DEVELOPMENT AND TESTING OF AN ELECTRICAL SWASHPLATE

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Abstract

To support the current trend towards the "more electric rotorcraft", ZF Luftfahrttechnik continues to explore the field of active rotor control within different research programs that focus on electrical actuation technology. One option besides others is the replacement of the conventional hydraulic primary control boosters and their linkages to the non-rotating part of the swashplate by integrated rotatory electrical actuators. This variant yields a compact and efficient solution which has been labeled "Electrical Swashplate".

Based on the broad experience in control system design accumulated during various programs, several alternative concepts of helicopter control systems have been investigated. Based on a detailed technical assessment as part of a comprehensive trade study, different layout variants have been analyzed of which one has been selected for further investigation. This layout was then conceptually sketched and evaluated with respect to its kinematic properties before a full scale laboratory demonstrator was built.

The chosen concept features three electrical internally redundant rotatory actuators which are kinematically connected to the non-rotating part of a ring-shaped swashplate. This paper presents the underlying design concept and discusses the particular features and advantages compared to conventional hydraulic control systems. Further on, the design, fabrication, and test bench integration of a demonstrator specimen are described. Finally, first test results, which bolster the positive feasibility assessment, are summarized.

NOTATION

δ_0	Collective control position [%]
δ_x	Longitudinal (pitch) control position [%]
δ_y	Lateral (roll) control position [%]
α_{x1}	Roll1 actuator position [°]
α_{x2}	Roll2 actuator position [°]
α_y	Longitudinal actuator position [°]
Ψ	Rotor azimuth [°]
EMA	Electro-Mechanical Actuator (acronym)
M	Actuator moment [Nm]
F	Force hydraulic cylinder [N]
T	Temperature [°C]
TEF	Trailing Edge (Blade) Flaps (acronym)
VAR	Fully Active Rotor Control (acronym)

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1. INTRODUCTION

Traditionally, the primary control system of the vast majority of helicopter uses multiple hydraulic and mechanical elements that connect the pilot stick to the blade control horn in the rotating frame. Usually, the control forces, governed by the aerodynamic and inertial properties of the blades, mandate to amplify the pilot inputs by dedicated hydraulic boosters. In most helicopters, these actuators are still mechanically linked to the pilot stick. Only few certified rotorcraft use fly-by-wire systems, which substitute the first part of the mechanical control chain by electrical signals. However, hydraulic power is still needed to actuate the swashplate.

Starting from the idea to stay electrical as long as feasible, ZF Luftfahrttechnik has assessed different types of electrical control systems. It became obvious that rotatory drives were the preferred solution when it comes to reliable and sufficiently redundant systems, which would eventually be capable to satisfy all certification requirements. Therefore, in a second step it was investigated how such drives could be connected to the swashplate as efficient as possible. One aim in particular was to avoid unnecessary conversions from rotatory to linear motion and vice versa. Previous "more electric" attempts had been built upon jackscrew type actuators which transform the rotatory motion of an electrical motor into a linear motion, which at the end of the system of levers and linkages is reverted back into the rotation (i.e. tilt) of the swashplate. It was felt that the intermediate conversion to a linear motion does not provide any significant benefit, while considerably increasing the mechanical complexity.

2. DESIGN OF ELECTRICAL SWASHPLATE

2.1. Requirements

The requirements for this type of control system are basically the same as for a conventional primary control system. Thus, for the presented design exercise the basic load specifications have been derived from available pitch link load data of an EC-145 helicopter. With respect to the required actuator authority and bandwidth, flight test data from several agile ADS-33 maneuvers recorded by the DLR Braunschweig with a smaller BO-105 testbed have been analyzed [1].

The following maneuvers were analyzed with respect to actuator acceleration and speed.

