Helicopter In-Flight Simulator EC 135 FHS

10

Jürgen Kaletka

With contributions from Heinz-Jürgen Pausder and Wolfgang von Grüngahen

J. Kaletka (✉)
Braunschweig, Germany
e-mail: juergen.kaletka@dtv-hifi.de

P.G. Hamel (ed.), *In-Flight Simulators and Fly-by-Wire/Light Demonstrators*,
DOI 10.1007/978-3-319-53997-3_10

10.1 Introduction

The helicopter in-flight simulator Bo 105 ATTHeS, described in Chap. 8, was operated by DLR from 1982 to 1995. In 1993, it was decided to replace ATTHeS with a new airborne simulator. The definition, selection, and development of the new simulator, based on an EC 135 as the host vehicle, are described in detail in this chapter. Further on, some selected results from typical utilization programs are presented. As the helicopter was initially defined as an active control technologies (ACT) demonstrator as well as a helicopter in-flight simulator (*Flying Helicopter Simulator*—FHS) it was called EC 135 ACT/FHS.

10.2 FHS Definition and Planning Phase

10.2.1 How It Began

A broad application spectrum of the Bo 105 ATTHeS provided a deep experience on the benefits of helicopter in-flight simulators. They included the definition and evaluation of flying qualities criteria for modern helicopters, the training and education of test pilots and flight test engineers, and the design and evaluation of new cockpit and display technologies. In addition to ATTHeS, the German Air Force Flight Test Center (WTD 61) in Manching operated a BK 117 (AVT) for cockpit component tests. However, it was not possible to modify its flight characteristics.

The development of new and complex control and cockpit technologies requires early testing of the components in a realistic environment, ideally in flight. It allows a detailed evaluation and analysis pertaining to pilot workload, safety aspects, operational benefits, and technical and economical risks. It became apparent that appropriate test facilities were needed to reduce development costs and risks. To be prepared for the realization of new key technologies for future European rotorcraft there was the need for a test vehicle with a much wider application range. Initiated by the DLR Institute of Flight Systems, a Memorandum of Agreement (MoA) was signed in 1993 between Eurocopter France, Eurocopter Germany, and DLR. It was entitled “Development and Operation of an Active Control Technology Demonstrator and Flying Helicopter Simulator ACT/FHS”. “*This MoA was motivated by the need for future helicopter test facilities in order to replace the DLR Bo 105 ATTHeS In-Flight Simulator and to support the Eurocopter ACT Demonstrator Policy*”. The required application areas for industry, research organizations, and government organizations were:

- *Technology integration and demonstration,*
- *Flying qualities evaluation and flight control systems research, and*
- *Support for government agencies and flight test centers.*

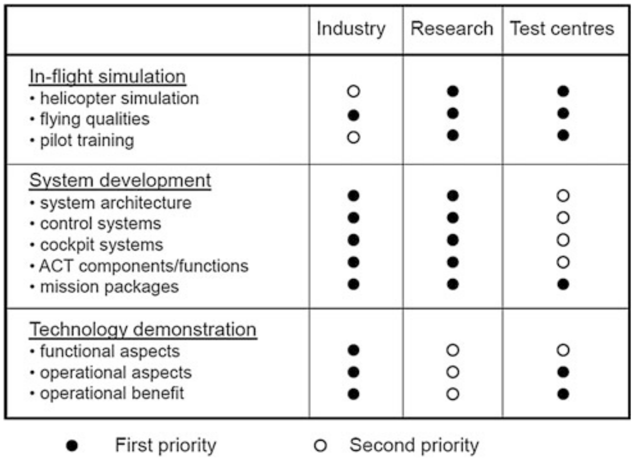
In 1994, a national working group was set up with members from Eurocopter Germany, DLR, and WTD 61. After one year of extensive deliberations, this working group generated a definition study on the development of an “ACT Demonstrator-Flying Helicopter Simulator (ACT/FHS)” with the major sub-tasks:

- Definition of spectrum of utilization,
- Definition of an appropriate system architecture,
- Selection of a suitable test vehicle, and
- Planning of the development phase.

The final report was the main basis for the decision of the MoA partners to develop the ACT/FHS [1]. Main parts of the study are presented in the following sub-sections.

10.2.2 Definition of Applications

It was agreed that ACT/FHS had to be designed for a wide application spectrum to meet the requirements of industry, research originations, and test centers. Priorities were focused on in-flight simulation, system development and integration, and technology demonstration (see Fig. 10.1). The formulated ACT/FHS application requirements were also compared to the capabilities of actually existing test helicopters:



	Industry	Research	Test centres
In-flight simulation			
• helicopter simulation	○	●	●
• flying qualities	●	●	●
• pilot training	○	●	●
System development			
• system architecture	●	●	○
• control systems	●	●	○
• cockpit systems	●	●	○
• ACT components/functions	●	●	○
• mission packages	●	●	●
Technology demonstration			
• functional aspects	●	○	○
• operational aspects	●	○	●
• operational benefit	●	○	●

● First priority ○ Second priority

Fig. 10.1 ACT/FHS utilization spectra

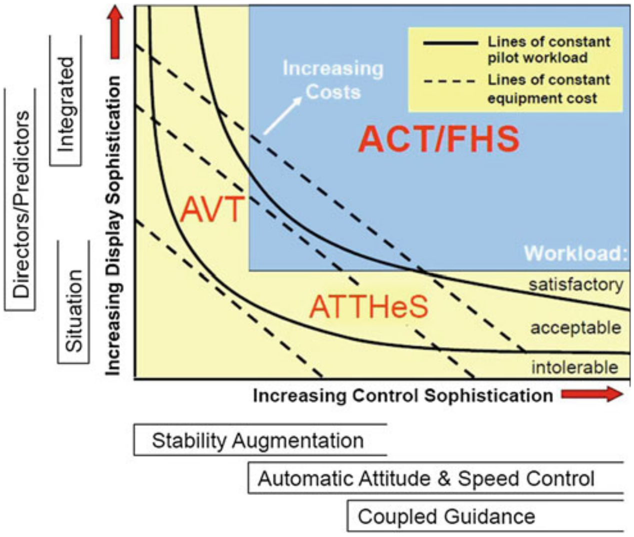


Fig. 10.2 Comparison of requirements and user areas

- Bo 105 ATTHeS, DLR, (see Chap. 8),
- BK 117 AVT, WTD-61,
- AS 365 Dauphin 6001, Eurocopter France (see Sect. 6.2.4.3),
- BK 117 FBW Experimental Helicopter, Kawasaki Heavy Industries (see Sect. 6.2.5.2), and
- JUH-60A RASCAL (*Rotorcraft Aircrew Systems Concepts Airborne Laboratory*), NASA (see Sect. 5.2.2.17).

