ELECTRIC, SWASHPLATE-LESS INDIVIDUAL BLADE CONTROL SYSTEM TO BE WIND TUNNEL TESTED IN FULL-SCALE

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Abstract

This paper describes a novel principle of helicopter main rotor primary control, which is scheduled to be demonstrated within a full-scale wind tunnel test campaign. The presented concept uses individual high performance electrical actuators to control the pitch angle independently for each rotor blade. Thereby many limitations of conventional hydraulic control systems are overcome and new functionalities can be introduced which largely improve the rotor performance and attenuate its inherent limitations. First, the rationale behind that idea and the basic concept is described. Then the chosen test platform is introduced and its unique suitability for this technology is highlighted. The key requirements that have primarily driven the design are presented. Further, the practical realization and the system integration into the test rotor is detailed. Key components such as the actuator, actuator control unit and power electronics are described in more detail. Finally, the preparatory test setup in the System Integration Lab (SIL) test is discussed.

ABBREVIATIONS

ACU	Actuator Control Unit
APCU	Actuator Power Control Unit
BLDC	Brush-less DC (Motor)
DAS	Data Acquisition System
EMA	Electro-Mechanical Actuator
FCC	Flight Control Computer
IBC	Individual Blade Control
LIBRAS	eLectrical Blade Root Actuation System
NFAC	National Full-Scale Aerodynamic Complex
RTA	Rotor Test Apparatus
SIL	System Integration Lab
TCC	Test Control Computer

1. INTRODUCTION AND MOTIVATION

1.1. State of-the Art

While the idea of urban personal transport preferably by means of electrically propelled vertical take-off and landing (eVTOL) small aircraft has recently attracted a lot of interest, the classical helicopter designed for a decent transport performance (payload load times distance) will continue to rely on combustion engines and hydraulic control systems. However, assuming there will be a „More Electric“ phase before achieving the full „All Electric“ goal, it is time to prove that electrical systems can replace at least the hydraulic components traditionally used to boost the pilot's or autopilot's control inputs. Driven by this rational, ZF Luftfahrttechnik (ZFL) has been pursuing that idea now for several years and triggered the interest of several helicopter manufacturers, which eventually led to a close collaboration with Sikorsky Aircraft Corporation, a Lockheed Martin Company.

The principle of controlling the blade pitch of a helicopter rotor has hardly changed since the days when the first practical helicopters took off. The key idea has always been to transfer control inputs from the non-rotating frame into the rotor by a mechanical device, of which the most common variant is known as the swashplate. By design, such devices allow for collective control (common offset) and cyclic control (periodic motion) of the blade pitch angle. The kinematic restrictions of this design limit the pitch control to exactly the same mono-cyclic motion for all blades. As long as the control inputs are provided by the pilot, the blade pitch motion is limited to one cycle per rotor revolution. This does allow to trim the flight condition and to maneuver the rotorcraft but is far from an optimized blade pitch time history required to keep vibration, noise radiation and power losses to the inevitable minimum.

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1.2. Individual Blade Control

For many years, ZFL has pursued the concept of Individual Blade Control (IBC). Several flightworthy systems have been developed and successfully demonstrated during various wind tunnel and flight test campaigns, see e.g. [1], [2] and [3]. This technology uses separate blade-individual actuators that allow for higher frequency (usually harmonic) pitch variations at each blade. The primary control system remains unaltered and the authority of the IBC system is limited to one or two degrees. During flight tests, fuselage vibrations have been reduced by up to 90%, the radiated noise has been attenuated by 3dB to 9dB, and the rotor power requirement was consistently lowered by more than 5%. Moreover, such active systems enable in-flight track and balancing and inherently provide reconfiguration capabilities, which allow compensating dangerous Foreign Object Damage (FOD) or battle damage effects.

1.3. Moving from Hydraulic to Electric Systems

One obvious approach that has already been attempted tries to replace the hydraulic servos by equivalent electrical actuators without changing the control system topology itself. In contrast, the present effort has attempted from the beginning to focus on a system architecture that would bring in all the multiple benefits provided by IBC in addition to the primary flight control functionality. Whereas the legacy IBC systems had been sophisticated add-ons mounted in the rotating frame independently from the primary control, it is now intended to combine both functionalities within one integrated system. Therefore, ZFL had started to develop novel rotor control systems, which are based on multiple redundant, electro-mechanical high performance actuators. In the most advanced variant covered in this paper, not only are all hydraulic elements replaced, but also all mechanical control linkages from the fuselage to the rotor blades can be eliminated. This motivation is summarized in Figure 1. A successful R&D program had demonstrated the principle feasibility of this approach in a bench test framework [4].

Besides the classical primary control functions, such swashplate-less systems inherently provide full IBC functionality and thereby allow realization of all the demonstrated improvements that are enabled by IBC. The complete removal of the hydraulic system is a strong incentive since the containment and safe distribution of hot pressurized and flammable oil requires many heavy maintenance-prone provisions on board the aircraft. On the other hand hydraulic actuators show very high power densities that can hardly be matched by their electrical counterparts. Therefore, only if we manage to leverage the opportunities of a completely new control system topology a competitive system weight can be achieved. The key idea of the described technology, which further on is referred to as LIBRAS™ (eLectrical Blade Root Actuation System), is to combine the primary control and the IBC functionalities within one single system.

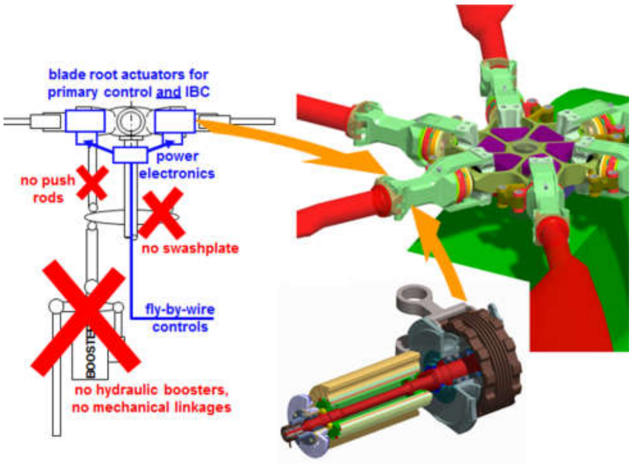


Figure 1: **Motivation and Approach of Electrical Swashplateless Rotor Control**

This provides the additional benefit that the IBC functionalities by default have the same level of reliability that is obligatory for the primary control portion. Thus, IBC can also be used for safety critical active control applications such as ground resonance suppression (offering the chance to also remove the often heavy lag dampers). Moreover, it is conceivable that local failures at a single blade (be it the blade pitch actuator or the blade itself) could be compensated through suitable reconfiguration of the control inputs applied to the remaining blades. Respective simulations have supported this concept. A comprehensive overview of the prior work in this field can be found in [4].