- Pirouette Maneuver
- Turn to Target
- Acc / Dec Maneuver
- Sidestep Maneuver
- Slalom
- Transient Turn
- Pullup / Pushover
- Yo-Yo Maneuver
- Landing Maneuver
- Bob up / Bob down

From these maneuvers angle and rate requirements have been derived, which are certainly at the upper end of the dynamic range. However, from similar activities [2] it was known that the inevitable redundancy of such systems will lead to extra control power in the non-degraded case which allows to fulfill such requirements and even provides a certain margin for higher harmonic control inputs. Therefore, the high bandwidth was considered a welcome design feature.

The work presented in this paper was conducted within the framework of a multi-partner research program, see acknowledgements at the end. One partner was primarily focused on the development of trailing edge blade flaps (TEF) for secondary individual blade control. Therefore, it was suggested to evaluate whether the combined application of electrical blade root control via the swashplate plus IBC via additional TEFs could lead to mutual benefits for either of the systems.

The standard application of the Electrical Swashplate requires from the system to react the usual pitch link loads introduced by the aerodynamic and inertial blade forces. If, however, it was considered worthwhile to incorporate trailing edge flaps to improve the rotor properties through (higher harmonic) IBC inputs, one could think of operating those flaps also in an 1/rev mode synchronous to the cyclic primary control such that the control forces would be reduced. I this case, the sizing requirements for the primary actuators could be reduced.

2.2. Simulation Results

To evaluate the mentioned potential benefit from combining a trailing edge flap system with an Electrical Swashplate, corresponding simulations have been carried out by the DLR Braunschweig. The data set for the target helicopter EC-145 was determined based on scaled EC-135 trim results. Then, DLR's S4 rotor simulation code was extended to model the effect of the TEFs. With this blade model and the scaled EC-145 data, trim calculations were conducted. To assess the potential benefit of coordinated flap inputs to lower the pitch link loads, different flap inputs at different flight conditions were calculated.

The example of Figure 1 compares the results for the baseline case (V = 240km/h; no IBC-input) and the TEF case with optimized input (mixed mode; 1/rev with 4.5° and 2/rev with 0.5° amplitude).

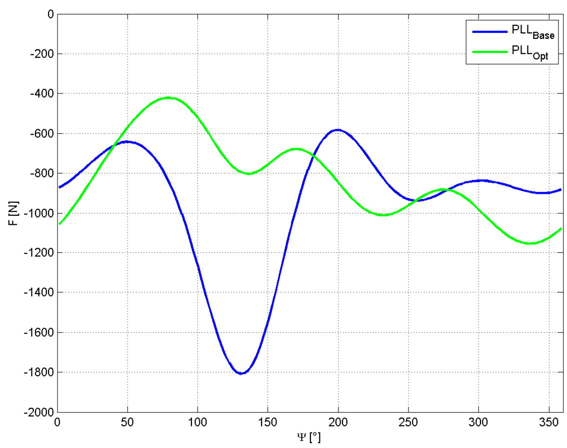

Figure 1: Simulation Results of Control Load Reduction by Coordinated TEF Operation

The results confirm that by applying the appropriate 1/rev amplitudes and phases (plus 2/rev in some cases) to the trailing edge blade flaps, the required control forces can indeed be significantly lowered.

This result might become of interest when designing an Electrical Swashplate for a TEF equipped rotor, because any lowered load requirements would consequently reduce power, volume and weight of the electrical actuators, the required generators as well as the corresponding power electronics. However, for the sizing of the demonstrator presented in this paper, load requirements were not reduced according to this philosophy.

2.3. System Architecture

After studying several alternative concepts, a unique actuator integration was devised which combines guidance, support, articulation and position control of the swashplate in an elegant manner. Based on the detailed assessment of different geometric layouts two feasible and promising variants have been selected of whom one candidate was finally selected for deeper investigation. This architecture, see Figure 2, was further detailed by means of a virtual model and evaluated with respect to its kinematic behavior. Figure 3 shows the key components of the layout selected for the first demonstrator.

