulty system. In this constellation, the problem cannot be solved by switching off the faulty line and by transferring the operation to the redundant system. If there is no dedicated redundancy structure foreseen in the design, the concept of redundancy is only suitable as a countermeasure to a cable break in the motor supply lines.
The challenge to be addressed by the proposed approach is to find an architecture which can guarantee that no fault occurs which causes permanent damping in the faulty system.

In this context, first of all a fault-tolerant architecture for the driving motor is analyzed with regard to the question whether a duplex or a triplex system is required.
Due to the architecture of the winding design, different numbers of coils are affected by the fault. This may lead to a benefit for a triplex-system compared to a duplex-system although the triplex-system requires much more effort with respect to the power electronics.
A further aspect influencing the decision between duplex or triplex system is related to the scaling of the construction spacing. Two lanes are still operating a triplex system when the failure of one system occurs and a switch-off of this lane is initiated. If a duplex system is in use, only one lane will be available after the switch-off of the faulty lane has been executed.
This circumstance causes that motor has to be oversized by a factor of ~1.3 if the winding design does not feature more active slots for a duplex system working in failure mode compared to a triplex system. In this case it has to be considered that the choice of a suitable slot to pole combination is very limited, if a certain speed and therefore operating frequency has to be achieved.
In this context, it has also to be considered that for a duplex system and a combination of 16 poles and 18 slots, the number of slots per system cannot be freely chosen with regard to the constraints of the winding schematics. Compared to a triplex system, only one additional coil per system is operating. For a duplex system, this leads to a reduction of the power density.
With regard to the structure of the duplex and triplex systems, respectively, the effect of a short circuit of one phase of the coil group towards the lamination core ground will be shown.

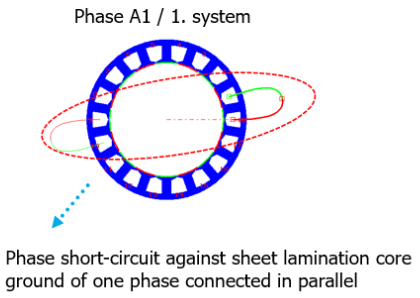

Figure 11: Considering a phase short circuit in a triplex system

How can be seen in Figure 12, a decaying short circuit behavior of the magnetic torque can be detected for the triplex system. It can be concluded that the required motor torque can be achieved after a short period of time, even if the controller has to compensate significantly more torque oscillation.

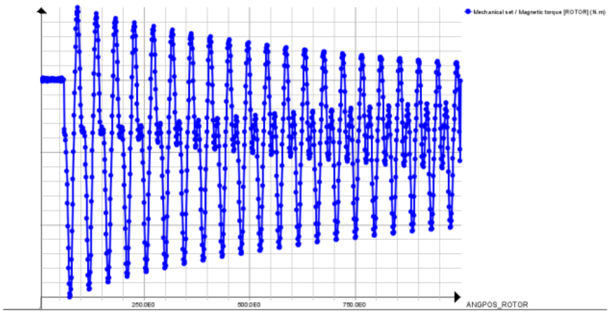

Figure 12: Characteristic of the torque after the occurrence of a shortcircuit

Next, that influence will be considered for a duplex system following a short circuit of one phase of the coil group towards the lamination core ground.

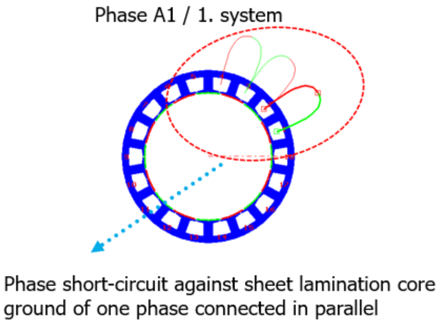

Figure 13: Considering a phase short circuit in a duplex system

As Figure 14 shows, no decaying short circuit behavior of the magnetic torque can be observed for the duplex system. Therefore, it can be concluded that the required motor torque cannot be achieved in the further process of operation.

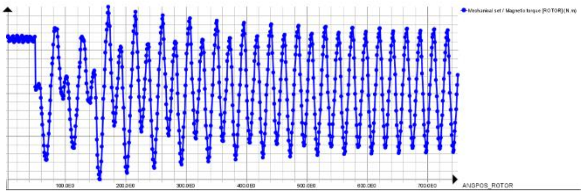

Figure 14: Characteristic of the torque after the occurrence of a short-circuit

This analysis leads to the finding that a triplex-system should be considered within this motor design.

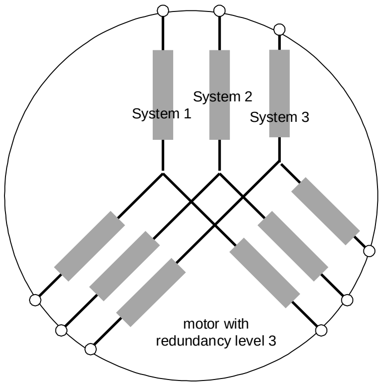

Figure 15: Schematic diagram of a triplex redundant motor

On one hand, as reported in [14] the only method to avoid damping effect conditions is to use electrically isolated systems. On the other hand, the systems have to be designed with an architecture that decouples the individual winding systems. The structure in Figure 15 represents this approach for a triplex system with the possibility to have three fully decoupled systems.

