DEVELOPMENT, MANUFACTURING, AND COMPONENT TESTING OF AN INDIVIDUAL BLADE CONTROL SYSTEM FOR A UH-60 HELICOPTER ROTOR

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Abstract

Within the framework of a cooperative research program joined by ZF Luftfahrttechnik GmbH (ZFL), NASA Ames Research Center (ARC), and Sikorsky Aircraft Corporation (SAC) it was agreed to develop and manufacture a full-scale UH-60 Individual Blade Control (IBC) system to be installed in the LRTA and tested in the NASA National Full-Scale Aerodynamics Complex. The LRTA is NASA's new Large Rotor Test Apparatus which was designed to test helicopter and tilt rotors in the 40- by 80-foot and 80- by 120-foot Wind Tunnels. The objectives of the UH-60 IBC wind tunnel test program were to demonstrate the feasibility of the IBC system and to quantify the benefits to be gained when applied to and operated with a UH-60 main rotor.

This paper describes the UH-60 IBC system engineering design, development, manufacturing, and component testing conducted by ZFL. The servo-hydraulic IBC actuators to be installed between the swashplate and blade pitch horn were designed to withstand the control forces produced by a full-scale UH-60 rotor in a centrifugal field of up to 40 g. They were designed to produce up to ±6.0 deg blade pitch motion at the 2/rev frequency, diminishing to ±1.6 deg at the 7/rev frequency. A set of actuator test specimens was manufactured and fatigue tested with simulation of the control forces and centrifugal load. Prior to the 80- by 120-foot wind tunnel testing, that was concluded by the end of September 2001, the complete IBC system was functionally tested (non-rotating and rotating, blades off). This paper discusses the IBC system integration issues as well as the test stand set-up used for actuator and system level testing.

Introduction

Active rotor control using full-scale blade root actuation devices has proven successful in reducing vibration, noise, and other negative effects associated with helicopter rotors operating in egdewise flow. The early developed Higher Harmonic Control (HHC) systems which actuate the swashplate of a conventional helicopter in the fixed frame are restricted to certain frequencies of N/rev, (N-1)/rev, and (N+1)/rev, where N is the number of rotor blades. Hence it follows, that for a four-bladed rotor the important 2/rev frequency can not be generated by these fixed-frame HHC systems. This can only be achieved by rotor-mounted devices such as, for example, active pitch links, which replace the rigid control rods by servo-hydraulic actuators. Each rotor blade can thus be controlled independently from the others in a certain pitch angle range superimposed over the primary flight controls. Other current Individual Blade Control approaches employ on-blade actuation devices like trailing edge flaps or tabs, active blade tips, or integral blade twist systems. All these concepts pose difficulties for the design and fabrication of the highly loaded main rotor blades, so that most of them have not been implemented in full scale, to date.

Under a previous cooperative U.S./German program, NASA tested an IBC system in the Ames 40- by 80-foot Wind Tunnel in 1993 and 1994. The testing was performed with a BO 105 rotor on the NASA/U.S. Army Rotor Test Apparatus using IBC actuators manufactured by ZFL. The 1994 entry demonstrated simultaneous reductions in vibratory loads and noise for some IBC inputs, and modest improvements in performance at high-speed flight conditions. As a result of these findings, Sikorsky Aircraft, the U.S. Army, NASA Ames, and ZFL entered into a joint program to evaluate the potential of IBC to benefit the UH-60 Black Hawk helicopter. As a step towards reducing the risk

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and cost of flight testing, the IBC technology should first be evaluated on a Black Hawk rotor in the 80- by 120-foot and 40- by 80-foot Wind Tunnels at the NASA Ames Research Center.

IBC system design

The full-scale IBC system for helicopter main rotors described in this paper was developed and manufactured by ZF Luftfahrttechnik GmbH of Germany. The IBC equipment has been installed into NASA Ames' Large Rotor Test Apparatus (see Fig. 1) which carried a Sikorsky UH-60 Black Hawk main rotor system. The current UH-60 blade pitch links were replaced by ZFL's servo-hydraulic IBC actuators with a bandwidth sufficient to perform blade pitch motion control up to 7/rev (30.1 Hz).

Fig. 1: LRTA in NASA Ames wind tunnel preparation area

It was agreed to design IBC actuators mating with a standard UH-60 main rotor and being capable of superimposing IBC angles of up to ±6.0 deg. Corresponding hardware has been laid out as an experimental system for wind tunnel tests and fundamental active rotor control research. Development, design, and fabrication of the IBC system components was based on the considerable experience of ZFL regarding IBC equipment production and hardware testing (Refs. [1] – [9]). Though utilized for wind tunnel tests only, all conceivable safety aspects have been addressed during design and manufacture of the IBC hardware. With regard to the fabrication of the hydraulic system, particularly the actuator components, ZFL was able to refer to processes used in the CH-53G IBC flight test program carried out together with the German Army (Ref. [3]). The consideration of quality assurance aspects during procurement and production follow examples of corresponding CH-53G methods that yield to flightworthy hardware. The IBC electronics, on the other hand, were based upon the BO 105 wind tunnel test hard- and software used in the successful 1993 and 1994 campaigns (Refs. [6], [7]).

Subassemblies

The mechanical layout of ZFL's IBC system focuses on modular design for easy installation into NASA ARC's LRTA operating a UH-60 main rotor. The IBC system is composed of the following main subassemblies:

- 4 blade root IBC pitch actuators,
- hub-mounted hydraulic parts comprising
  - hydraulic distribution collar,
  - hub adapter,
  - hydraulic pipes, hoses, and fittings,
- non-rotating LRTA-mounted parts comprising
  - hydraulic slipring (rotary transmission lead-through),
  - hydraulic manifold including magnetic shutdown valves,
- electronic hard- and software.

Fig. 2 shows the general arrangement of the equipment. For clarity reasons a neat grouping is shown omitting all mechanical parts of the LRTA test stand excepting the rotor shaft leadthrough.