The envisaged ACT/FHS utilization potential was compared to the national test vehicles ATTHeS and AVT. It became clear that the new helicopter can only fulfill the various requirements with a freely programmable active control system and modular installation equipment to allow fast changes and implementation of new elements for future cockpit and mission technologies (see Fig. 10.2).

10.2.3 ACT/FHS Concept

An essential and largest part of the study was concerned with a very detailed proposal for the technical concept of the helicopter. The objective was to specify the layout of an open architecture modular system with a high degree of variability. The specified system had to be designed to support, test, and evaluate new components from their experimental status in the design phase until their final version for a serial production (*criticality should include non-essential and essential to critical*). It was suggested that, for flight tests, the helicopter be always flown by two pilots, a safety pilot and an evaluation pilot who conducts the tests. It was mandatory that the safety pilot was always in a position to take over the control of the helicopter on his own decision, independent of the actual flight condition.

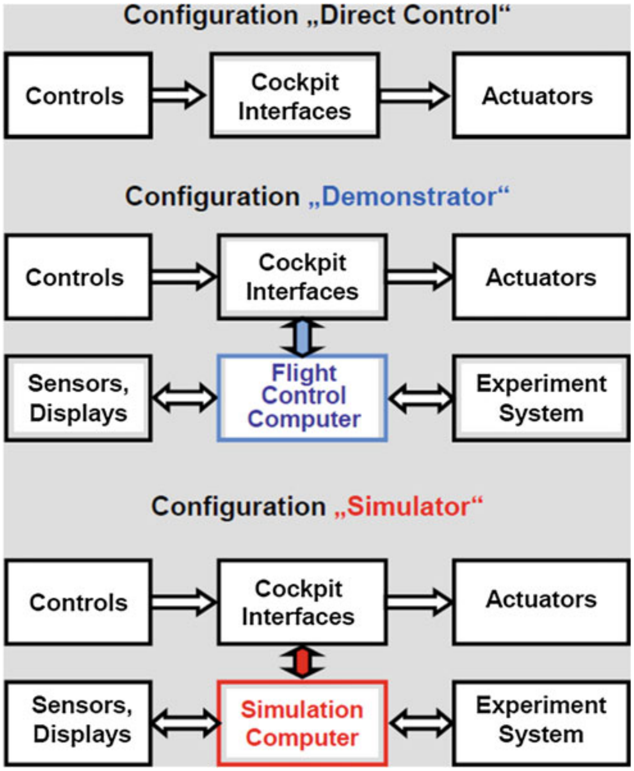


Fig. 10.3 Proposed system concept configurations

Modular and hierarchical system architecture with a standardized interface was proposed. As shown in Fig. 10.3, the hierarchy is composed of three configuration levels:

1. Direct Control using the standard mechanical control; safety pilot in command.
2. Demonstrator Configuration: Fly-by-Wire/Light direct control, no modification of control inputs; evaluation pilot in command.
3. Simulator Configuration: an experimental computer can modify the pilot control inputs; evaluation pilot in command.

A workstation for a flight test engineer was to be provided behind the two pilots. For a later expansion phase, this seat can optionally be modified for a second experimental pilot. Emphasis was placed on a system layout that allows fast and easy modifications and the installation of new components (both, hardware and software) in the future.

The complete ACT/FHS concept also includes extensive ground facilities, namely (1) ground equipment needed for the helicopter operation, (2) a mobile ground station, and (3) a system simulator.

10.2.4 Selection of the Basic Helicopter

For the selection of a suitable standard helicopter for the development of the future ACT/FHS several candidates were considered. A general definition for the test configuration was:

- Payload between 250 and 500 kg,
- 3 man crew, and
- Minimum 2 h flight with MCP (Maximum Continuous Power).

The assessment of the candidate vehicles was structured into the following six criteria:

- flight performance and operational range,
- flying qualities, agility,
- space for crew and equipment,
- suitability for use in the operational environment,
- development and operational risks, and
- economic efficiency and costs.

Considered helicopter candidates were:

- EC 135,
- BK 117 C+,
- Tiger PT1,
- Dauphin 365 N2,
- Super Puma, and
- NH 90.

The EC 135 was selected, as it demonstrated a well-balanced and homogenous evaluation result, in particular, pertaining to the technical and economic criteria. In addition, it incorporated the state of the art technology, especially with its bearingless main rotor system (high dynamic response capability) and digital engine control.

10.2.5 Schedule and Costs

During mid-1995 the working group finalized a detailed proposal for the ACT/FHS development. It included project structure, responsibilities and work-sharing, cost estimates, and time schedule. The proposal included: acquisition of the basic EC 135 by DLR by mid-1997, first flight with the direct (mechanical) control system by end of 1998, and preliminary airworthiness certification and begin of the utilization phase by end of 1999.

It was mutually agreed to develop the research helicopter as a national project. To save time and costs, it was suggested to postpone the implementation of active rotor control elements as well as the development and integration of a certified flight control computer in addition to the experimental computer. Before the actual development started, the concept was refined, system specifications were documented, and various analyses were performed.

The revised and new documents served as the basis for the contract to develop the new in-flight simulator which began in 1996 [2, 3].