1.4. Demonstration Program

In order to validate the feasibility of this concept, Sikorsky and ZFL have joined forces to set up a technology demonstration based on full scale hardware to be tested under realistic operating conditions (see [7]). Based on the selected platform, the rotor system of the X2® high-speed compound helicopter, Sikorsky has defined all relevant high level system requirements that concern the mechanical and primary control performance, operating loads, electrical interfaces, and IBC performance. Whereas the first items could be derived from the existing testbed aircraft the latter ones had to be generated from scratch for this project. Simulations have been conducted to estimate the required IBC authority at the respective higher harmonic frequencies. Although it is expected that

IBC can not only be used for the established applications like vibration and noise reduction but also in different and novel ways that relate to the unique characteristics of the co-axial rigid rotor (optimizing lift offset and/or enabling smaller inter-rotor spacing), it was decided to fit the LIBRAS components only onto a single rotor. This was primarily driven by the restrictions of the existing Rotor Test Apparatus (RTA), which was the only viable option for a carrier of the system in the National Full-Scale Aerodynamic Complex (NFAC) Wind Tunnel, see Figure 2. Background information on the ABC principle and the X2® high speed demonstrator can be found in [5] and [6].

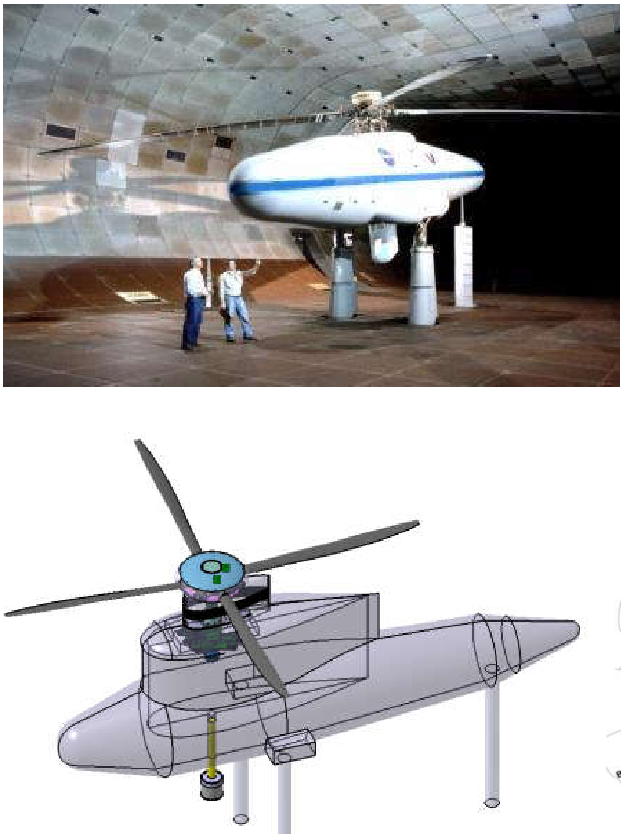


Figure 2: Wind Tunnel 80x40ft Test Section (Top) and RTA with LIBRAS™ Rotor Hub (Bottom)

2. SYSTEM ARCHITECTURE

2.1. Selection of Test Platform

In line with Sikorsky's current focus on high-speed rotorcraft and the continued work towards the perfection of the X2 configuration, the rotor of the 250 knot X2® Technology Demonstrator was selected as the most fitting platform of this advanced control system. One reason for the suitability of the LIBRAS concept especially for an X2® aircraft type rotor relates to the required number of actuators. In order to exploit the full potential of this unique coaxial rotor system, which uses the lift offset principle to extend the conventional helicopter forward speed limit, both rotor disks must be controllable by independent cyclic inputs. Therefore, two separate swashplate assemblies with three primary control actuators for each swashplate are required. If these boosters are now replaced by blade-individual actuators in the rotating frame, the number of necessary actuators increases only moderately e.g. from six to eight for a four-bladed X2 rotor. Therefore, this configuration in particular promises to benefit from the removal of the mechanical swashplates and the added possibilities of the blade-individual and higher harmonic control.

2.2. System Layout and Components

Based on the system requirements, ZFL has synthesized a system concept and harmonized it with Sikorsky. The high-level architecture of the LIBRAS installation and the supporting periphery is shown in the following Figure 3. Whereas ZFL's components primarily reside in the rotor hub, the hardware and software elements for the control and supply functions are mostly located in the non-rotating frame (olive-green). The overarching triplex architecture is easily recognized (shown in red, blue, and green) and carried through from the power supply to the blade root actuator's electrical machine and its sensors.

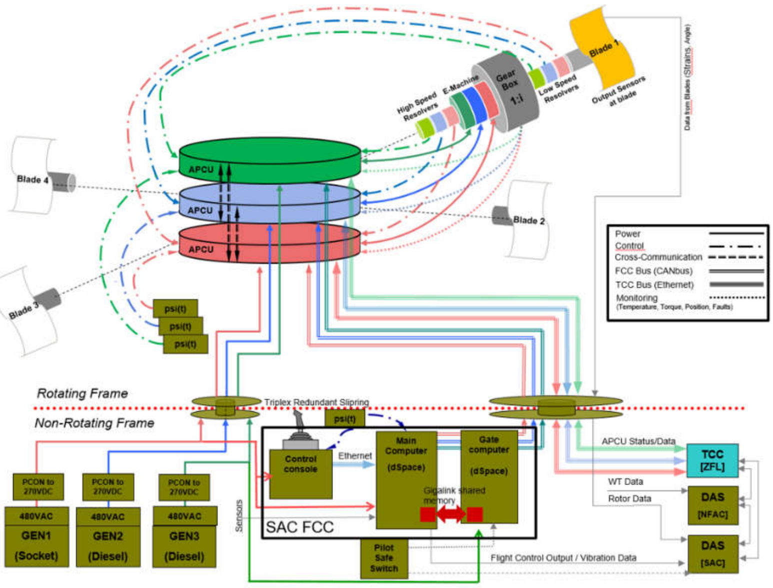


Figure 3: High-Level System Architecture and Control/Monitoring Periphery Setup

The following main components constitute the system as it will be operated in the 40x80ft² test section of the NFAC, located at Moffett Field in California, USA.

Rotating Frame

- Azimuth sensors, required to provide a reliable reference of the actual rotor position, crucial to convert the frequency domain control components into blade-individual time domain pitch commands [Sikorsky].
- APCU (Actuator Power Control Unit), comprising all subcomponents required to process the incoming command signals, to control the power electronics, to provide position control for the actuators and to monitor the compliance with the various limits (currents, torques, temperatures, etc.) [ZFL].
- Blade Root Actuators, comprised of the internally redundant E-motor, the multiple load path cycloid gearbox and the position sensors at both the high speed (motor) and the low speed (gearbox) actuator shafts [ZFL].
- Data Acquisition System (DAS), used to receive sensor signals from the usual rotor instrumentation installed to monitor the blade loads and other safety of flight parameters [Sikorsky].