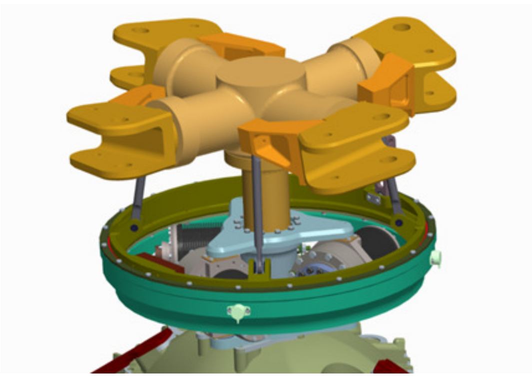

Figure 2: Selected Variant of Electrical Swashplate

The key features of this patented design are:

- No mechanical gearing/linkages between boosters and swashplate
- No unnecessary motion conversion from rotation (E-motor) to translation (spindle drive) back to rotation (swash plate)
- No non-rotating swashplate scissors required
- No swashplate gimbal and sliding guide required
- EMA boosters protected within ring-shaped swashplate

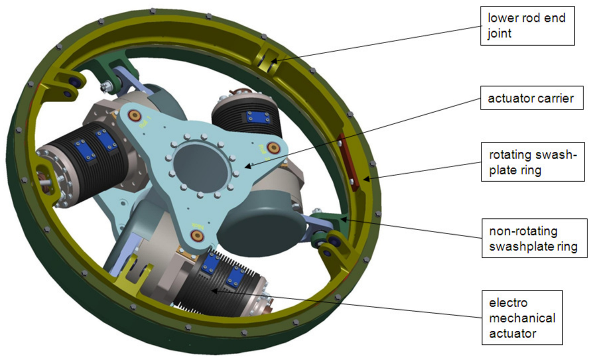

Figure 3: Key Components of Electrical Swashplate

Each of the three identical actuators consists of a highly redundant brushless DC motor that drives into a high gear-ratio multiple-load-path cycloid gearbox. A short lever arm connected to the gearbox output directly supports one of three lower rod end joints of the ring-shaped swashplate. Due to the way by which the three actuators are mounted to the fixed frame, the swashplate support is statically determined and neither any guiding elements nor the usual scissors are required.

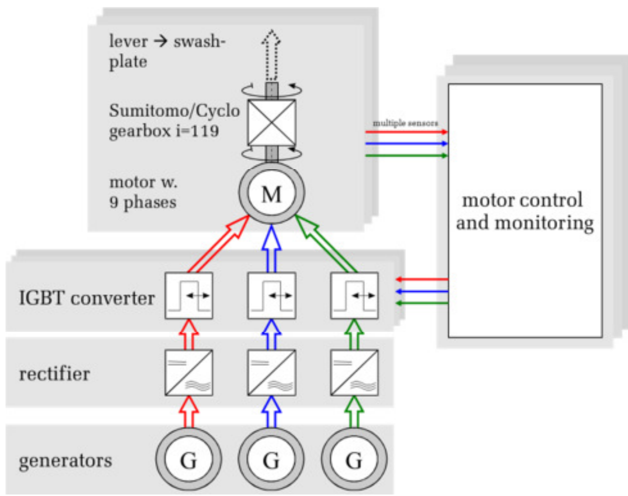

Figure 4: System Architecture

The principle redundancy architecture has already been proposed in [2] for an individual blade root control system. It is based on a triplex redundant layout, where on the electrical side from the power supply (generators) all the way into the electrical machine a strict separation between three independent lanes is maintained, see Figure 4.

The electrical brushless DC motor features multiple mechanically, magnetically, and thermally separated phases, which in principle constitute three separate motors in one housing. The motor output shaft directly drives into a high gear-ratio transmission, which also provides redundancy through multiple load paths.

These components have already been investigated in detail during previous programs, where especially all certification relevant questions concerning reliability, failure conditions, or degraded operation have thoroughly been investigated. For instance, deliberate short circuits have been introduced to evaluate the thermal behavior of the degraded actuator under high ambient temperatures. Likewise, low temperature tests have been conducted to validate the system performance during initial warm-up. Figure 5 shows photographs of the laboratory tests under controlled ambient temperatures in dedicated climate chambers.