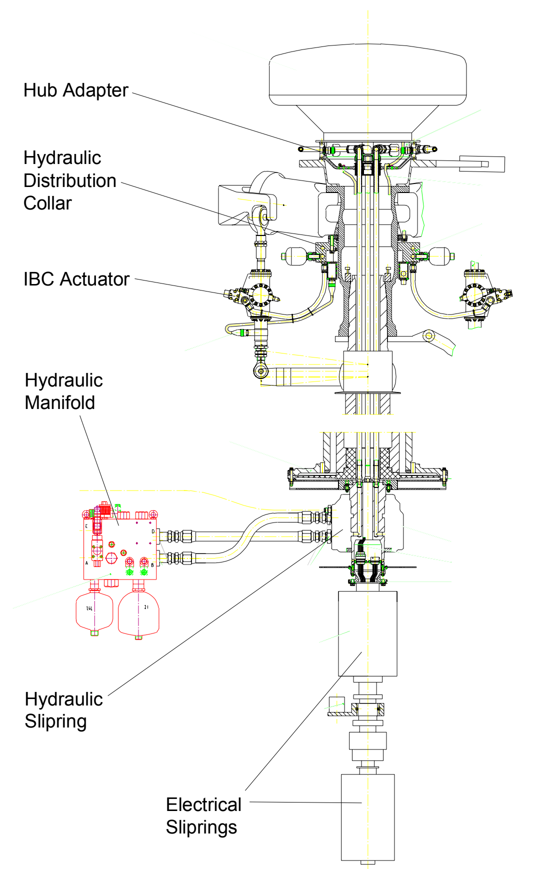

Fig. 2: UH-60 IBC system for LRTA installation

ZFL has designed and fabricated the IBC actuators and the control electronics. The adaptation hardware required to interface the IBC system to the LRTA and the UH-60 rotor has also been designed by ZFL. However, some parts and subassemblies like the hydraulic block and slipring have been manufactured by external suppliers. The general layout of the hydraulic block including the realization of the shutdown functions and a specification for the manifold as well as for the hydraulic slipring were defined by ZFL. For these important components ZFL has specified acceptance test procedures which had to be passed before the hardware could be approved. Most of the vendor parts as well as the materials used and semi-finished products have been purchased with test certificates. Essential hydraulic parts and connections (e. g. swivel joints) to be installed in the rotating frame were chosen to meet aerospace standards.

Actuators

The blade root pitch actuators are the most sophisticated technical components within the IBC system. Their design is based on the considerable experience that ZFL has gathered in several IBC wind tunnel and flight test campaigns during the past fifteen years. However, regarding the capability in actuator stroke (control authority) and axial load performance the UH-60 IBC actuators represent a unique design. The desired maximum IBC amplitude was specified to ±6.0 deg, which led to a maximum necessary actuator stroke of 18 mm (pp/2). The required design peak load resulted from the requirement to operate the IBC actuator in a pitch link load envelope of –1,000 +/– 3,000 lbf. The load requirements correspond to common level flight conditions with additional load portions due to IBC superposition considered. IBC operation especially in the wind tunnel should thus be possible for a wide range of the flight envelope.

With these boundary conditions, calculations regarding geometry and hydraulics were carried out. Hydraulic flow rate and working piston area were sized to control a harmonic stroke signal with 18 mm amplitude (pp/2) at a frequency of 2/rev under the specified load conditions. Table 1 gives an overview of the leading technical data of the actuator. Figs. 3 and 4 show the result of the actuator layout and detail design activities.

Table 1: Technical data of the UH-60 IBC actuator

Parameter	Value
Nominal actuator length	637.5 +/– 19.0 mm
Actuator stroke (mechanical limit)	±19.5 mm
Rated IBC stroke (max. usable @ 2/rev)	±18.0 mm
Rated max. piston velocity (2/rev, full stroke)	0.97 m/s
Working piston area	13.93 cm^2
Range of usable harmonics	2/rev – 7/rev
Design peak load (IBC on)	17,800 N
Rated min. holding load (@ lock-out)	34,100 N
Mean hydraulic flow rate	55.0 l/min
Actuator weight (incl. rod ends)	13.8 kg

The actuator makes use of a working piston which moves inside the main cylinder housing in response to the hydraulic pressure and flow control of a Moog servo valve. The piston extends and retracts, providing the motion or force commanded by the IBC controller. Actuator displacement is measured by two LVDTs (Linear Variable Differential Transducers); a full bridge strain gage is used to measure the axial (pitch link) loads during operation.

As the actuators were designed to replace the conventional rigid control rods it is absolutely necessary that any failure in the hydraulic or electronic circuits does not lead to catastrophic or even critical rotor states.