Non-rotating Frame:

- Flight Control Computer (FCC) including a Pilot Control Console, Higher Harmonic Controller, and a Gate Verification System [Sikorsky]
- Power Supply, to provide the required electrical power at 270VDC to the rotor via three independent lanes that correspond to the triplex over-all redundancy architecture [Sikorsky].
- Test Control Computer (TCC), acting as the non-rotating interface to the LIBRAS system; it allows configuring the APCU software before the actual operation and monitors the condition of the LIBRAS system when active; it also features an HMI, which allows to supervise the operation in real time [ZFL].
- Multiple Data Acquisition Systems collect data received either from the rotating frame provided by the rotor instrumentation or from the TCC, which forwards data originating from the LIBRAS system [Sikorsky].
- Slip Ring, transferring both electrical power for the actuation and digital bus signals for the bidirectional communication between the FCC/TCC and the APCU [Sikorsky].

In addition to the elements mentioned above, ZFL is responsible for specification compliance testing, along with qualification testing such as static, fatigue, and endurance testing prior to integration of the full system with the rotor head and power supply. Sikorsky is responsible for design and fabrication of a modified X2 rotor to accommodate LIBRAS, supporting test hardware such as controllers, power supply, slip rings and general data acquisition.

3. SYSTEM REQUIREMENTS

3.1. Performance

The LIBRAS system has been designed to provide sufficient control bandwidth and authority for primary flight control in combination with IBC functionality. While in typical flight conditions the main rotor is operated at rotor speed levels within the range of 360 to 446 RPM, the LIBRAS system is required to be operational starting from 0 RPM. The upper operational limit of the LIBRAS system is a rotor speed level of 513 RPM. Taking the IBC functionality into account, the control input bandwidth of the LIBRAS system ranges from 0 Hz (primary collective control) up to 42.75 Hz (5/rev IBC inputs at 513 RPM). The required control authority depends on the input type. The primary collective and cyclic control requires a larger control authority than the IBC functionality at higher frequencies (typically multiples of the rotational frequency of the main rotor). Table 1 gives an overview of the control authorities for the different harmonic input types.

Input Type	Harmonic Frequency	Pitch
Primary Collective Control	0/rev	-4° to 22°
Primary Cyclic Control	1/rev	±12°
IBC	2/rev	±2.0°
IBC	3/rev	±1.5°
IBC	4/rev	±1.5°
IBC	5/rev	±1.0°

Table 1: Input Control Authority

The mechanical and electrical design of the EMA along with the power electronics is driven by the required rotor blade pitch moment versus pitch rate capabilities. Blade pitch moments and pitch rates depend on the flight condition of the aircraft e.g. level flight, climb, maneuver, and the related flight control inputs. The requirements in terms of pitch moment and pitch rate for the LIBRAS system were derived from flight test results with the X2® Technology Demonstrator [6] and from the results of comprehensive CFD/CSD simulations by Sikorsky in which the impact of the IBC control inputs (2/rev – 5/rev) on the pitch moments was evaluated. The requirements for the LIBRAS system are given by a set of boundary conditions for three classes of operation: Severe maneuver, moderate maneuver, and continuous operation, and by typical time histories of pitch moment vs. pitch rate over one rotor revolution (Figure 4).

In addition, a simplified duty cycle is used to define the percentage in which the LIBRAS system is being operated in one of the three classes (Figure 5). The information contained within the time series and the duty cycle is essential for the dimensioning of the EMA and the power electronics with respect to their thermal limitations.

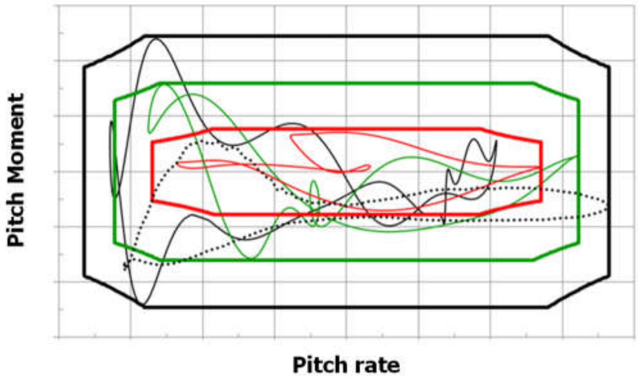


Figure 4: Example of the Specified Boundary Conditions for Three Classes of Operation Including Typical Time Histories

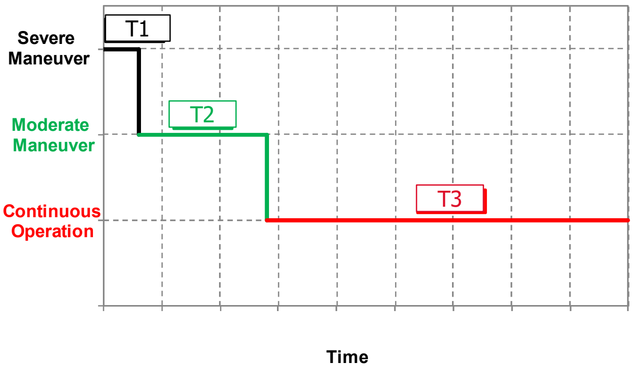


Figure 5: Example of the Definition of a Duty Cycle

As the architecture of the LIBRAS system consists of three independent power and signal lanes, the requirements for the pitch moment versus pitch rate capabilities depend on the operational state of the LIBRAS system's three lanes. Therefore, the specification of the LIBRAS system has performance limits for pitch moment and pitch rate and the related duty cycles for the operation with one, two or three power lanes active, thereby covering situations in which healthy lanes need to take over the torque generation of defect (unhealthy) lanes.

3.2. Safety and Reliability

Compared to the requirements for a flight worthy system, the safety and reliability requirements for a wind tunnel test are slightly less stringent. Nevertheless, the approval for the operation of the LIBRAS system in the wind tunnel requires an extensive safety assessment including a hazards analysis at the aircraft and system level as well as a fault tree analysis. The following Figure 6 shows as an example a small extract of that fault tree analysis.

For safe operation in the wind tunnel it is specified that, based on the triplex redundancy architecture, the probability of an occurrence of any combination of detected and undetected failures that results in the inability to control one single lane of the LIBRAS system shall be less than 1.6e-004 per 1hr of operation. With respect to the hardware and software Design Assurance Levels as used throughout DO-178 and DO-254, respectively, the obvious choice is Level A for the development of the Actuator Control Unit. However, for the wind tunnel test a few relaxations (e.g. with respect to the documentation) on the requirements have been applied to keep the development effort in terms of cost and time in an affordable range.