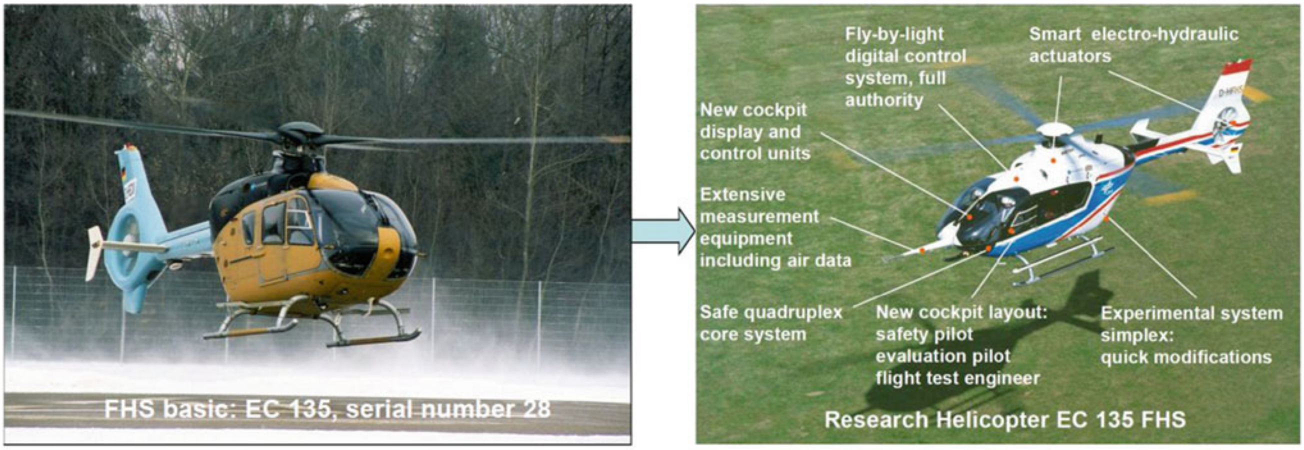
10.3 From Serial to Research Helicopter

10.3.1 Introduction

The development of the FHS was started in 1996 in a close cooperation between Eurocopter Germany, LAT (Liebherr-Aero-Technik, today: Liebherr Aerospace), and DLR. As a host vehicle, the Eurocopter EC 135, S/N 28, was selected and acquired by DLR in 1997. The modifications of the basic EC 135 were planned and conducted by all three partners. As already pointed out in Sect. 10.1, the helicopter was called ACT/FHS. However, for better readability, the abbreviation FHS is used hereafter in this chapter.

The conversion of the original EC 135 helicopter into the FHS research platform required significant modifications (see Fig. 10.4). Therefore, the empty EC 135 hull was taken from the production line and transferred to the Eurocopter Germany prototype construction department. Here, the integration of the standard and FHS specific components was undertaken and all further modifications were implemented. From the beginning of the FHS development, the cooperation between all partners was essential to meet the objectives of very different future applications for both research and technology programs. It was anticipated to design and build a vehicle with a high application oriented flexibility and adaptability to cover a wide range of user requirements in order to support various national and international research and technology programs.

The first FHS flight using the mechanical control system took place in August 2000. Two years later, the helicopter had passed successfully extensive flight tests for all components and mode conditions. Ready for use, it was delivered to DLR in November 2002 and received the aircraft registration D-HFHS. The FHS operational system was complemented at DLR Braunschweig by two ground stations: a ground-based simulator for the preparation and support of individual flight test programs and a mobile



Basic EC 135: Light multi-role helicopter, twin-engine

Length	12.19 m	Maximum speed	259 km/h	Hover ceiling	3045 m
Height	3.51 m	Cruise speed	230 km/h	Maximum altitude	6095 m
Main rotor diameter	10.20 m	Main rotor RPM	395 U/min	Maximum range	635 km

Fig. 10.4 Standard EC 135 becomes FHS

Fig. 10.5 FHS presentation at the European Rotorcraft Forum 2003 at Lake Constance

telemetry station for communication, flight test control, data recording and evaluation. In 2003, FHS was presented to the international public at the Berlin Air Show (ILA) and during the European Rotorcraft Forum (ERF) in Friedrichshafen, Germany (see Fig. 10.5), [4].

10.3.2 Application Domains

The FHS was to be used to examine the feasibility of new technologies, to evaluate their pros and cons, and to demonstrate the benefits of new helicopter concepts [5, 6]. It was designed for a wide application spectrum and it could support all phases during the development of a new system from the first layout until the final testing. There are three major application areas covering the spectrum of user needs:

Airborne Simulation

In the case of in-flight simulation, the pilot control inputs are first fed to an onboard computer. According to the implemented program, the inputs are modified and transferred to the control actuators. Flying simulation gives the possibility to change the dynamic characteristics of the basic helicopter in a way, such that the pilot has the impression of flying a different vehicle. Such modifications could just be the variation of a single parameter, for example, an increase of a time delay between pilot input and actuator response. This allows the demonstration of pilot induced oscillations (PIO) tendencies or rotor-pilot coupling, as described in Sect. 8.4.1. Such effects can support the qualification and training of pilots. More demanding and more complex tasks could also be simulated, such as the dynamic behavior of a completely different type of helicopter. This new helicopter may not even exist in reality but can still be in a design phase. The pilot can fly and test it and give his evaluation comments. In comparison to ground-based simulators, the pilot flies the vehicle in a true airborne environment with real visual and motion cues. The in-flight simulation is not only an excellent tool for basic and applied research in handling qualities, controls, displays, and human factors, it will assist in the design, development, and evaluation of future helicopters before their first flight. This avoids the expensive modifications in the development process of a real helicopter at a later stage. For the fast changes required in a research environment, a high degree of flexibility must be provided for the airborne simulation role.

Development and Testing of New Systems

A further application area of the FHS is the development, implementation, and evaluation of new electronic flight-control systems. Many aircraft still use a mechanical control system consisting of a sequence of rods and/or cables to link the pilot controls to the hydraulic actuators that move the control surfaces. These systems are relatively heavy, require careful routing through the aircraft and cannot be adapted to flight conditions. Their major advantage is demonstrated reliability. However, techniques to transmit pilot inputs by electrical signals have been developed and are now in use also for non-experimental aircraft. The required reliability is obtained by multiple individual signals to provide redundancy but still at less weight than a mechanical control system. With such a digital Fly-by-Wire control system the pilot control inputs are immediately converted into electrical signals. Now, the conventional pilot controls can be replaced by more effective and intelligent devices such as control inceptors. As the FHS is equipped with a redundant Fly-by-Wire/Light system, it is a perfect tool for the development and evaluation of new control systems like active sticks. Active sticks are programmable and they offer a wide range of applications. Pilot control forces are adapted to the actual flight conditions. Tactile cues like vibrations, breakout forces, and soft-stops provide warnings, prevent unintended inputs, and inform on aircraft operating limits. In comparison to optical or acoustic signals, the haptic feedback is immediately sensed by the pilot and he can react faster and more intuitively. It is anticipated that active control systems will reduce pilot workload and will help to make flying less stressful and safer.

The programmable onboard computer allows the testing of new control law concepts. The FHS programmable multi-function display can help to define the most appropriate information to be displayed for the pilot with respect to the actual flight condition and task.

Technology Demonstration

The third key area for the FHS utilization is the integration and qualification of innovative technologies, like active control components, new flight control laws, and advanced cockpit systems. Technology demonstration encompasses evaluating and proving the functionality and operational benefits of new technologies up to the point of certification. Also, these applications need a high flexibility for component and system integration including both hardware and software modifications.

An important example of innovative technologies for helicopters is the FHS control system itself. It was for the first time that a full authority digital Fly-by-Light control system was implemented. It was the primary control for all flight conditions including the start and landing phases. For this purpose, a new system architecture was developed. Here, a major emphasis in the design was placed on two essential factors, namely high safety standards according to the stringent civil certification requirements and at the same time, maximum flexibility for configuration changes to meet user needs. The FHS control system will be described later in detail.