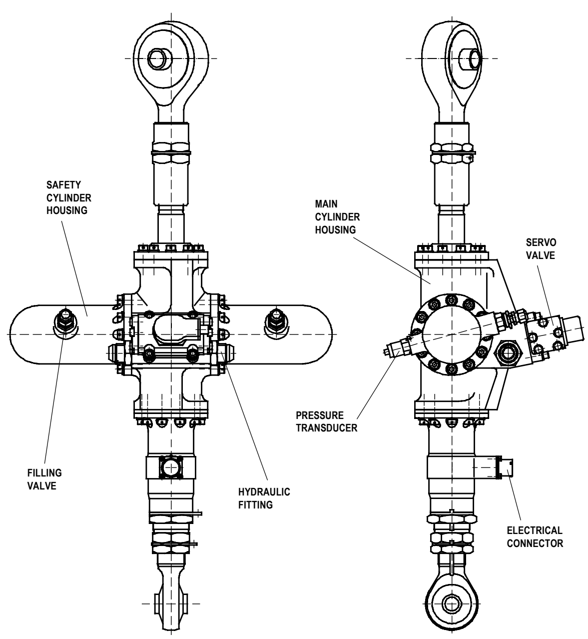

Fig. 3: Two-way view of the IBC actuator

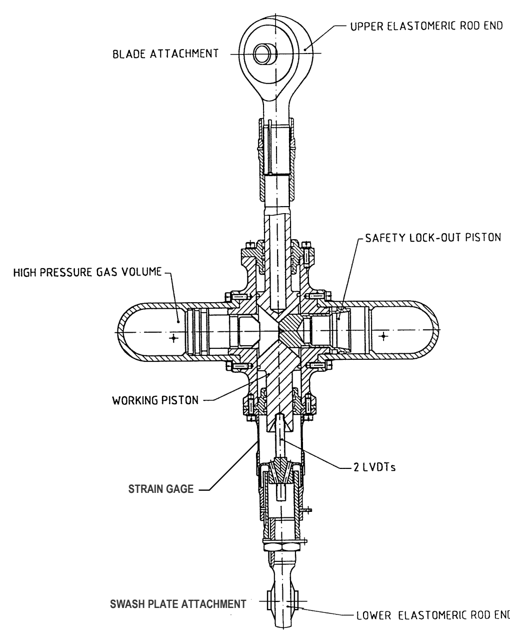

Fig. 4: Sectional view of the IBC actuator

To a priori avoid such situations the actuators have been designed and equipped with an automatic fail-safe lock-out mechanism, that in case of emergency forces each actuator working piston to immediately return into its mid position. In that configuration the length of the actuator is equal to the conventional push rod geometry and remains fixed. For this purpose the actuators employ a dual gas cylinder safety system making use of lock-out pistons which are retracted against a gas spring by application of the 3,000 psi hydraulic system pressure (see Fig. 4, left safety cylinder). These pistons have wedge-shaped ends that accurately fit into corresponding openings machined into the working piston.

On loss of hydraulic pressure, both pistons automatically center, driven by the pressurized gas volume always present during normal operation (see Fig. 4, right safety cylinder). Thus the safety philosophy is to generate an immediate pressure drop in the main hydraulic circuit when a failure or malfunction of the IBC system is detected (fault detection algorithms and reconfiguration in the presence of detected faults are provided by the control system). In this case the working piston is forced to immediately move into its mid position and remain there fixed as long as the hydraulic system pressure is down. Once the piston is locked, static friction ensures a rated holding load of more than 34 kN. It should be noted that only one of the two independent safety pistons is sufficient to lock the actuator, in this sense the safety system is dual redundant.

Material selection and fabrication processes for the actuator component parts as well as foreign supplies and contract services had been monitored by ZFL's quality management and assurance departments to make sure that all relevant procedures met aerospace standards. The main and safety cylinder housings are made of high-quality wrought aluminum alloys, all the other parts arranged in the main load path (working and safety pistons, lower housing, tapped and threaded bushes) are made of vacuum heat-treated steel. Crack detection of each machined metal part has been conducted according to MIL-STD-1949.

Fig. 5: Test specimen of the UH-60 IBC actuator attached to a mounting plate

Surface coating and treatment had carefully been chosen as they determine wear of the sealing and guiding elements as well as fatigue strength of the loaded parts. The elastomeric rod ends and jam nuts provided by NASA are attached to the actuator by means of tapped bushes. A photo of an assembled specimen for actuator fatigue tests is shown in Fig. 5.

Three actuators were built and used for functional and fatigue testing only. For the wind tunnel test campaigns 5 brand-new actuators were available, meaning that there was at least 1 back-up unit including the controller hardware for the fully-equipped UH-60 baseline rotor with 4 blades. Spares for most of the vendor parts and some of the structural actuator components were also available.

Hydraulic system

A hub adapter was designed to sit on top of the UH-60 hub-mounted bifilar absorber (see Fig. 6) using a 15" diameter flange bolt circle for bifilar-to-adapter attach bolts.

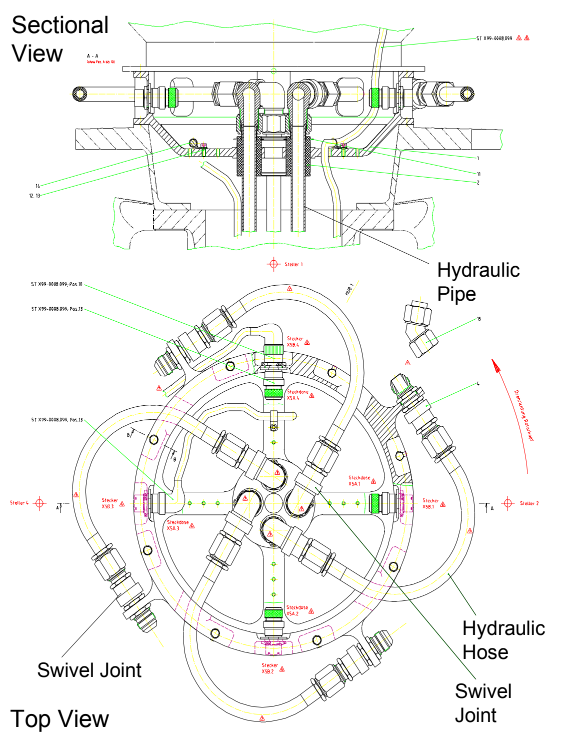

Fig. 6: Hub adapter with hydraulic pipes and hoses, swivel joints, and electrical connectors

The adapter has 4 supporting struts which merge in the center of the hub where 4 hydraulic standpipes end (2 pressure and 2 return lines). These pipes were connected to the rotating shaft flange of the hydraulic slipring with screwed sockets welded on the lower end of each tube. The pipelines were routed through the LRTA transmission and rotor shaft up to the rotor head, where they were guided through and supported by plain bearing bushes installed in the hub adapter's central disk area. Each pipe was then linked to a flexible hose by means of a 90 deg elbow swivel joint. The hoses were led out of the hub adapter in radial direction through 4 outlet holes. They were attached to 4 brackets by another set of ball bearing swivel joints so that the vertical loads due to frictional forces resulting out of a movement of the rotor hub relative to the pipes were negligible. Between the brackets and the hydraulic distribution collar again hydraulic pipes were installed (not shown in Figs. 2 and 6). The installation height of the hub adapter was 70 mm (distance between the bifilar flange and the upper hub adapter flange). On its top flange the identical bolt pattern as on the bottom was used so that the base plate of NASA's rotor-mounted data acquisition system (RMDAS) unit could be mounted onto the hub adapter in the usual manner. Four connectors were integrated into the hub adapter as depicted in Fig. 6. They interconnect the mast-guided wire bundles with the cables coming from the actuators via electronic boxes which were mounted to the bottom of the hydraulic distribution collar.