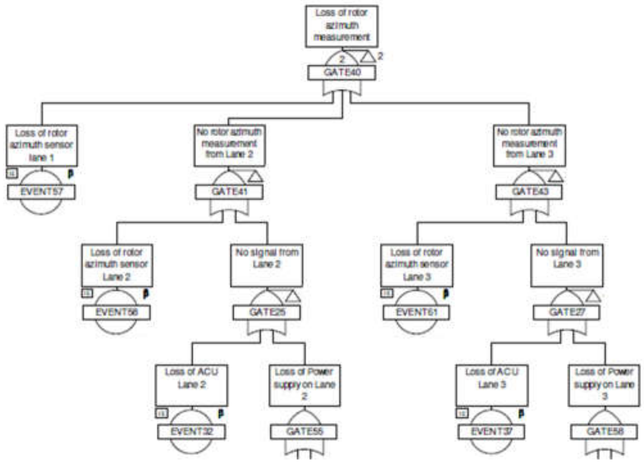


Figure 6: Extract of Fault Tree Analysis as used to derive Safety-relevant Hardware and Software Design Requirements

4. SYSTEM DESIGN AND INTEGRATION

Following the high-level system architecture described above, the rotor hub layout was devised. In contrast to the notional design as conceived for the previous project [4], it was now impossible to collocate the blade root actuators directly coaxial to the blade pitch axis. Since the rotor blade design had to be accepted as is, along with the fact that this type of rotor requires a particular strong and stiff blade attachment, it was agreed to position the actuators coplanar in the rotor plane between the rotor blades with their axis of rotation pointing in radial direction. A short pitch link connects the actuator output lever to the modified blade pitch horn. The lever arm ratios were chosen to introduce an additional 0.7 transfer ratio. A rendering of the LIBRAS rotor head is shown in Figure 7.

The blade root actuators (EMAs) consist of three major sections: (1) the electrical machine, (2) the reduction gearbox and (3) the sensor compartment. The BLDC motor follows the topology as described in [4].

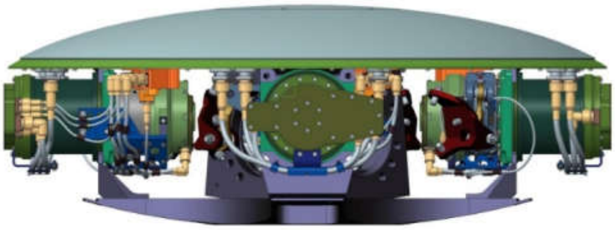
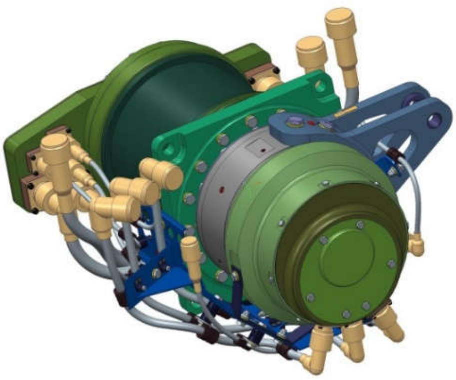


Figure 7: LIBRAS System Integration within the Rotor Head (Rotor Blades not shown)

Conceptually, three independent motor stators which carry the phase windings are combined within one housing and are imposing their magnetic flux onto a single low inertia rotor with bandaged permanent magnets. The motor shaft drives into a cycloid gearbox of reduction ratio 30:1. This particular gearbox type features three parallel load paths and has been found to be very reliable. Overload tests have shown that even with local cracks on internal load carrying components the functionality is only marginally affected. The onset of developing damages could safely be detected by monitoring the actuator stiffness derived from the position measurements at the gearbox input vs. output. The triplex redundant input and output position sensors (two sets of different types) are located in a separate sensor compartment.



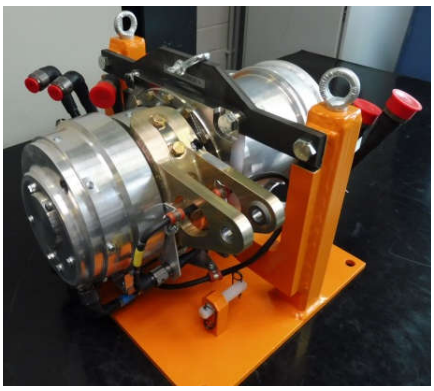


Figure 8: Electro-Mechanical Actuator (EMA) for Individual Pitch Control of One Rotor Blade

The power and signal wires are routed in separate channels as far as possible to prevent local failures to spread over adjacent components. Thus, the triplex architecture is respected on all component levels. Single point failure elements (bearings, pitch link, etc.) are similar to conventional control system layouts and will be verified during fatigue testing prior to the wind tunnel test. Figure 8 shows a 3D rendering of the actuator unit, looking from the rotor hub outwards and a corresponding photograph.

As shown in the architectural overview, the power electronics inverters are collocated in the rotating frame in a 'beanie' like housing above the rotor plane. Although this has introduced considerable challenges with respect to the available volume and the later assembly, there is no other sensible choice. In [4] test data were presented that show how the actual blade pitch control power demand varies over one rotor revolution. It becomes clear that high momentary power peaks alternate with phases of low power consumption or even power reflux. Therefore, the actuators are designed to operate in both normal (power required by the actuator) and regenerative mode, which allows for recuperation of energy over certain segments of the rotor revolution as they are produced by the airloads acting on the blades. It would be very inefficient to send these (peak) currents up and down via the slip ring to the rotor. Obviously, it is better to equalize these power fluctuations by connecting the blades electrically via a buffered DC link in the rotating frame. Consequently, the power electronics also need to be installed in the rotor head. To keep the signal lines as short as possible, it was then decided to combine the actuator control unit (ACU) and power electronics (PCU) within a single unit, the actuator power control unit (APCU).

Discussions between ZFL and Sikorsky led to the decision that only a realistic packaging within the dimensions of a notional rotor hub fairing would allow the present effort to explore relevant design challenges of incorporating such a system into a rotor head as would be needed for a production-ready design. Therefore, the form factor was changed from the initially proposed test setup to a more elegant and seamless integration. Thus, in the finally realized concept these components are mounted in the upper part of a streamlined rotor hub fairing. To avoid the necessity for a liquid-based cooling system, which would add weight and complexity to the rotor, it was decided to spread out the power electronics including the MOSFETs that switch the high currents directly underneath that rotor cap. Therefore, the large upper surface of the aerodynamic fairing has been designed to provide sufficient convection to transfer the heat generated by the electrical losses from the semiconductors to the ambient air stream. The PCBs are mounted directly underneath that aluminum housing such that the critical components have good thermal contact with the upper cowling body, see Figure 9.

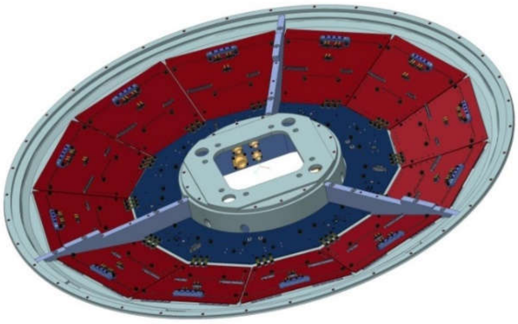


Figure 9: Placement of PCBs for Power Conditioning (Blue) and MOSFET Power Electronic Circuits (Red) underneath the Hub Cowling (Shown Upside Down)

Again, the triplex architecture can be recognized from the fire-wall-separated PCB compartments, in which the ACUs for the four blades each are mounted. Thermal simulations were used to validate the heat distribution under various operational conditions as shown in Figure 10.