10.3.3 EC135 Becomes FHS

In the series production of the EC 135 and Bo 105 the helicopters were equipped with a mechanical control system. The pilot control inputs are transferred to the rotor actuators by control rods. In the development of the Bo 105 ATTHes (see Chap. 8) the standard control system was maintained. In the simulation mode, the control inputs were calculated by the onboard simulation computer. They were fed to electro-hydraulic actuators that were connected by clutches to the standard control rods (see Fig. 8.5 in Chap. 8). In the definition phase of the FHS, it became clear that this concept will not meet the needs of future users. Therefore, the mechanical control system was completely replaced by a full-authority digital control system using Fly-by-Wire/Light technology. The system architecture was specified to meet two essential requirements:

Safety: The standard operation of the helicopter is the Fly-by-Light mode at all flight conditions, including low altitude, transition, start, and landing. This configuration had to comply with civil certification requirements. A modified mechanical control system was still installed but should only serve in the case of emergency.

Flexibility: For the conduct of user programs and in particular for the simulation task, it is absolutely necessary to easily change control laws or models or to implement new hardware components. Even during a flight test campaign, some modifications should be allowed. This flexibility is only possible without stringent safety and certification constraints.

Obviously, these two requirements are contradictory. The safety of electronic systems is based on multiple redundancies for all components of hardware and software. By continuously comparing the redundant signals it is possible to detect failures and malfunctions and to disconnect the faulty channel. Here, at least a triple redundancy is needed to compensate for errors. It is evident that the development of such a control system is quite complex and entails a large amount of work, cost, and time. Once it is designed, built, tested, and certified, it is practically “frozen”. Modifications are no longer possible without starting a new documentation, testing, and certification process. On the other hand, flexibility implies fast and uncomplicated modifications according to user needs: at best no redundancy, no extensive testing, and no certification. In other words: a more vulnerable system.

One of the most demanding tasks during the FHS design phase was how to build a control system that fulfills all aircraft safety regulations and still allows the use of less reliable hardware and software components for experiments?

FHS System Architecture

The FHS control system uses a hierarchical architecture and was installed in two associated onboard units, as illustrated in Fig. 10.6. It consists of a “core system”, which provides the required safety, and an “experimental system”, which gives the flexibility for modifications [7]. The core system meets civil certification requirements with a probability of catastrophic failures less than 10^{-9} per flight hour. It was achieved by quadruplex redundancy in all components together with the dissimilarity of both hardware and software. The heart of the core system is the core system computer. It is the central interface that receives the control signals from both pilots and flight state signals from all onboard sensors. It communicates with the experimental system, which can modify the control commands from the evaluation pilot. The hierarchical architecture becomes obvious when the responsibilities of the core and the experimental system are compared. All signals are fed to the core system computer and based on this comprehensive information the core system checks all data and finally decides whether the resulting control inputs are acceptable. Only then they are applied to the hydraulic smart actuators. The experimental system offers a lot of freedom for the individual user programs. It calculates new control input signals and sends them to the core system computer without a detailed data check. In principle, the core system can be considered as the “boss” who gives the final OK. The experimental system is his “employee” who develops new ideas but is allowed to be wrong. Some additional functions of the core system are addressed below. As the core system is quadruplex with dissimilar DO-178B Level A certified software in the core system computer and the smart actuator electronics, it is obvious that any later changes of the core system will require a significant effort, in particular with respect to testing, documentation, and qualification. Consequently, the core system should not be modified unless it is absolutely necessary.

The main elements of the experimental system are the experimental computer and the data management computer. The first one communicates with the core system computer. It receives the evaluation pilot command signals, modifies them according to the programmed control laws and transfers them back to the core system. The data management computer collects all data provided by basic sensors and by sensors in the experimental system and transfers them to the telemetry, the onboard data recording, and to the graphics computer that controls the displays. In contrast to the core system, the experimental system is only simplex to allow relatively easy and fast modifications. The criticality level is “minor”, which implies that the system may fail and produce errors. Therefore, several safety features are implemented in the core system computer to avoid critical helicopter flight responses due to unrealistic control inputs.

All components of the core system are quadruplex, beginning with the sensors for the pilot control motions up to the hydraulic smart actuator electronics. Redundancy is also provided for the other helicopter components. There are two independent hydraulic systems, two electrical generators, and four backup batteries. The FHS has also a battery operated auxiliary hydraulic system, which allows pre-flight checks and preparations without any external equipment.

Figure 10.7 illustrates the technical realization of the architecture and some of the major helicopter modifications. As also shown in Fig. 10.8, the EC 135 cabin accommodates a three-person crew with a safety pilot in the left pilot seat and an evaluation pilot in the right pilot seat (unlike most fixed wing aircraft). A flight test engineer station is located behind the two pilot stations. Both pilots have conventional

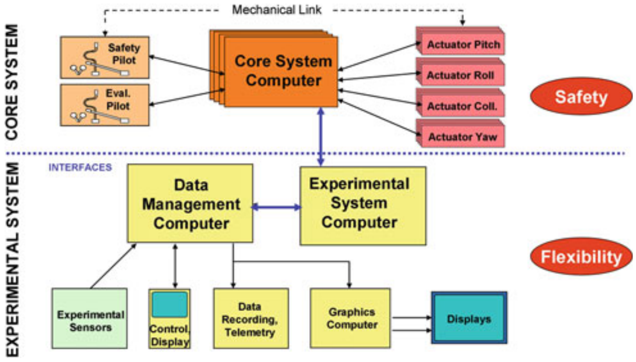


Fig. 10.6 FHS system architecture

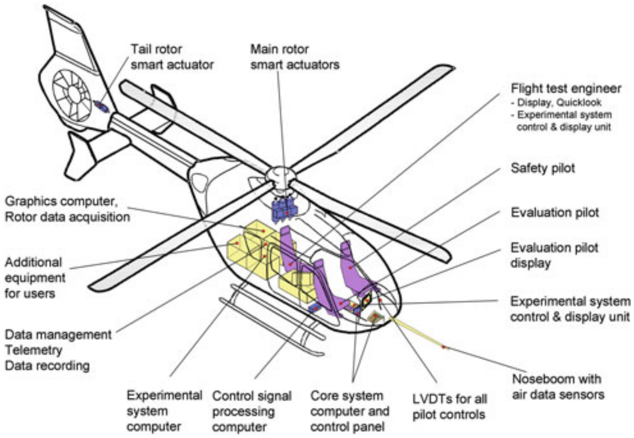


Fig. 10.7 Main FHS modifications

Fig. 10.8 Cockpit view

controls (stick, collective, pedals). The control positions are measured by linear variable displacement transducers (LVDT) with four sensors for each pilot control. LVDT has high resolution and measurement accuracy. The sensor works within an electrical field without contact or friction between the LVDT's core and coil assembly, providing a fast dynamic response and has a long mechanical life. The electrical outputs can directly be used without amplification and are sent to the four core system computers.