In addition, massive overload tests with this particular gearbox type have shown that the transmission degrades without causing any jammed or open load path condition. A gradually reduced stiffness, which can easily be detected, indicates the buildup of internal damages at an early stage. Figure 6 shows the test setup for these mechanical overload tests.

Figure 5: Validation of Thermal Behavior and Low Temperature Performance of Electrical Machine (Top) and Actuator Gearbox (Bottom)

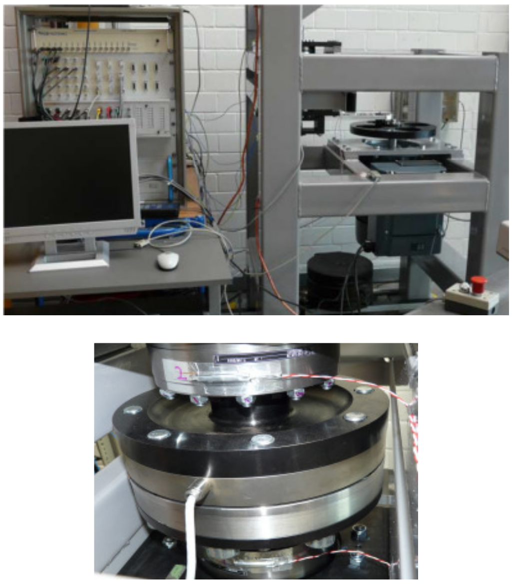

Figure 6: Back-to-back Overload Testing of Actuator Gearbox

2.4. Detailed Design

Several geometrically and kinematically slightly different concepts have been investigated and compared. Respective CAD models were composed which allowed comprehensive kinematic and load analyses. For the preferred variant a fully parameterized model, which precisely represents all actuator and hinge motions with their respective degrees of freedom and which simulates external loads has been used to predict the load distribution throughout all relevant components. These simulations were also used to confirm that even in extreme swashplate positions the distortion of the sinusoidal blade pitch motion stayed within negligible limits, see Figure 7.

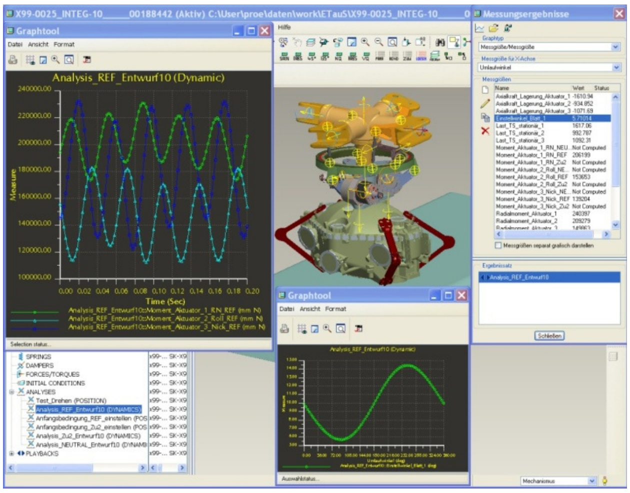

Figure 7: CAD Model Used for Kinematic and Load Simulations

After completion of the virtual design, the demonstrator configuration was synthesized and designed in detail. Test stand integration aspects as well as sensor application had to be taken into account. It appeared desirable to provide condition and load monitoring besides the precise measurement of the swashplate position and tilting angles during the envisioned tests. Therefore, DMS elements have been applied to the motor output lever arms in addition to the various angular sensors. Motor position control is based on both the high speed rotor shaft as well as the slow gearbox output. Figure 8 shows the actuator with its interfaces and gearbox output sensor.