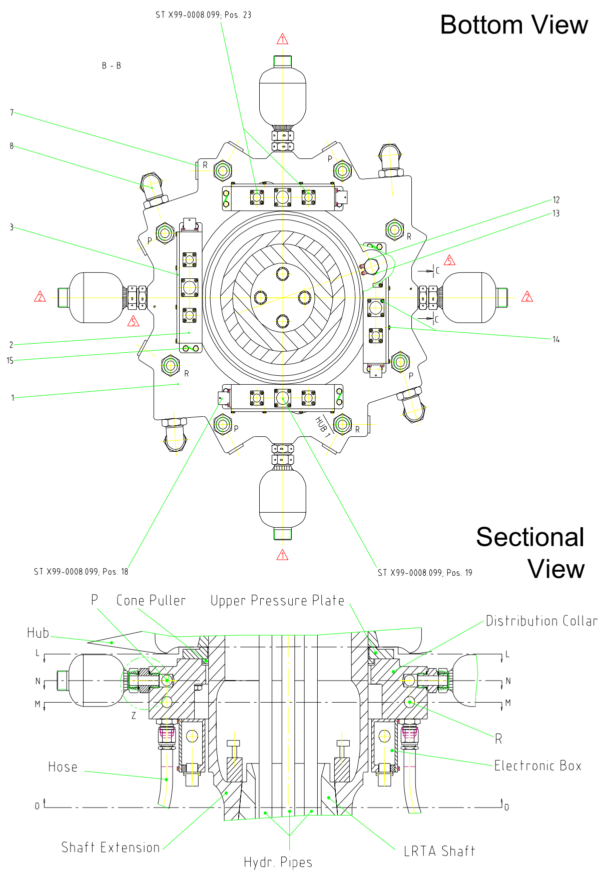

Fig. 7: Drawing of the hydraulic distribution collar with gas accumulators, hydraulic fittings, and electronic boxes

The hydraulic distribution collar (see Fig. 7) was attached to the upper pressure plate of the rotor head using 4 threaded pocket holes around an 11.68" diameter bolt circle (unequally spaced). The 4 hydraulic pipes that come down from the hub adapter (2 pressure and 2 return lines) were each connected to the distribution collar by means of 90 deg elbow joints. Two joints were linked with the pressure oil duct, and 2 with the return oil duct located inside the distribution collar.

To each hydraulic oil duct system 2 accumulators and 4 hoses were connected. Four pairs of these 8 hoses ran off the distribution collar from its bottom side directly to the actuators (1 pressure and 1 return line per actuator). Thereby the hydraulic circuit to and from the hydraulic slipring was closed. For each actuator 1 electronic box was attached to the bottom side of the collar. These boxes contained amplifiers, inner-loop controller elements and interface units for the IBC electronics.

A hydraulic rotary transmission leadthrough (hydraulic slipring) was used to connect the hub-mounted hydraulic components with NASA's wind tunnel facility hydraulic supply. Hydraulic power in terms of oil pressure and fluid flow rate was fed into and returned out of the rotating frame by special diaphragm gland cartridges integrated in the hydraulic slipring. The seal between stationary and rotating parts of these cartridge elements was effected by sealing gaps which were kept to a specified value by means of a hydrostatic control mechanism that permitted slight wobble and eccentric running of the shaft. This hydrostatic control system ensured that the gap widths of up to 15 µm were kept constant even at 3,000 psi of hydraulic pressure. Elastic, pressure dependent deformation was ruled out by a hydraulic compensation system. Fig. 8 shows some details of the hydraulic slipring design.

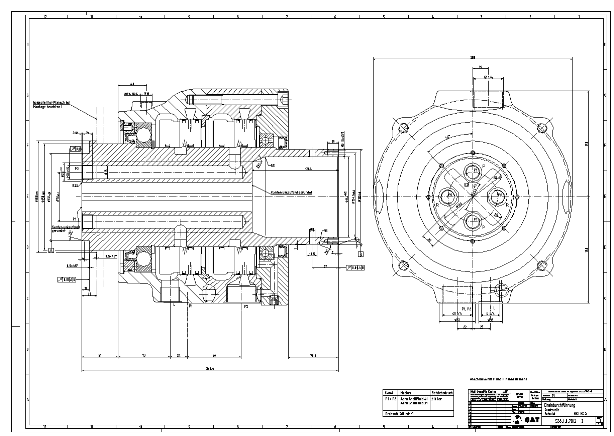

Fig. 8: Detail design of the hydraulic slipring

The hydraulic slipring rotor was attached to the hollow LRTA transmission output shaft by means of a mounting bar designed and fabricated by ZFL. An arrangement of 2 electrical sliprings and a phototach was attached to and in-line with the hydraulic slipring shaft. The upper one of these electrical sliprings was directly mounted beneath the hydraulic slipring using an adapter fabricated by ZFL to mate with the RMDAS slipring flange. The adapter additionally carried an electrical connector holding device and a splash disk to protect the electrical sliprings against hydraulic fluid in the event that a leakage occurs in the hydraulic slipring rotary shaft seals. The hydraulic slipring shaft was fabricated with a cross-shaped center clearance (see Fig. 8) to allow some wire harnesses coming from the electrical sliprings to be led through the LRTA rotor shaft assembly. For easy installation and disassembly of the electrical sliprings a plug-in connection for the wire harnesses was utilized.