The FHS layout was based on the use of the Fly-by-Light control system for all flight conditions. Consequently, the original mechanical control system of the EC 135 was not implemented. However, for the safety pilot an additional mechanical link from his controls to the hydraulic actuators was installed as a backup in case of an emergency. Instead of conventional solid rods, flexball cables were chosen. In principle, they are similar to the better known Bowden wire cables. They have an inside wire and can only transmit pulling forces. The interior of a flexball cable is more complex. A flexible central blade can be moved between two lines of balls imbedded in bearing cages (see Fig. 10.9). A flexball cable reacts for tension and compression. It has a high mechanical efficiency with very low backlash even with long routings. It can easily be installed and has a high flexibility. Maintenance or lubrication is not needed. However, there are constraints with respect to allowed minimum bending radii.

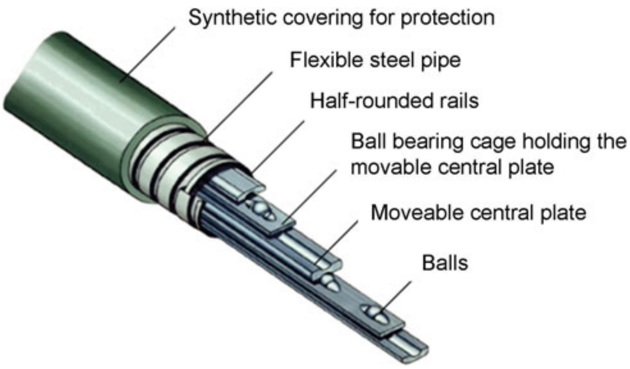


Fig. 10.9 Structure of flexball cable

In the FHS the cables for the main rotor actuators were routed within the windscreen center frame. The cable for the tail rotor actuator is below the cabin floor.

The FHS cockpit is shown in Fig. 10.10. The safety pilot panel (left side) is equipped with an *Avionique Nouvelle* glass cockpit with standard instrumentation. In the center console between the two pilots is a control unit for the core system. Both the evaluation pilot (right side) and the flight test engineer (seated behind the two pilots) have a freely programmable multifunction 10-inch experimental display and a control panel for the display. The units are identical but independent from each other; hence the pilot may select navigation instruments on his display while the flight test engineer can choose a quick-look from recent flight measurements. The flight test engineer has also access to the experimental system, for example, for changing configurations and parameters. The flight test engineer seat is located in the center of the cabin so that he can also observe the cockpit instruments and has a free view to the outside. His workstation is on his right-hand side (see Fig. 10.11).

The four core system computers are located in two separate housings, each with its own cooling system, under the cabin floor. Each housing contains two computers, which are dissimilar in hardware and software. The original hydraulic actuators were replaced by FHS specific smart actuators underneath the main rotor and close to the tail rotor. The actuator electronics receive the control commands from the core system computers via optical fibers. Most of the components of the experimental system were installed in the cargo compartment behind the flight test engineer [8]. They were mounted on three aluminum pallets. The pallets were fixed on rails and could easily be removed from the helicopter or reinstalled. It allowed fast modifications and testing in the laboratory or on the fixed-base simulator. A fourth pallet is free for user specific equipment. As a research helicopter, the FHS is fully instrumented with a number of redundant sensors and measuring equipment. The instrumentation system mainly includes two air data units, two attitude and heading reference systems (AHRS), a radar altimeter, FADEC (full authority digital engine control) data, linear accelerometers, an inertia navigation system (INS), nose boom air data (static and dynamic pressure, angles of attack and sideslip, temperature), differential GPS, and control input signals at various positions.

FHS Operational Modes

Pertaining to the signal flow and the pilot in command, the FHS has three commonly used control modes: (1) safety