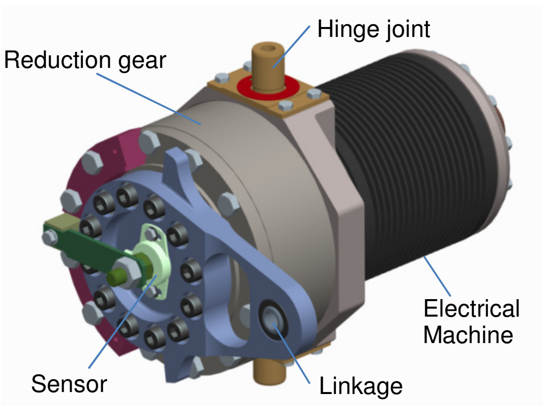

Figure 8: EMA as Core Element of the Electrical Swashplate

2.5. Electrical Design and Power Electronics

The principle design of the electrical machine is described in [2] and [3]. For the thermal design a worst case duty cycle was generated based on a time weighted mixture of the above listed maneuvers along with continued periods of less demanding steady flight conditions. Based on this duty cycle magnetic and thermal simulations were performed to support the electrical design of the motor. Core components of a previous demonstrator machine are shown in Figure 9.

Figure 9: Highly Redundant Brushless DC Motor

The control and power electronics required to provide the high current PWM signals for the separated and isolated motor phases have been subject of a parallel research program. Main contractor for the design and manufacture of the demonstrator unit was the IZM Fraunhofer Institute in Berlin. In [4] the design philosophy is laid out in more detail. Besides the obvious aspect of high reliability, robustness against short circuits, open phases, or other partial failures forms the critical requirement for this element. During those studies it was possible to demonstrate that after single or multiple failures the utilized control algorithm was able to instantaneously reconfigure the control signals and maintain degraded operation at very low levels of residual torque ripple. Figure 10 shows the prototype of an actuator power control unit as developed for the actuator of Figure 9.

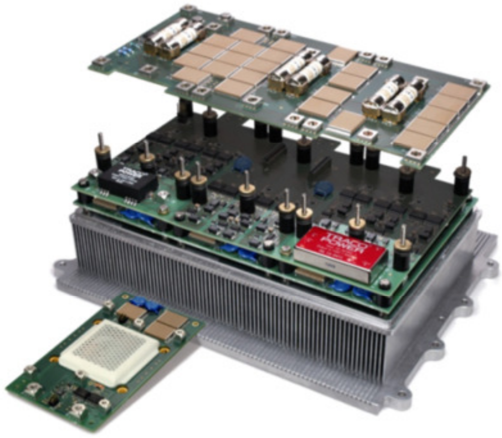

Figure 10: Power Electronics Unit for Full Functional Laboratory Testing

2.6. Manufacturing

To enable rapid and cost-effective manufacturing of the demonstrator, some components have been chosen off-the-shelf knowing that an optimized and certifiable system would have to be based on custom-designed parts. For example, the brushless DC motors used within the demonstrator are adapted kit-motors, which lack the consequent phase separation that would be required for a flightworthy embodiment. Moreover, several components show a simplified non-weight-optimized design driven by cost and manufacturing time considerations. Figure 11 shows the Electrical Swashplate after assembly and mounting onto the test rig support.

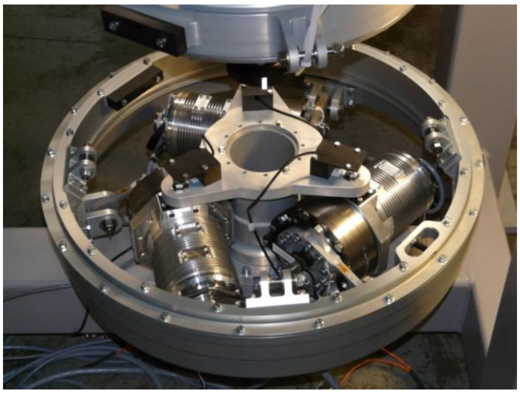

Figure 11: Electrical Swashplate Demonstrator

3. TESTING

3.1. Test-Stand Design

In order to allow the application of loads during functional testing of the Electrical Swashplate, a test rig concept was conceived in which a secondary swashplate is used to support the upper ends of the pitch links. Through the provision of eccentric static and/or higher harmonic loads onto the non-rotating part of this secondary swashplate by a hydraulic cylinder, pitch link loads can be created which approximate typical flight loads.