ZFL's rotor-mounted IBC hardware was linked with NASA's hydraulic supply by means of a hydraulic manifold (see Fig. 9) which contained the IBC emergency cut-off circuitry as well as 2 pressure (A and B) and 2 return ports (C and D) for hydraulic supply and return lines.

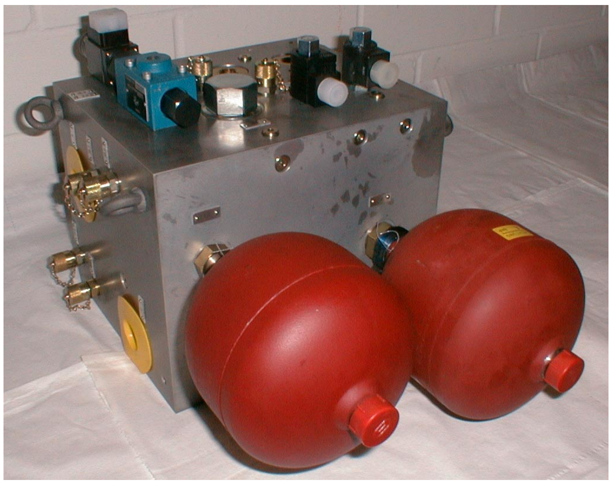

Fig. 9: Photo of the hydraulic block lying on its back side

The manifold mainly employed a couple of magnetic and other valves that sat in or on a rectangular solid aluminum block. This block has been designed and manufactured according to ZFL's specification in order to allow hydraulic fluid to flow from port A to B and back from D to C during standard IBC operation. The A and C ports were to be connected with the LRTA's main hydraulic supply (A) and return (C) lines. Between the ports B and D sat the hydraulic slipring and the rotor-mounted IBC system components, particularly the 4 IBC actuators as main power consumers. Fluid from the NASA supply was conditioned by redundant control circuits as described below. Beyond the vital safety functions, the hydraulic manifold provided some additional features like controlled pressure rise with adjustable fluid flow rate, pressure measurement in the supply and return lines, and pulsation damping.

During normal IBC operation 2 main passage valves located between ports A and B are kept open while 2 bypass valves are closed by hydraulic pressure built up in 3 independant control circuits. This pressure build-up was maintained in the control circuits as long as the hydraulic system pressure (3,000 psi) provided by the NASA test facility was present on port A and each of 4 magnetic safety lock-out valves were closed by application of 24 VDC from the main controls. In case of a manually or automatically triggered shutdown the electrical voltage over these safety lock-out valves would be switched off so that they would mechanically open (this would also occur when the control system fails due to a complete loss of electrical power). In this case the pressure immediately would decrease in the open control circuits which would lead to a mechanical shutdown of the main passage valves and thus cut the IBC system off from the hydraulic supply. Fluid flow would be interrupted at once which also would lead to a pressure drop in the hub-mounted hydraulics. Simultaneously, the bypass valves of the manifold would open which would allow the hydraulic fluid to pour out of the rotating system components into the return line. The cut-off circuitry provided at least twofold redundancy, because every essential part of the shutdown chain existed twice where both parts acted independently of each other.

Electronic control system

The IBC electronic hardware mainly consisted of

- a main and monitoring VME bus computer system for digital and analog signal processing (2 units for each system),
- the control console (operator-terminal, potentiometer control and emergency shutdown buttons),
- a hydraulic block valve control system,
- 4 actuator controller boxes (1 for each actuator), and
- the hub-mounted wire harnesses.

The control system virtually consisted of 2 physically and functionally partitioned channels within the same physical package. Most of the main control and monitoring electronics were installed in a 19" rack enclosure which also contained a drawer for taking up the control console hardware as shown in Fig. 10.

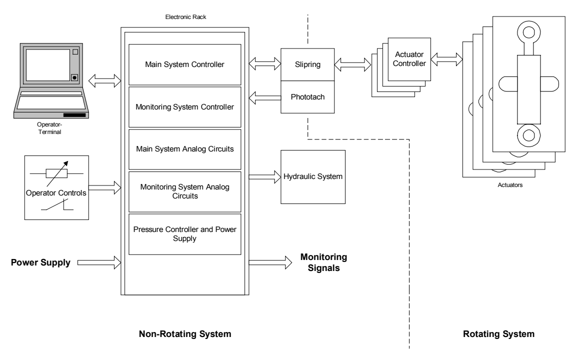

Fig. 10: Overview of the control system components

The main computer system was designed to control the actuators by generating the command signals for the servo valves and to perform the signal conditioning for 1 LVDT set (1 set corresponds to 4 LVDTs, 1 per actuator). The monitoring system mainly performs monitoring duties and signal conditioning for the 2nd set of LVDTs. Failures could be detected by both systems. They had equal (highest) priority to trigger an emergency shutdown. Thus a redundant stroke monitoring was realized using 2 LVDT sensors for each actuator. Actuator travel versus command value was monitored by the two completely independent (main and monitoring) systems, each of them including a computer for FOURIER analysis and synthesis. When a certain stroke difference between commanded and actual value at least of one of the LVDTs was detected or any other malfunction occurred, hydraulic power was shut down which immediately disengaged the safety lock-out pistons and mechanically bolted the actuators in their zero positions. This feature made uncontrolled actuator travel impossible. A shutdown signal would also be generated when the measured axial load in any one of the actuators reached a preset threshold value.