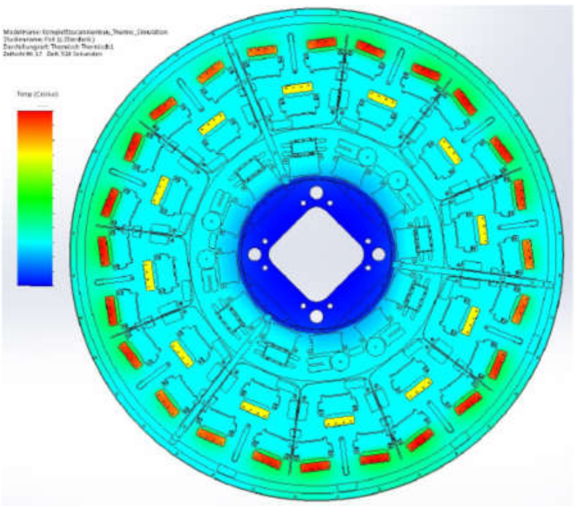
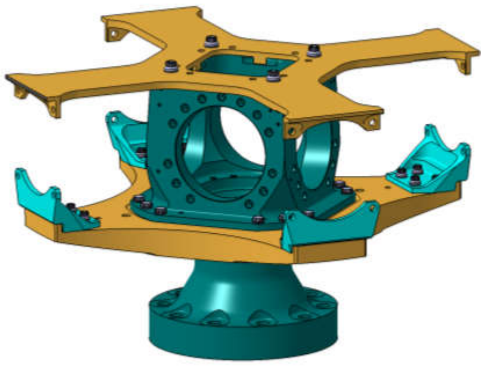


Figure 10: Simulation of Heat Distribution across the MOSFET Power Electronics PCBs

The whole system layout is strongly driven by the reliability requirements. Based on a safety concept, which is tailored to the particular needs of the wind tunnel operation and includes acceptable modes of degradation, the mentioned triplex redundancy concept was chosen. Although it is expected that a test run will be aborted after a major first failure (e.g. complete loss of one power lane), the sizing of the actuators and the power electronics is based on the assumption that the nominal performance can be maintained after such first failure. Even a second failure, despite the resulting performance degradation, should leave sufficient actuation power to continue safe flight within a reduced envelope, albeit IBC would have to be faded out immediately.

As described above, the X2® aircraft rotor blade remains unchanged from the X2® Technology Demonstrator design, while the rotor head incorporates design modifications to accommodate the LIBRAS system. As shown at the top of Figure 12, the design incorporates existing X2® aircraft blade retention, and accommodates two plates (golden colored) that serve primarily as EMA retention. This hub is capable of mounting to the Sikorsky whirl stand located in Stratford, CT by means of its lower flange, and also to the NFAC RTA with a splined section internal to the hub. The right side of Figure 11 shows the LIBRAS EMAs and APCU components in gray with Sikorsky components, including blades in black, which maintain their original X2® Technology Demonstrator retention to the hub along with the same pre-cone angle and torque offset.



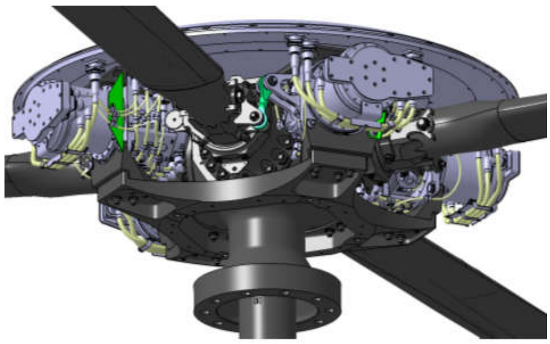


Figure 11: LIBRAS Rotor Head Design (Top) and Integration of System Components and Rotor Blades (Bottom)

As shown in the architecture diagram in Figure 3, a significant amount of non-rotating support hardware and equipment has been procured and/or designed for this wind tunnel test. Three off the shelf power converters (one for each redundant lane of the LIBRAS system) are used to tie into separate sources of 480 VAC facility power to provide true power redundancy.

These converters provide the LIBRAS system with the required 270 VDC used in the rotating system. Embedded within this triplex power distribution system are three custom designed shunt boxes, which accommodate excess power generated by the LIBRAS system during power regeneration. When this mode of operation occurs, excess power from the LIBRAS system raises the bus voltage beyond an adjustable voltage limit at which the resistors in each shunt box are triggered to remove excess energy by converting it into heat in the fixed system.

The slip ring design presents some unique challenges in the wide variety of power and signal that it must transmit. Slip ring power channels support 270 VDC current at high amperage and use fiber brush technology rather than traditional graphite blocks to handle the power cleanly and reliably. Sikorsky data acquisition from the rotating system includes a suite of accelerometer, strain gage, and thermocouple measurements in analog format. Data from the LIBRAS system data meanwhile is transmitted to the fixed system via a high-speed digital Ethernet protocol. Commands to the LIBRAS system from the FCC are transmitted using CANbus. These commands, along with LIBRAS data acquisition and power are transmitted through the slip ring with triplex redundancy (as shown in the system architecture in Figure 3).

Figure 12: Actuator Control Unit (ACU)

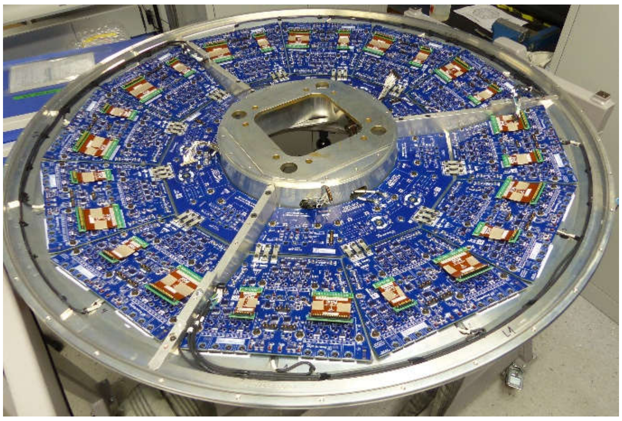


Figure 13: Assembly of the Power Supply and the Power Electronics onto the Aluminum Cowling

5. DESIGN AND MANUFACTURING CHALLENGES

The dense packaging of the components within the rotor hub fairing resulted in a very sophisticated design of both the mechanical as well as the electronic parts. One important factor was to ensure optimal thermal contact of the active power electronics components to the heat conducting housing (Figure 9, Figure 10). This required the adherence to very small geometric tolerances for both the housing as well as the components mounted on the PCBs. Moreover, the considerable centrifugal forces had to be considered for the PCB design. It was found that very few suppliers were able to fabricate the PCBs for the ACU due to their extreme form factor (Figure 12 - Figure 14).