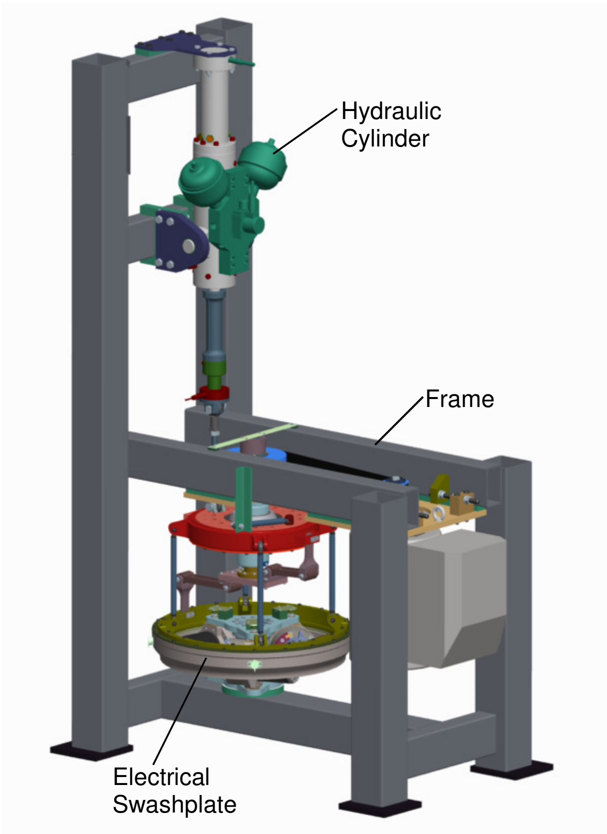

Figure 12: Test Stand Design

Figure 12 and Figure 13 show the test rig setup and some details of the design. The rotation is introduced by a shaft stub suspended from the upper frame of the test rig and driven by an electric motor via a cog belt. This shaft is connected to the rotating parts of both swashplates via two pairs of scissors and thus mimics the rotor rotation. The rotatory actuators are mounted at the keel beam of the test stand by a support plate that represents the mechanical interface to the gearbox. The Electrical Swashplate itself, which is actually a more ring than plate, is freely floating supported only by the output levers of the actuators.

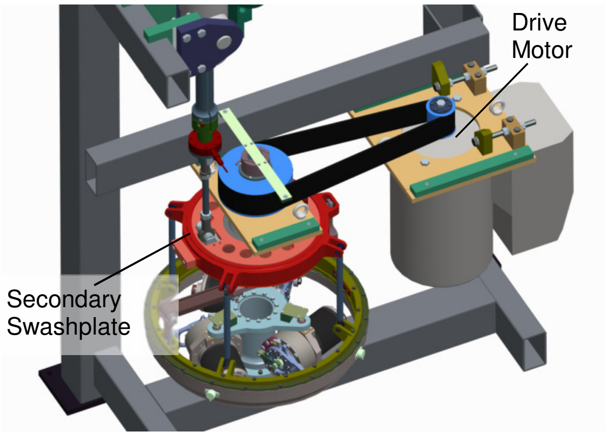

Figure 13: Details of Test Stand Drive and Loading Systems

Figure 14: Final Test Setup

The control of the electric machines and the hydraulic load cylinder as well as the sensor data acquisition is realized by a dSPACE rapid prototyping system. The final laboratory test setup is presented in Figure 14.

3.2. Functional Testing

In preparation of the actual testing, the actuator control loops had to be established and fine-tuned. Current, speed, and position control of the cascaded control structure were stepwise activated and the respective parameters were adjusted for optimum control performance.

The first tests were focused on the kinematic behavior of the system under steady loads. The next experiments were focused on the swashplate operation under dynamic loads while commanding representative collective and cyclic control inputs. Figure 15 shows the demonstrator swashplate in operation.