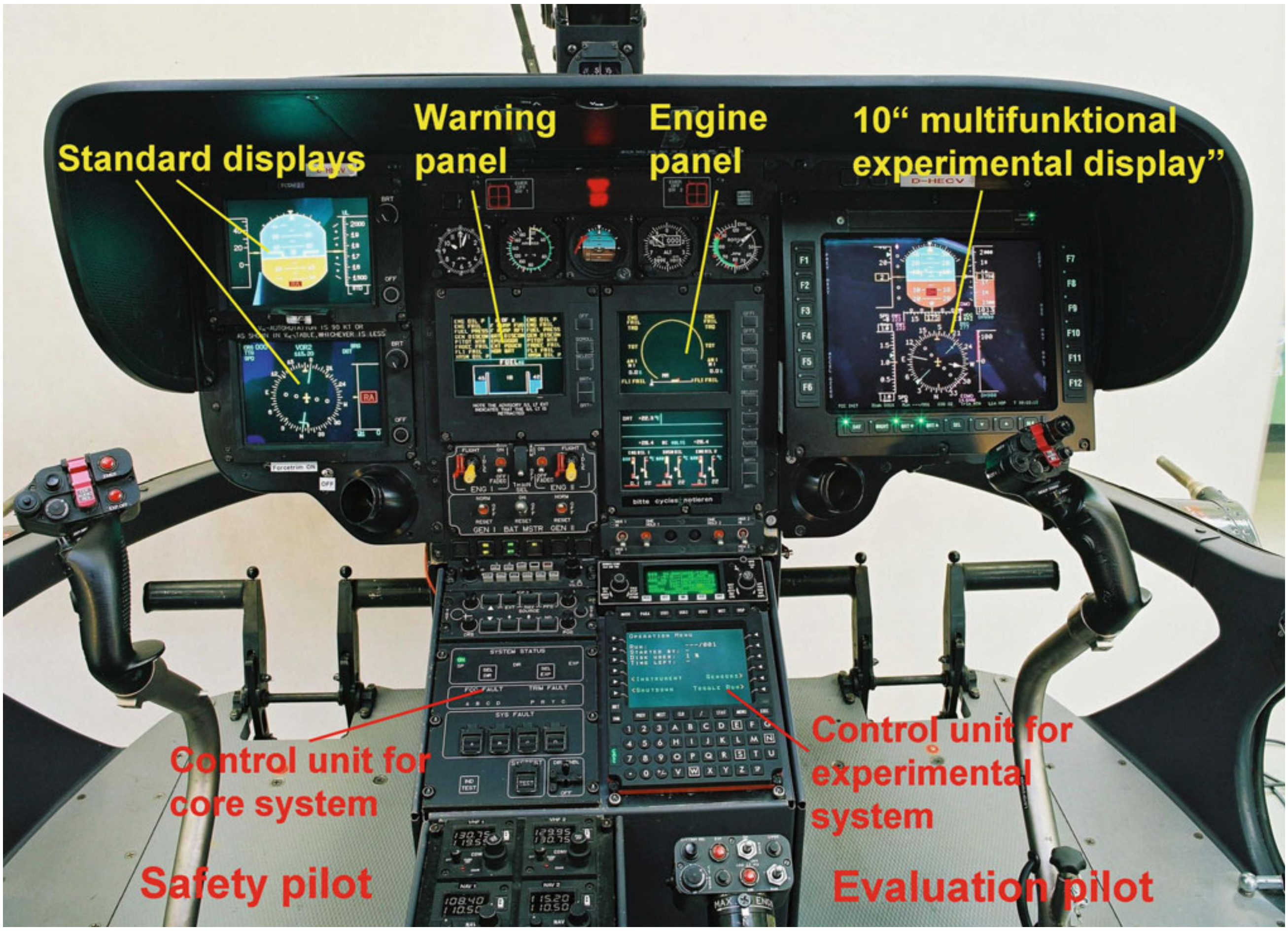


Fig. 10.10 Cockpit panel

Fig. 10.11 Workstation for flight test engineer

pilot mode, (2) evaluation pilot direct mode, and (3) evaluation pilot experimental mode. In a fourth mode, the mechanical backup can be used. The mechanical link is not intended to be a standard control mode, but it plays an important role in the evaluation pilot modes. The corresponding data flow for the individual modes is shown in Figs. 10.12, 10.13, 10.14 and 10.15. For simplification and better understanding, only one pilot control element (stick) and one data channel are presented in these figures. However, it has to be kept in mind that all four pilot controls have identical equipment and that all core system components are quadruplex redundant, from the sensors, measuring the pilot inputs, up to the actuator electronics.

Safety Pilot Mode

As shown in Fig. 10.12, the control positions, measured by LVDTs, are transmitted by electrical wires to the core system computer and demodulated. As the computer is located close to the sensors, only short wires were needed. The core system computers send the inputs via optical fibers to the actuator electronics, which control the hydraulic valves and consequently the actuator motion. The distance from the core system computers to the actuators is longer (in particular to the tail rotor actuator) so that full advantage is taken of the fiber optics technology. The mechanical flexball cables are attached to the pilot controls and they follow the

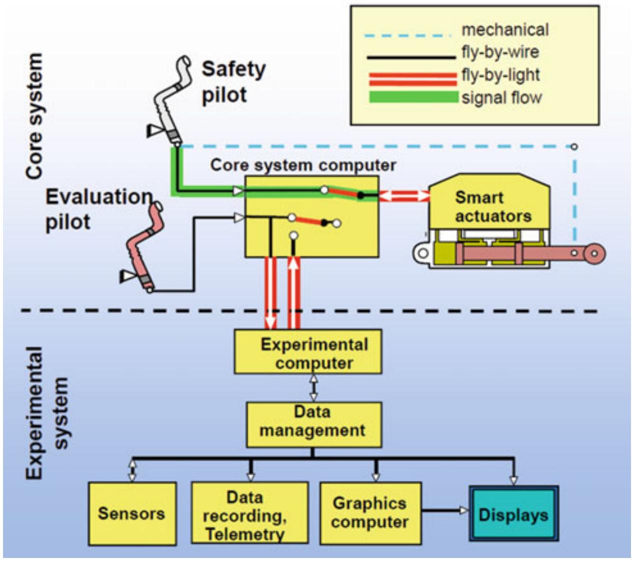


Fig. 10.12 Control configuration "safety pilot"

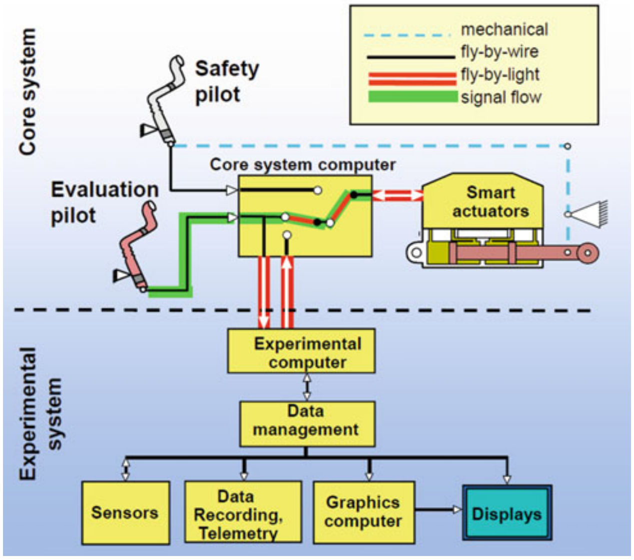


Fig. 10.13 Control configuration "evaluation pilot direct"

control motions. However, in the safety pilot configuration a hydraulic clutch in the smart actuators decouples the cables from the actuators and they have no effect. It is possible to use the experimental system, for example, for data recording and telemetry. But its output channels are switched off and the core system computers do not accept any signals from the experimental system.

Evaluation Pilot Direct Mode

In this operation mode, the pilot in command is the evaluation pilot, see Fig. 10.13. Similar to the safety pilot mode, the measured control positions are transmitted to the core system computer and sent via the optical fibers to the actuators. As there is no mechanical link to the evaluation pilot controls, the pilot flies the helicopter in a pure Fly-by-Light mode. In contrast to the safety pilot mode, the hydraulic clutch in the actuator is closed. Now, the actual positions of the actuator piston rods are back driven by the flexball cables to the safety pilot controls. Apart from the emergency case, this is the second major role of the mechanical control system. It synchronizes the safety pilot control positions with the actuator positions. For the evaluation pilot direct

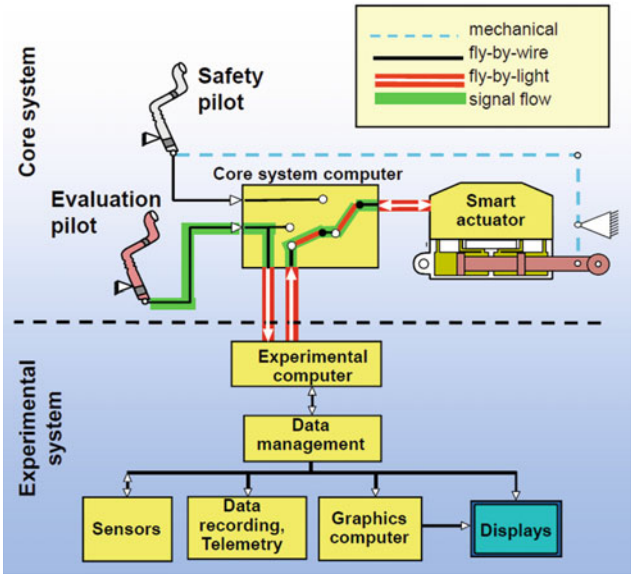


Fig. 10.14 Control configuration "evaluation pilot experimental"