Regarding the hardware, each actuator was equipped with a controller board that was manufactured in SMD (Surface Mounted Device) technology. The controller board was contained in a separate electronic box (1 for each actuator). It performed the conditioning of the strain gage and the 2 LVDT signals. The power supply for both LVDT signal conditioners (36 VDC) was provided independently for redundancy purposes. An analog controller with P characteristic controlled the servo valve (inner loop). Finally, each actuator employed 2 gas pressure sensors to continuously monitor the status of both independent safety systems. All signals were transmitted as 4 to 20 mA currents. The pressure sensor signal receiver with 8 current signal input channels was associated to the monitoring system. In every channel the current signals were transformed into voltage signals (0 to 10 V) which were transmitted to the VME bus computer of the monitoring system. The actual pressure values were displayed on the operator-terminal. If 1 pressure value fell below a certain threshold this would be indicated by a color change (from green to red) of the respective display.

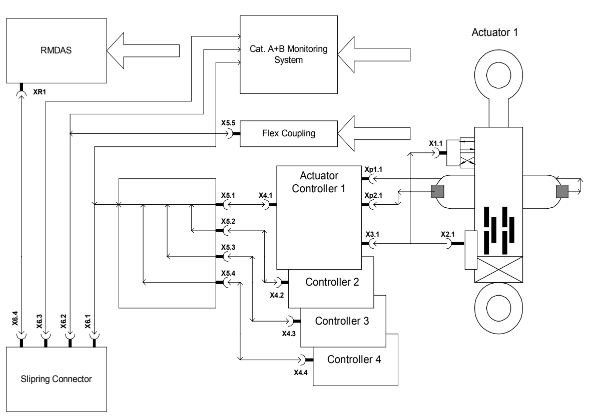

Fig. 11: Electronic hardware components in the rotating frame (cabling and connector layout)

Fig. 11 outlines the electronic components that were located in the rotating system. It also sketches the wires and connectors purchased or manufactured by ZFL. While ZFL was responsible for the fabrication of the rotor-mounted wire harnesses, NASA made the cables between LRTA (electrical slip rings, hydraulic block) and control room (IBC control rack). For connecting the IBC lines from the hydraulic block and from the stationary side of the electrical sliprings to the IBC rack ZFL had supplied NASA with mating plugs as well as details of their pin assignments.

From each actuator 3 wire harnesses ran to their corresponding controller boxes. These bunches contained the cabling for the servo valve, 2 LVDT sensors, the strain gage, and 2 gas pressure sensors of every actuator. Four additional harnesses (1 per actuator each combining the lines of the previous 3 cables) were installed between the 4 controller boxes and the hub adapter (Fig. 6 shows the connectors where these cables end). Inside the hub adapter these IBC cables (altogether 4 × 16 = 64 lines plus 1 shield) were brought together with 35 NASA analog signal line wires to 1 single wire harness. This harness together with 2 supplementary 100 line wire bundles (reserved for NASA analog signal transmission) and one RMDAS cable (NASA digital signal transmission) was routed through the LRTA rotor shaft and through the hydraulic slipring to meet with 4 plug receptacles in an electrical connector holding device. NASA wired these plug receptacles to the control lines from the rotating side of the electrical sliprings to mate with the 100 pin connectors wired to the 4 rotor shaft traversing cables. Details of the pin assignments had been sent to NASA together with the connector parts. ZFL manufactured all their wire harnesses (most of them with connectors) and conducted continuity checks as well as voltage and insulation tests (testing voltage: 500 V).

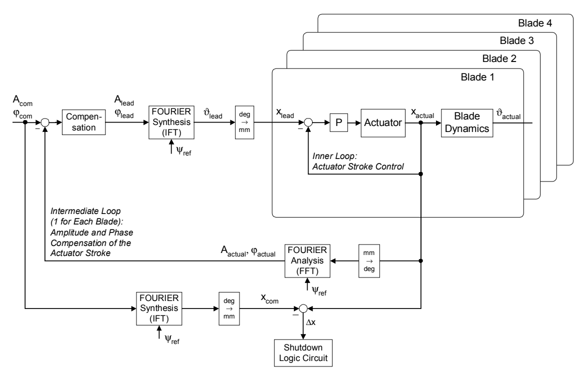

Fig. 12: Control system architecture (inner and intermediate loops)

The actuators together with their corresponding controller boxes were installed in the rotor head with the electronic boxes mounted on the bottom side of the hydraulic distribution collar. They contained the inner loop controllers for actuator stroke control, which had been designed to optimize each actuator's dynamic response in the time domain. Fig. 12 gives an overview of ZFL's control system architecture comprising the inner and an additional intermediate loop which both constituted the core element or "open-loop" control level of the IBC system. The intermediate loop was used to adjust the input IBC amplitudes and phase angles in an adaptive manner to compensate for any remaining amplitude and phase errors of the actuators. This loop was set up in the frequency domain and based on fast/inverse FOURIER transform (FFT/IFT). FOURIER analysis of the actuator displacement was performed to determine if those coefficients agreed with the commanded motion coefficients. The error signals were fed back to drive the adaptive compensation block until the measured harmonics matched the commanded. Separate feedback loops were provided for each actuator, thus it was guaranteed that all actuators performed equally though phase shifted according to their individual rotor azimuth. A third, outer loop could be added to this cascade architecture and thereby “closed-loop“ control capability could be realized very easily. The outer loop generated command values for the IBC amplitudes and phase angles according to the preset values (open-loop) or derived from suited state variables (closed-loop). The range of usable harmonics went in integral multiples of 1 rotor revolution from 2/rev up to 7/rev.

The electronic rack needed to be connected with the hydraulic manifold in order to control the IBC hydraulics. ZFL provided a wiring diagram for the required cable harness which was fabricated by NASA. Fitting plugs for the connection of the wire harness with rack and manifold were also provided by ZFL.

IBC system installation

The IBC hardware was installed into the LRTA in summer of 2000. These activities took place in the Ames wind tunnel preparation area, where all the assembly work and preliminary testing could be performed with the necessary support.