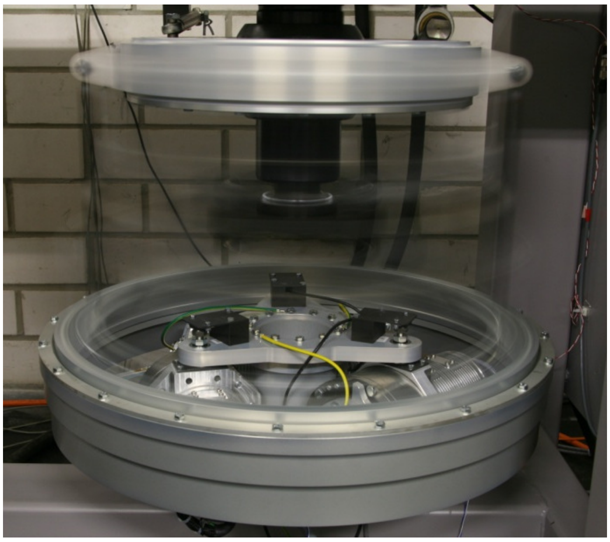

Figure 15: Rotating Tests

After the application of simple input functions, control time histories recorded during real helicopter flights have been played back to stimulate high bandwidth operation of the primary controls. Figure 16 shows such time histories for all three control axes from an aggressive slalom maneuver.

Figure 17 presents the measured actuator motions that correspond to the time slice marked in the previous figure. The high frequency content becomes particularly obvious from the shown speed signals as processed within the speed control lop.

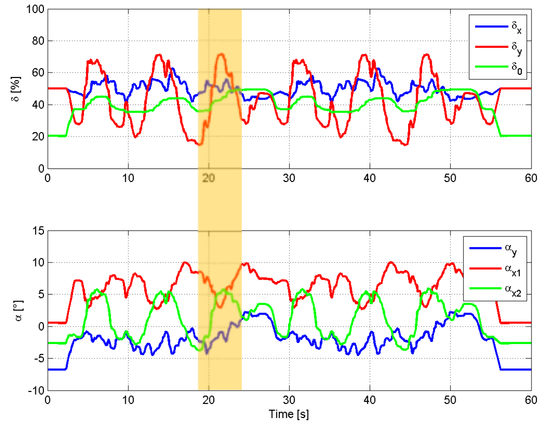

Figure 16: Slalom Maneuver according to [1] (Orange Marking: Time Slice of Figure 17)

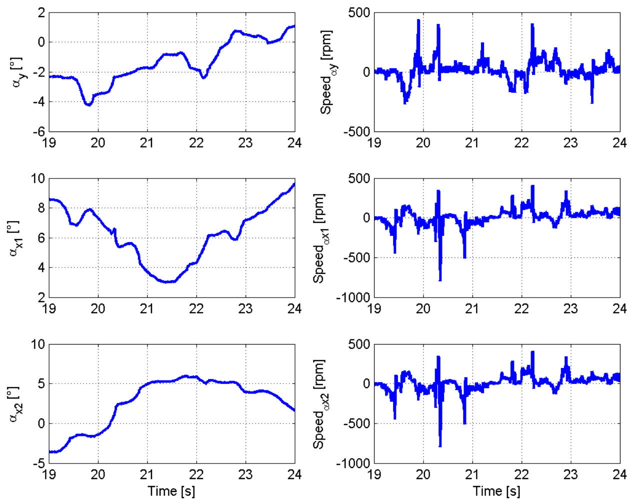

Figure 17: Resulting Actuator Angular Positions and Rates for Example Time Slice of Slalom Maneuver

It is worthwhile mentioning that the control accuracy did satisfy the imposed requirements throughout all simulated maneuvers.