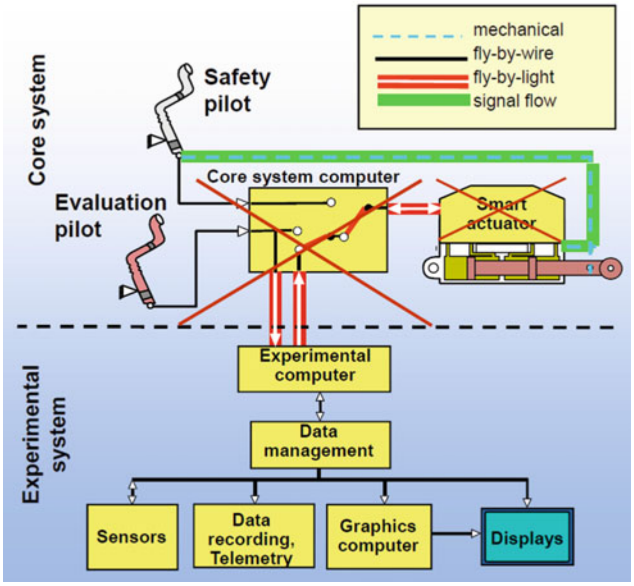


Fig. 10.15 Control configuration "safety pilot mechanical"

mode, it means that the control positions for both pilots are the same. The experimental system has no influence.

Evaluation Pilot Experimental Mode

As in the previously described mode, in the present case too, the evaluation pilot is in command, see Fig. 10.14. But now the experimental system is fully engaged. The control inputs are received by the core system computer and transferred to the experimental computer. Here, the control inputs are modified according to the implemented user software and sent back to the core system computer. After a detailed data check they are transferred to the actuators. The actuator motion and consequently the FHS dynamic response is now due to the modified inputs and no longer directly related to the pilot inputs. The evaluation pilot flies the helicopter with modified flight characteristics in a pure fly-by-light mode. The hydraulic clutch is closed. The actual positions of the actuators are back driven by the mechanical link to the safety pilot controls. Therefore, his control positions always correspond to the motion of the helicopter control surfaces. They are in agreement with the hydraulic actuator outputs and different from the evaluation pilot controls. Whenever the safety pilot takes over the command and the FHS is switched into the safety pilot mode his controls are automatically in the correct position and he can continue the flight without any further synchronization.

Safety Pilot, Mechanical Control System

This configuration, shown in Fig. 10.15, does not belong to the "normal" operation of the helicopter as the FHS is developed and certified for the Fly-by-Light mode in all flight conditions. It will only be used in an emergency case if the optical system fails. The safety pilot controls are directly connected to the hydraulic smart actuators by the mechanical flexball cables. All other components of the core system are inactive. The pilot flies the standard EC 135 with a mechanical control system. This configuration can intentionally be selected by the safety pilot, for example, for testing or training purposes. In the worst case, when a severe error is encountered in the control system that cannot be compensated or corrected, it leads to a full breakdown. To avoid a fall back into the mechanical control mode, various procedures have been implemented in the core system computer and the smart actuator software to detect and eliminate wrong or unrealistic data channels. It is evident that such a malfunction in the Fly-by-Light system is a highly critical situation for the primary control system. It will require an intensive investigation and most probably a new effort to keep or renew the certification while the helicopter is grounded.

Role of the FHS Crew

Various procedures have been implemented in the core system to detect data errors and to eliminate or alleviate their influences. The efficacy of these techniques was successfully demonstrated during the FHS testing phase. Nevertheless, the human capabilities like awareness, judgement, and reaction should not and cannot be replaced. Therefore, the FHS crew and in particular the safety pilot are essential in the FHS safety concept.

Flight Test Engineer: The flight test engineer keeps track of the planned flight test program. Before starting a new test he informs the pilots about details of the test and the required flight condition. He has a working station with a multifunctional display and has direct access to the experimental computer. He can select any pre-programmed configuration, change parameters and configurations. During and after a test the flight test engineer documents comments and can make a first evaluation of the test data. He also communicates with the crew in the ground station.

Evaluation pilot: The evaluation pilot conducts the individual flight experiments as the pilot in command. He is in close contact with the flight test engineer and the ground crew and gives evaluation comments on the actual test. Like the flight test engineer he has a multifunctional display connected to the graphics computer of the experimental system. Various information can be displayed like flight instruments, camera signals, supporting graphics as help for the test conduction, and quick-looks of recorded measurements.

Safety pilot: Although each individual test scenario is tested and evaluated on the ground-based simulator, critical situations can arise in the experimental mode, for example, due to hardware failures or non-realistic software commands. Therefore, the safety pilot continuously observes the motion of his controls, the helicopter response, and the flight condition. During the experimental mode, he is flying "hands-on". He can immediately take over the command by pressing a button or by overriding the control forces. Then, the core system switches to the "safety pilot" mode which is still in the Fly-by-Light mode. Due to the mechanical control system feedback, the control positions of the safety pilot are always in the correct position. To evaluate and prove that the safety pilot is able to react fast enough to critical situations, a major part of the FHS flight test program was used to generate both single axis and multiple axis runaways in the experimental computer. It was demonstrated that (1) the limiters in the core system computer are able to decelerate the control inputs, (2) the safety pilot is able to immediately obtain control, and (3) the safety pilot is able to stabilize the helicopter without difficulty and without significantly losing altitude.

The safety pilot is responsible for the total flight, including the intervals where the evaluation pilot is in command. Due to this responsibility and the specific safety task for the FHS, the pilot must have a test pilot qualification and FHS flying experience. Therefore, the safety pilot will, in general, be provided by DLR, independent from the individual user of the helicopter.

Switching between Operational Modes

The appropriate modes are selected by using the core system control unit and switches on the safety pilot and evaluation pilot controls. The control unit for the core system (see Fig. 10.16) is located on the center console between the two pilots and can be observed by all crew members. It provides switches to select a mode, to start test routines, and to test and reactivate disconnected data channels. Lamps inform on the actual mode, switching status, errors, and warnings. A change of the control mode is announced and confirmed by an additional acoustic signal.

A new control mode is selected on the core system control unit or by switches on the pilot controls. According to the complexity of the three control modes they are ordered from “low” to “high”, which means from “safety pilot” to “evaluation pilot direct” and to “evaluation pilot experimental”. The respective conditions for switching are outlined in Fig. 10.17.