The wiring within the segregated cable guides turned out to be especially laborious but could be completed without issues.Likewise, the EMA design was driven by the requirement for utmost separation of the elements of one lane against the others. Separate cable guides have been incorporated also throughout the electrical machine (Figure 15).

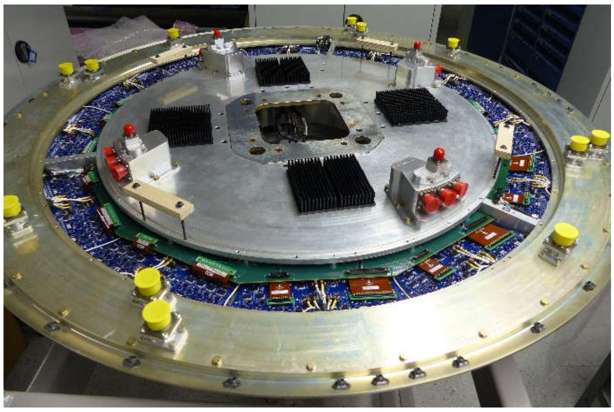


Figure 14: Assembly of the Actuator Control Unit, Power Supply, Power Electronics, and cable guides onto the Aluminum Cowling

Since the motor changes its direction of rotation multiple times per rotor revolution, it was key to keep the inertia of the rotating parts to the absolute minimum. This has led to a hollow shaft design which required precision welding.

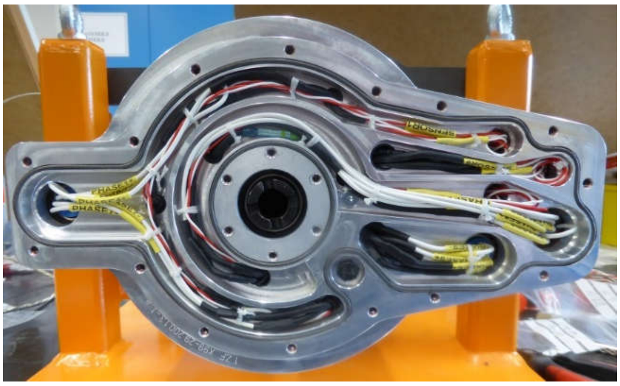


Figure 15: Cable Guide for the separated redundant Power Lines

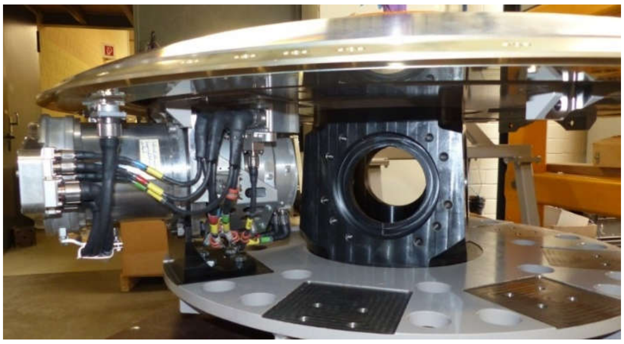


Figure 17: Mating the Electrical Machine with the Gearbox and the Sensor Compartment and Fit Check with the Electronics Compartment (Cowling) and the Dummy Rotor Hub

6. COMPONENT SIMULATION AND TESTING

The verification of the mechanical design, the EMA's performance, and the software functionalities were performed by simulation and various test setups. The electrical machine's geometry was the result of several iteration loops using state-of-the-art tools for the electro-magnetic and thermal design of BLDC motors. After the assembly of the first E-motor test specimen but before mating it with the actuator gearbox, the electrical machine underwent a first bench test to check the predicted performance data. On this rig the isolated motor was operated against the load created by a load machine, see Figure 16. Centrifugal forces could partly be simulated by a passive spring mechanism. Having passed all defined test points, the assembly of the EMA was completed by mounting the cycloid gearbox and the sensor compartment to the E-motor, as shown in Figure 8 and in Figure 17 during a fit check into the rotor hub dummy of the rotating system test rig.

Figure 16: E-Motor (far left) mounted onto the Motor Performance Test Rig

In parallel, the various software tests according to a tailored set of requirements based on the DO-178 standard were performed to verify the complex sensor data processing, position control, cross-communication, voting and error handling functionalities of the ACU software, of which an example block diagram is presented in Figure 18.

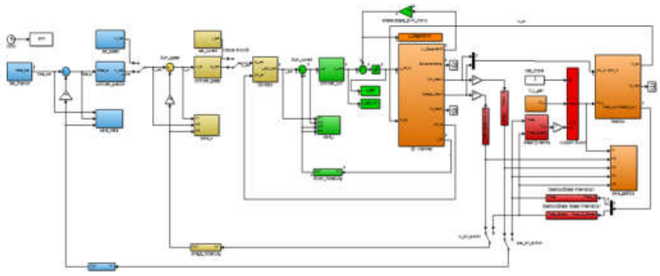


Figure 18: Example of a Low Level Block Diagram of the Sensor Signal Processing and Position Control

Then, the software was ported onto the final hardware, as shown in Figure 19, and the full set of requirements has been tested within a highly automated test environment. With the availability of the first assembled and functional Actuator Power Control Unit the control of the EMA could meanwhile be tested and demonstrated. However, within the first initial operation tests it became evident that due to the highly condensed integration of control and power electronics inside the APCU the operation of the system is hampered by EMI disturbances. The sources for these disturbances have been identified and counter measures have been derived and validated by tests.

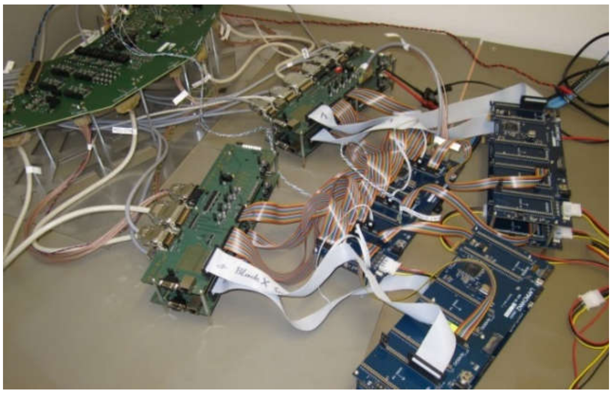


Figure 19: Hardware and Software Integration Tests in a Laboratory Test Setup

After the initial operation testing and the formal acceptance tests two EMA specimens, mounted on a custom designed test rig, as shown in Figure 20, will undergo performance and fatigue testing. The chosen test rig layout allows simulating external loads largely independent from the EMA motion. Since the two EMA units can be braced against each other by a force-controlled hydraulic cylinder, true four quadrant operation can be simulated, in which all permutations of pitch rate and load orientations can be dynamically combined.