In order to validate the load transfer and distribution within the control system elements, steady and periodic forces were imposed upon the secondary swashplate by the hydraulic load cylinder. Through the appropriate choice of the load frequency approximate "booster" loads could be simulated. The example of Figure 18 compares over one "rotor" revolution the introduced load with the resultant moments as measured at the three actuators. The input frequency was chosen to simulate the typical 4/rev periodic forces as seen by the boosters of a four-bladed rotor.

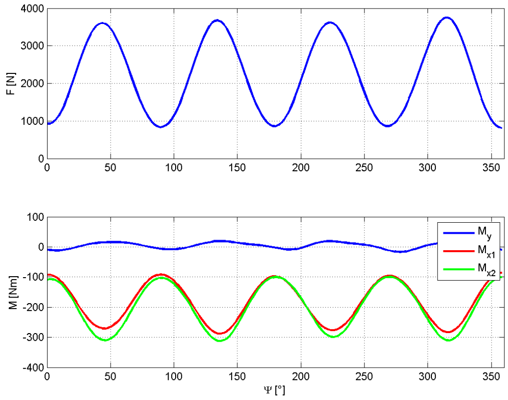

Figure 18: Controlled Hydraulic Cylinder Force and Resulting Moments as Reacted by the Actuators

The last Figure 19 shows a corresponding temperature plot for the available sensor locations. It becomes obvious that the thermal aspects are of no concern in this particular operating condition. From past experiments it is known, however, that the thermal design of the actuators is driven by the extreme failure condition when two lanes have been lost and the remaining one third of the actuator phases has to provide the complete torque.

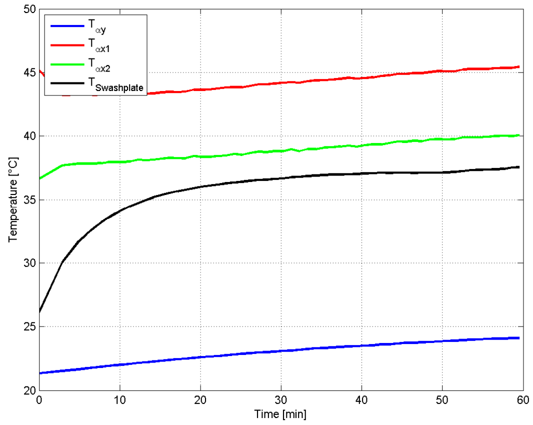

Figure 19: Actuator and Swashplate Bearing Temperature during Long Term Tests

4. CONCLUSION AND OUTLOOK

As result of the described program it has been shown that the unique design of the Electrical Swashplate is a feasible solution for the replacement of traditional hydraulic primary control systems. It provides all-electric high bandwidth control while maintaining the upmost mechanical simplicity. The key features and advantages can be summarized as follows.

- No hydraulics, pure electrical operation, inherently Fly-by-wire compatible
- Cost savings from simplified support of a “hydraulic-free” aircraft
- Reduced maintenance requirements through mechanical simplicity
- Weight reduction (if taking all control system components like power supply into account)
- Depending on the actual upper gearbox shape an alternative kinematic variant enables a smaller swashplate diameter
- The Concept is scalable to different helicopter sizes
- Power-efficient through recuperative operation of DC motors combined with high gear ratio actuator gearbox
- High Bandwidth Fly-by-wire capability enables active rotor control for improved handling qualities or advanced functionalities (e.g. ground resonance suppression without heavy lag dampers)
- HHC capability due to high actuator bandwidth as side-product of built-in redundancy enables highly effective vibration reduction
- Required thermal over-sizing leads to high performance margin (i.e. first major electrical failure does not affect the system performance at all, second major failure leads to mild degradation only)
- Design is capable of civil certification (catastrophic failure rate <10^{-9} per FH)

After this promising first step ZF Luftfahrttechnik is prepared to apply the Electrical Swashplate technology to a real aircraft. Despite several less successful attempts in the past, it is believed that this unique system architecture can help to eventually realize electrical primary control for helicopters.

ACKNOWLEDGEMENTS AND COPYRIGHT NOTICE

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