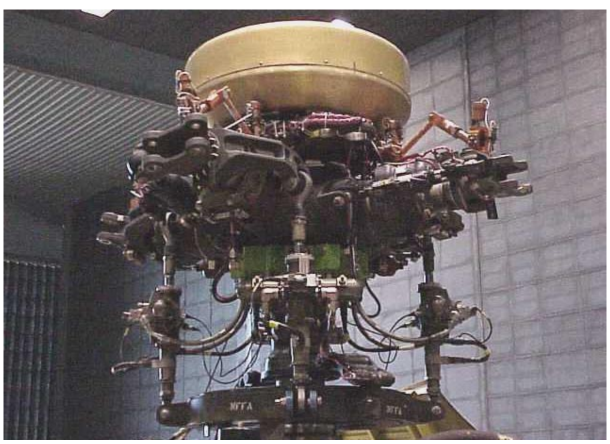

Fig. 13: UH-60 main rotor head with IBC actuators

The hydraulic and mechanical subsystem installation according to Fig. 2 could be set up without major interface problems, even though all the component parts of the IBC system had never been assembled before. This was due to a constant communication process established early between the involved organizations, that allowed a smooth and effective design work. A preliminary and a critical design review were conducted in 1998 in order to present the current design status and to clarify interface problems. The IBC hardware installation concluded with the successful connection of the hydraulic system with the control electronics components. Final non-rotating and rotating tests done in the preparation area without blades delivered the proof that ZFL’s IBC system worked as planned. In October 2000, NASA began the installation of the LRTA into the 80- by 120-foot test section with the IBC system integrated into the rotor hub as shown in Fig. 13.

Testing

IBC actuator testing

Comprehensive functional and fatigue testing was performed using a set of IBC actuator test specimens. These tests were conducted in ZFL’s test stand center on special rigs. Fig. 14 gives an idea of the set-up for the functional tests, where the test specimen was installed horizontally between a rigid frame and a hinged beam that allowed the actuator’s working piston to move inside the actuator housing.

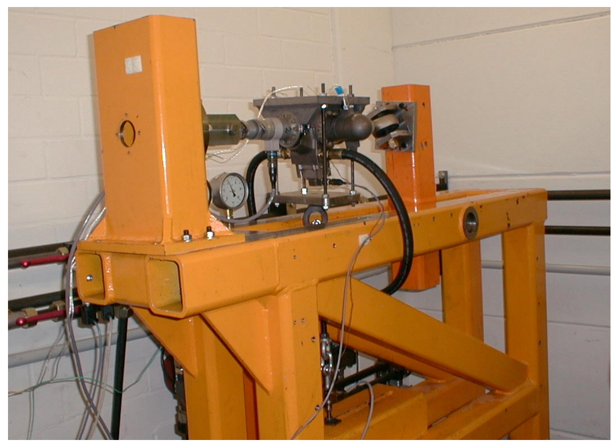

Fig. 14: Functional test of the UH-60 IBC actuator

Centrifugal load on the structure was simulated by a mechanical spring mounted between the frame and the actuator pulling it down in vertical direction. Two types of hinged beams existed for the test rig, which allowed different types of axial load excitation (against a static mass or a mechanical spring) to simulate blade loads. The functional test campaign was comprised by static leak checks at 4,500 psi (1.5 times the operating hydraulic pressure), static axial load tests at ±50,000 N, and extensive dynamic actuator testing. The dynamic properties and open-loop control characteristics of the IBC actuator were determined, showing that the specified control authority could be realized. Particularly, the safety lock-out mechanism was extensively examined, as it is a vital device for the system safety. A 200 hours run with sequences of all usable harmonics concluded the functional tests, where no mechanical damage on the guiding and sealing elements occured, and no hydraulic leakage could be detected.

Actuator fatigue testing was performed on another test rig, as depicted in Fig. 15. The test specimen was horizontally installed in a rigid frame unable to move and a centrifugal load was simulated by suspending weights to the actuator main housing. A force control cycle controlled the servo valve of the actuator, which generated alternating axial forces of ±26,000 N at frequencies of 13 to 18 Hz. The dynamic axial loads, produced by a hydraulic pressure of 3,000 +/– 580 psi, acted on the test specimen and were taken up by the stiff test rig structure. Axial forces were monitored and measured by the actuator strain gage and an additional load cell installed in the main load path of the test specimen. Thereby, a functional test of the actuator strain gage could be conducted, too.

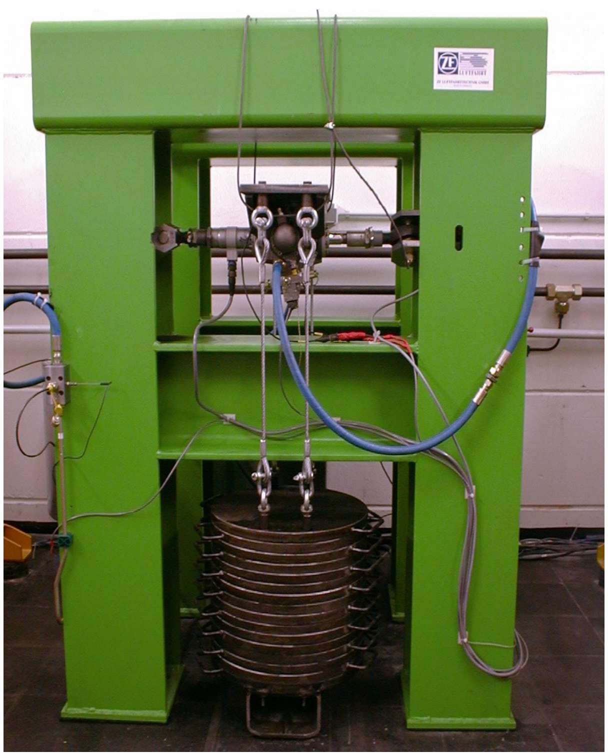

Fig. 15: Fatigue test of the UH-60 IBC actuator

A test rig extension according to Fig. 16 was developed in order to allow actuator fatigue testing with 2 specimens simultaneously. The test loads were generated with one (active) actuator while the other (passive) one was hydraulically unpressurized. However, the passive test specimen was in safety lock-out configuration with the safety lock-out pistons engaged (see Fig. 4). As this actuator was charged with the full test loads by the active test specimen via the lever shown in Fig. 16, fatigue testing of the lock-out system components could be performed as well.