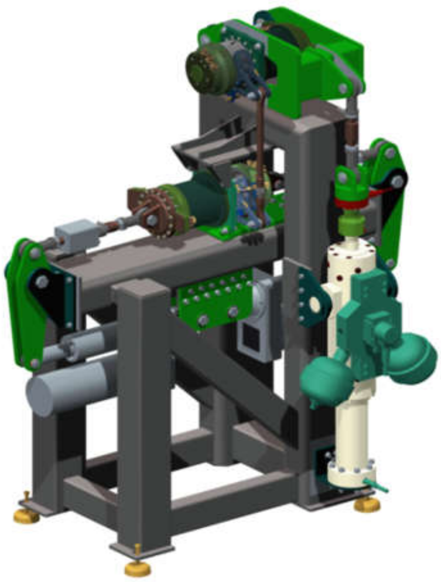


Figure 20: CAD Rendering of the EMA Function and Fatigue Test Rig

Following the performance test of the two EMAs, the complete system will be mounted onto the dummy rotor hub of Figure 21 and tested under a realistic centrifugal loading in combination with a rotor blade simulator (comparable to the test setup at Sikorsky, see the following section 7).

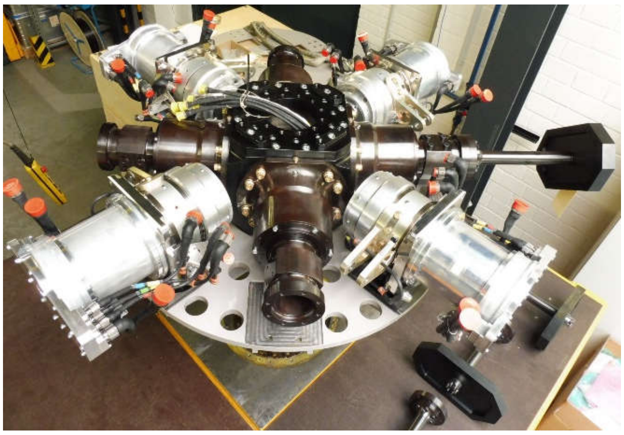


Figure 21: Assembly process of the dummy rotor head with EMAs and rotor blade simulator

7. SYSTEM INTEGRATION LAB TESTING

In parallel with qualification testing of LIBRAS which takes place at ZFL in Germany, a full LIBRAS system will be prepared and shipped to Sikorsky for a System Integration Lab (SIL) Test. This test will take place at the Sikorsky headquarters in Stratford, Connecticut and will validate the component technologies in a representative laboratory environment, simulating wind tunnel test conditions as closely as possible. This test, a stepping stone for the full-scale wind tunnel test, has the following primary objectives:

- Verify test article assembly and mechanical integration of the LIBRAS IBC system
- Verify Sikorsky Flight Control Computer (FCC) software in the fully integrated system
- Validate LIBRAS system operation through a range of rotor speeds and harmonic motions
- Demonstrate robustness of the triplex system architecture to induced faults
- Satisfy entrance criteria requirements for NFAC wind tunnel (endurance testing, vibration testing, and overspeed testing)

7.1. SIL Hardware Setup

From the outset of the program, the SIL test was designed in order to replicate the wind tunnel configuration closely. The electrical and architectural set up of the rotor with power supply, instrumentation, control, and data systems will be identical to that planned for the wind tunnel configuration. On the mechanical side, rotor components are identical with two exceptions. First, and trivially, an alternative rotor hub is used with a shortened flange to accommodate the limited vertical space available on the test rig. Second, 'blade simulators' replace the X2® rotor blades themselves to provide a dynamically relevant external load source for LIBRAS in a safe testing environment.

The SIL test allows for complete actuation of the LIBRAS system with rotation up to full rotor speed.

The blade simulators (Figure 22) were designed to mimic the relevant torsional properties of the X2 blades. The relevant blade properties matched in the design are the first torsion frequency, torsional (pitch) inertia, propeller moment, and low damping. Using this approach, the SIL test is almost completely representative of the wind tunnel test environment, differing only in that blades are replaced with blade simulators that have first order dynamics properties of the true X2 blades, and lack a source of aerodynamic loading.

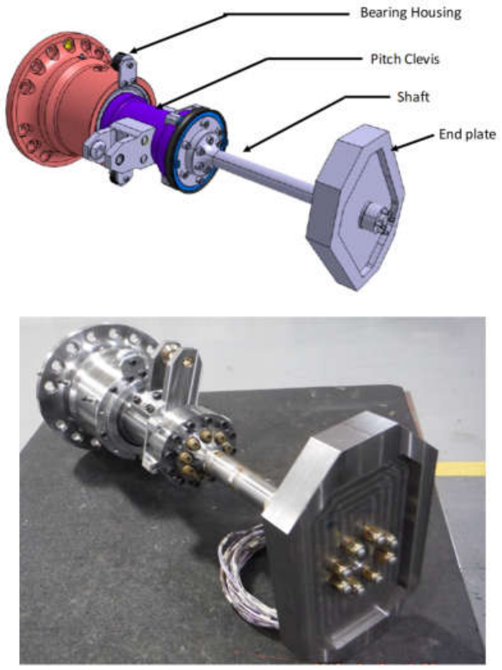


Figure 22: Blade Simulator Design and Hardware

The blade simulators are designed to attach to the rotor hub in an identical fashion to the rotor blades and conceptually consist of a simple plate rigidly attached to the end of a thin circular shaft. These are shown integrated into the SIL rotor design in Figure 23.

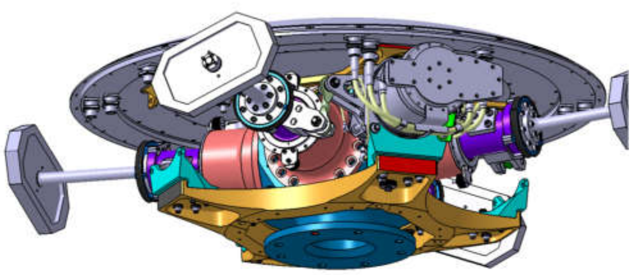


Figure 23: SIL Rotor Head with Mounted Blade Simulators

During the preliminary design process, the end plate was sized to match the torsional inertia of the blade, while the shaft diameter and length were driven by its stiffness requirement, itself a function of the required torsion frequency and end plate inertia. Lastly, an appropriate propeller moment (a restoring pitching moment unrelated to aerodynamics that rises with increasing blade pitch) was incorporated by flattening the end plate in the vertical axis and elongating it in the circumferential direction. Rotorcraft Comprehensive Analysis System (RCAS) was used both to model and validate the blade simulator design, as well as to define expected loads for stress analysis of the component.

The SIL test will take place on a rotating test facility called the Bifilar Rig, see Figure 24. This rig, previously used to test rotor-head bifilars, has been repurposed for rotating tests of advanced on-rotor components. As such, it also includes facility actuators capable of shaking the test asset in all three axes, and this functionality will be used for vibration testing of the system. The bifilar rig is capable of spinning above 500 RPM, which will allow testing to 110% rotor speed to satisfy the NFAC wind tunnel's overspeed entry requirement.