If this fully decoupled function of the phase winding systems is assumed, a triplex motor design can be developed. This concept would consequently allow subsequent operation with limited loss of performance even after a failure of a winding system.

Furthermore, the insulation material has to be designed with multiple insulation layers. In addition, the insulation system must incorporate a thermal reserve of one temperature class above the motor utilization in order to be able to achieve the defect probability of the system with the required failure rate.

So far, the focus has been put on the redundancy architecture. In addition to these considerations, the individual components of the helicopter must be built with very low weight. This is only possible if a gearbox is used, so that the motor operates at the highest possible speed and with reduced torque. In order to be able to achieve the highest possible speed, the rotor must be designed to be robust against the centrifugal forces. Rotors with embedded magnets have proven to be very robust for this purpose. Figure 16 shows this design approach by using a spoke rotor design. Designs with spoke magnets are very robust because the maximum possible amount of rotor material per pole can be used to withstand mechanical forces.

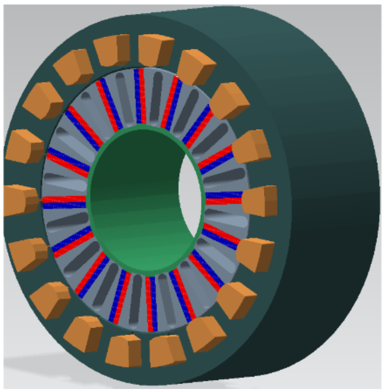

Figure 16: Motor- design with spoke- design rotor

The configuration of a spoke design is a common solution in order to achieve a compromise between power density and mechanical robustness.

For the pitch actuation system, the level of reliability is achieved by using a dual duplex electro mechanical actuator. The pitch adjustment has to meet the failure rate for catastrophic events. Since one motor cannot provide this level of reliability the actuator consist of two individual subparts both with a dual redundant electric motor. The rotational speeds of the subparts sum up to the output rotation speed. Due to the velocity summation, the loss of one subpart leads to a degraded actuation velocity but maintains the specific actuation force. Since the torque of one subpart is transferred to the output via the other subpart, it is crucial to lock the subpart upon a malfunction.

For the rudder actuator, the safety analysis showed that a reduced reliability can be accepted compared to the pitch actuation system. To minimize weight and installation space the level of redundancy of the respective actuator is reduced to a duplex architecture, which cuts both weight and required space by nearly a factor of two.

7. CONCLUSION & OUTLOOK

The analysis has shown that electrification of anti-torque devices extends the design options compared to conventional tail rotors. Especially the additional possibility to vary the rotor RPM in flight and removal of the mechanical link between main and tail rotor offer new possible configurations. Calculations with engineering models were carried out with various comprehensive tools and have identified potential power benefits especially at higher flight speeds. Both a reduced tail rotor RPM as well as an unloaded or completely stopped tail rotor create advantageous conditions. For further drag reduction in fast forward flight, actuated vanes can cover the rotor. However, this solution reduces the achievable tail rotor thrust.

Besides operational advantages as reduced in-flight emissions, the electrification of helicopter subsytems is an important step towards full electric flight. The outcome of this project may help to develop future hybrid- or full electric aircraft.

Based on these findings, it is decided to investigate an electrically driven tail rotor with electric pitch actuation. Furthermore an additional enlarged vertical stabilizer with an electrically actuated rudder and a one-sided cover for the tail rotor in forward flight using horizontal vanes will be developed.

The analysis of the regulatory framework showed that the ongoing RMT.0712 is likely to raise the required failure rates for catastrophic events to $1 \times 10^{-8} \frac{1}{FH}$ for helicopters like the AW09. Based on this assumption and EASA SC E-19 guidelines, the proposed system was analysed and the required level of redundancy defined. For pitch actuation, a duplex setup will meet the requirements, whereby the electric actuator itself will internally have a higher level of redundancy. For the tail rotor drive, a duplex system in theory meets the requirements as well. Analysis of different motor configurations as well as simulations have shown, that to compensate the breaking effect of faulty sub-motors, a triplex architecture is preferred over a duplex one.

Ongoing activities are the refinement of the motor design in accordance with the identified technical requirements and the defined emergency procedures. The maturity of the technology will be demonstrated on an iron bird test stand. Calculated power consumption for hover flight conditions will be verified and the ability to compensate a failure of either the tail rotor drive or the pitch system by the other one will be shown. Furthermore, to take advantage of the option to completely stop the tail rotor in flight, the implementation of an electrically actuated rudder as well as an electrical mechanism to cover the tail rotor at least on one side will be implemented.

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