In the course of the fatigue test campaign some actuator component modifications were implemented. The final design version which was manufactured for the wind tunnel tests had a proven fatigue endurance limit of ±7,300 N for 10^8 load cycles and a rated static limit of 48,250 N.

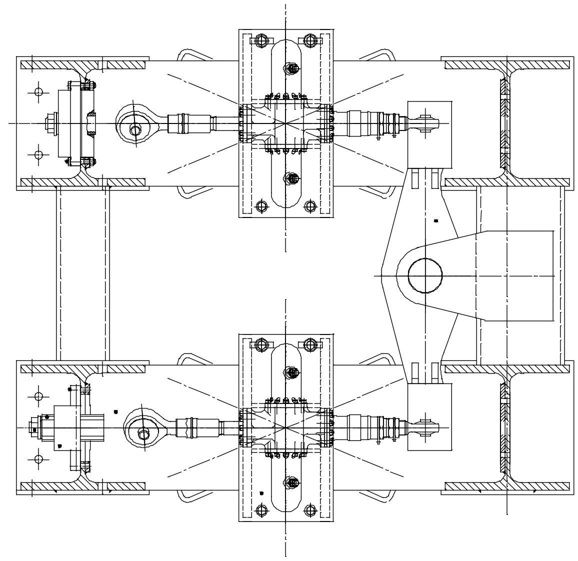

Fig. 16: Extension of the fatigue test rig

Hydraulic system component testing

For all vital rotating components comprehensive stress analyses had been conducted. Essential parts of the hub-mounted hydraulics as well as electrical connectors met aerospace standards. The hydraulic manifold and the hydraulic slipring were manufactured by external suppliers based on ZFL's layouts and specifications. These components were tested according to acceptance test procedures defined by ZFL.

The acceptance tests comprised leak and pressure checks, pulsation tests, hydraulic flow measurements, and additionally shutdown time determination for the hydraulic manifold, and internal leakage measurements for the hydraulic slipring. All parts and components could be qualified for the application in the UH-60 IBC wind tunnel test system.

Check-out test of the IBC system

Prior to the wind tunnel runs, which commenced in July 2001, the whole IBC hardware was tested on the system and subsystem levels in the 80- by 120-foot test section. Procedures for a pre-run check-out and a 50 hours check were derived from a failure mode and effects analysis (FMEA) prepared by ZFL and Sikorsky during the IBC system engineering design process.

The pre-run check-out test should demonstrate system level operativeness and was to be performed prior to each wind tunnel run. Essentially, the status of the electronic control hardware was determined. A check list was provided, that included every necessary check point to be executed. Similar check lists were provided for the 50 hours check, which basically tested the mechanical and hydraulic system components in order to discover hidden failures. This test was to be conducted after 50 hours of IBC operation.

Further non-rotating and rotating tests on the system level were conducted with the following objectives:

- check-out of the cabling, sensors, and gages,
- test of the data recording system,
- determination of the mechanical actuator stroke limits,
- determination of the control performance:
  - system damping and phase delay for each actuator and harmonic,
  - maximum IBC amplitudes for each harmonic,
- triggering of manual and automatic shutdowns,
- measurement of the shutdown time.

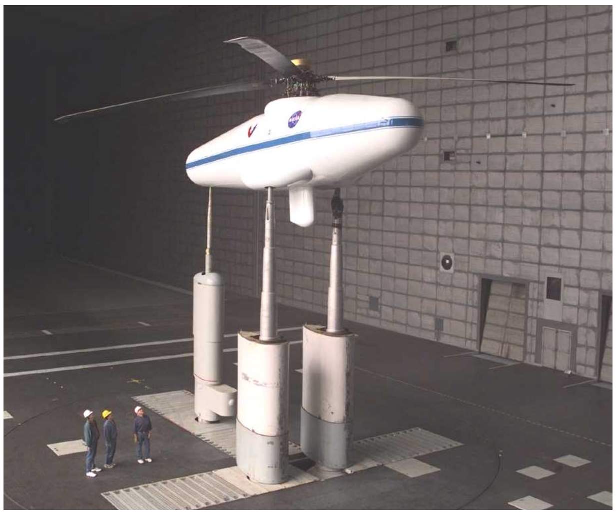

Fig. 17: LRTA with the UH-60 IBC system in the 80- by 120-foot Wind Tunnel

The rotating functional tests with the complete IBC system have successfully been accomplished and have shown that the specifications could be achieved. These activities concluded the preparatory installation work in April and May 2001 (see Fig. 17). The operatability of the control system as well as the shutdown functions could finally be shown.

Concluding remarks

The development, manufacturing, and component testing of an IBC system for a full-scale UH-60 helicopter rotor was described. Servo-hydraulic IBC actuators were designed by ZFL to replace the standard UH-60 pitch links realizing a blade root actuation system with one actuator per blade. The actuators were designed to produce up to ±6.0 deg blade pitch motion at the 2/rev frequency, diminishing to ±1.6 deg at the 7/rev frequency.

The IBC system was successfully integrated into the LRTA and prepared for UH-60 IBC wind tunnel tests in the 80- by 120-foot test section of NASA's National Full-Scale Aerodynamics Complex. Subsequent to the activities described in this paper two IBC wind tunnel test campaigns were conducted in July/August and September of 2001.

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