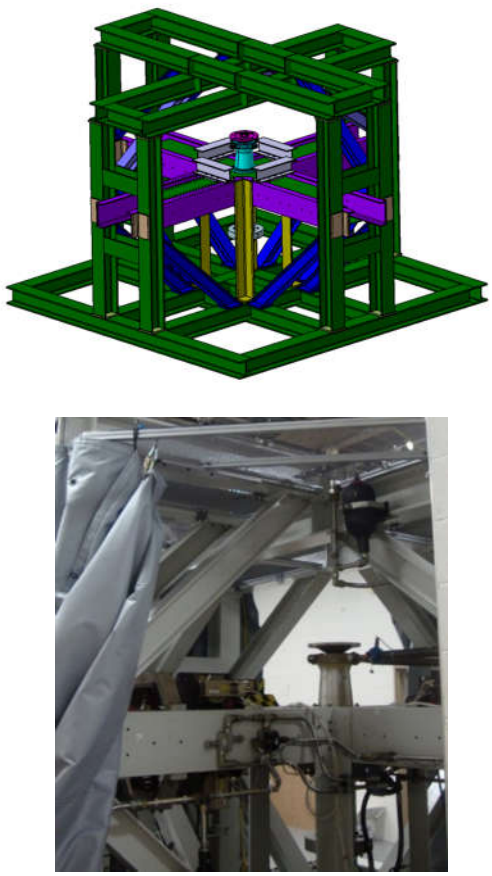


Figure 24: Sikorsky Bifilar Rig

7.2. Test Matrix and Test Build-up

The SIL test will consist of approximately six phases to expand the envelope of the LIBRAS system and test its capabilities. In summary, the test phases are as follows:

1. FCC System Checkout
2. SIL Preparation
3. Non-Rotating Functional Checkout
4. Rotating Functional Testing
5. Robustness Testing
6. Endurance Testing

The first two phases of testing are preparation and consist of verification testing of the Flight Control Computer components after they have been brought to the Bifilar Rig test lab and re-integrated together. SIL Preparation will take place during and after installation of the IBC rotor on the Bifilar Rig itself. Mechanical and electrical checkouts, including verification of control and data acquisition will take place. Pilot commands and HHC algorithms will be verified along with safety mechanisms designed to limit excessive control motions. Once initial integration bugs have been worked out, non-rotating testing will verify the functionality of the LIBRAS system using simulated azimuth signals in which linearity checks of increasing control inputs will be performed. Some level of loss and restoration of power and communication will also be performed, though this element of testing will be conducted much more thoroughly during the robustness testing phase. During this test, phase and amplitude sweeps will also be conducted for each harmonic and for multiple harmonics simultaneously that are expected to be encountered during rotating testing. Frequency sweeps will also be conducted.

During normal-operation rotating testing, a sample of the test points carried out during non-rotating testing will be repeated at multiple rotor speeds up to 100% nominal speed. Of interest during rotating testing will be assessing performance of LIBRAS with larger harmonic amplitudes, and primary plus HHC simultaneously.

7.3. Robustness Testing

During the design phase of this project, both the Sikorsky hardware (FCC) and ZFL hardware (LIBRAS) were designed to have sufficient error mitigation algorithms and checks in place for a safe wind tunnel test, and to prove the viability of a triplex architecture for such a system. While normal-operation testing in the SIL will demonstrate the overall reliability of the system, robustness testing will include seeded faults of the system to demonstrate proper functionality in the event of degraded operation. High-level faults were identified through a failure modes and effects analysis, and those deemed most likely to occur and/or with the most severe consequences will be probed. Triplex functionality will be evaluated such that cross communication and voting occurs correctly, and such that the system can meet its specification with one and two power lanes not operational. A subset of the robustness test points is shown below:

- Removal of one or two lanes of the triplex power source
- Removal of one command lane to the APCU
- Transmission of dissimilar triplex commands to the APCU to test voting algorithm
- Transmission of out of range commands to the APCU
- Issue of rapid hard-over and slow creeping commands by the FCC
- Azimuth encoder simulated failure
- Complete FCC failure

Success for this portion of testing is defined by predictable and correct response of the system to the seeded faults above. If this criteria is met, it provides confidence that the system will behave in a similar fashion during the wind tunnel test in which its environment will be quite similar.

7.4. Endurance Testing

A 1:1 endurance test at minimum will be conducted in the SIL according to a usage spectrum estimated for the wind tunnel test. This will provide confidence in the mechanical robustness of LIBRAS under centrifugal forces and relevant external load via the blade simulators. Planned on the order of 100 hours, this will be a significant portion of the SIL test in duration, and will be conducted after the other test phases. It should be noted that given the SIL does not include aerodynamic loading due to the rotor blades, a given control input will not precisely match to control load expected in the wind tunnel for that control input. A balance was reached in defining the spectrum such that control input amplitudes will be elevated to better match the external load spectrum applied to the LIBRAS system for the test.

7.5. Wind Tunnel Test

After the SIL test is completed, rotor components will begin to be shipped to the NFAC in preparation for the wind tunnel test, which will take place in the 40x80ft^2 test section with a second LIBRAS system provided by ZFL. Major wind tunnel test objectives include the following:

<u>Demonstrate primary flight control</u>

- Fly the wind tunnel model through the X2 Technology Demonstrator's steady envelope (0 to 250 knots) in addition to high load factor conditions

Quantify the benefits of IBC

- Closed loop vibration control
- Tip control and blade load alleviation
- Performance improvement
- Automated rotor tracking
- Gather data for analysis correlation

Evaluate IBC design and implementation challenges

- Clean data and power transfer through the slip ring
- Feasibility of power regeneration
- Thermal management

Evaluation of the objectives above will provide ZFL and Sikorsky both with information necessary to size such a system for a potential follow on flight test, and with engineering data necessary to perform aircraft level trades to determine with accuracy what kind of high-level benefits this technology may hold for both conventional and forward-learning vertical lift configurations.

8. CONCLUSION

Based on the lessons learned from a previous project, ZFL has partnered with Sikorsky to demonstrate the feasibility of a purely electrical, swashplateless control system designed to combine both primary and IBC functionalities. Many practical challenges had to be mastered to fit all system components into the rotor hub fairing. To match the efficiency of a mechanical swashplate, not only the electro-mechanical actuators but also the redundant Actuator Control Units, the power electronics and a strong DC link had to be placed in the rotating frame. Thus, the necessity to transfer high currents over long distances or even up and down the electrical slip ring could be spared.

All components have been manufactured and passed the respective acceptance tests. Component testing has mostly been completed and system integration has been accomplished. The motor performance has been validated, but fatigue testing of the complete EMA is still pending. Likewise, software coding and HW – SW integration testing has been completed, whereas functional testing against the high and low level requirements is in the final stages and will be completed in time for the SIL testing. Parallel testing at ZFL in Germany (actuator fatigue and system function) and in the SIL at Sikorsky will continue through the second part of 2019. Wind tunnel testing is expected to commence by the begin of 2020 and to run over a period of three to four months.

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