For the transition to higher modes (for example, from safety pilot mode to evaluation pilot mode) the new mode is first pre-selected and the evaluation pilot controls are synchronized with the current actuator position or the position obtained from the actual model in the experimental computer. The evaluation pilot controls are driven by the trim motors. During this process, lights flash on the core system control unit for pilot information. A continuous light confirms successful synchronization. Then, the actual mode change is activated by the pilot in command by pressing a button on his collective lever. Due to the synchronization and an additional fading function transition errors during mode change are avoided.

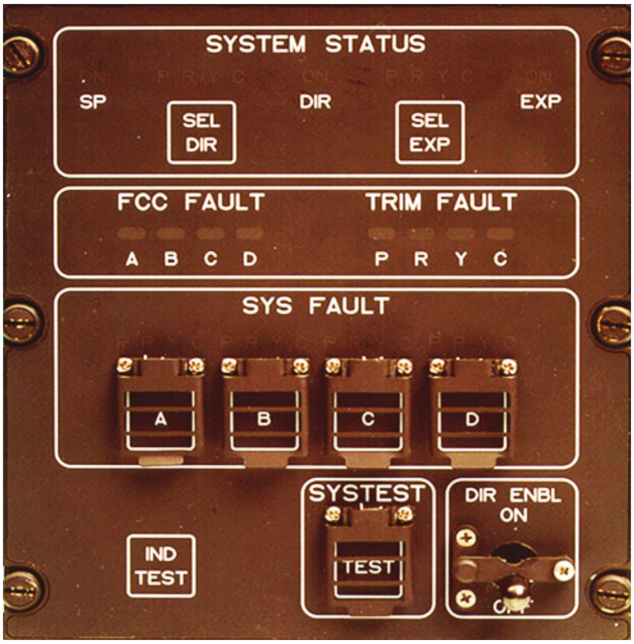


Fig. 10.16 Core system control unit

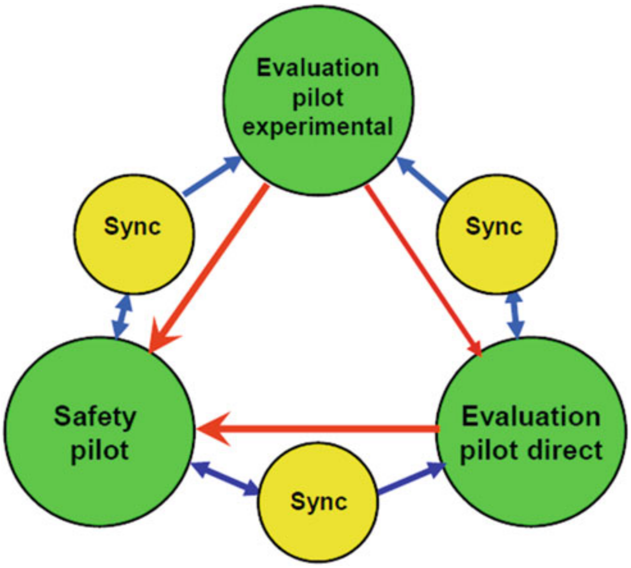


Fig. 10.17 Conditions for configuration changes

Switching to “lower” modes (for example, from experimental mode to safety pilot mode) does not require synchronization as the controls are already in the right position. The desired mode is immediately active. This fact is essential as it allows the safety pilot to take over control of the helicopter without delay by either pressing a button or by overriding the control forces.

10.3.4 Technical Details

More detailed information on the core system computer, the smart actuators, and optical data transfer are provided hereafter.

Core System Computer

The core system computer (see Fig. 10.18) is the heart of the FHS control system. It initiates control mode changes, generates the command signals for the smart actuators, and performs most safety functions. To provide the required safety, the computer layout is also based on the concept of redundancy and dissimilarity. The core system computer consists of four functionally identical lanes. The hardware is housed in two segregated boxes with its own cooling system. They are installed at different locations beneath the cockpit floor. To avoid system inherent failures, dissimilarly is applied for both software and hardware. Each box contains two dissimilar hardware lanes, with one lane based on a

Fig. 10.18 Core system computer

microcontroller and the other one on a signal processor, built by different manufacturers.

The core system software was developed following the rules for Level "A" functions, according to RTCA/DO-178B and ARP 4754. System requirements were translated into two dissimilar software requirements. Software design and verification were performed by two different teams, each team designing the software for both hardware variants against one of the two software design documents. This leads to four dissimilar sets of software. All software was written in the C language.

All lanes run asynchronously with a cycle time of 2 ms. To detect any abnormalities each lane has a number of continuous tests and watchdog timers installed. An optical cross-communication between the lanes exchanges mode switching information. Figure 10.19 shows a diagram of the signal flow within the core system computer. The signal path starts at the LVDT control position sensors for the two pilots. The signals are demodulated and A/D converted, fed to the LVDT monitor, and checked. The evaluation pilot control positions are passed to the experimental flight control computer, where they may serve as an input to the control law. In the "evaluation pilot experimental" mode, control input signals from the experimental system are sent back to the core system. Because of the low reliability of the (simplex) experimental system, these signals can be wrong. Therefore they are checked by the data monitor for parity (parity bit), validity, and update. In addition, the signals are passed through a runaway limiter to prevent faulty input signals from structurally damaging the helicopter. The algorithm used by the runaway limiter restricts the actuator rate for large and fast signals, but not for slow or for fast short signals. As such, the runaway limiter provides the largest possible flight envelope protection without endangering the aircraft. The definition of the limiter values is based on simulation results, existing flight data, and data from specifically conducted flight tests with the FHS helicopter. The evaluation uses the relationship between maximum control actuator speeds and amplitude, and duration of the control input. Three sets of limiters with different restriction levels are currently defined. The most restrictive limiter permits experimental mode operations throughout the flight envelope. The other two limiters are less tight but have altitude and speed restrictions. Flights without a runaway limiter would be only allowed with a safer experimental system.

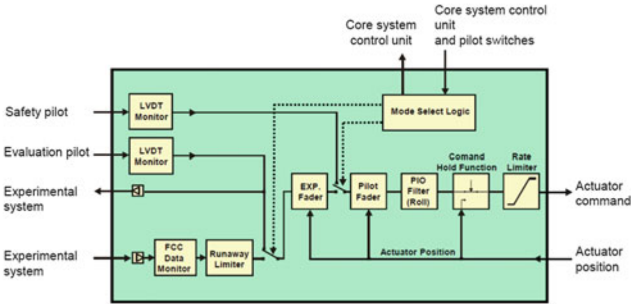


Fig. 10.19 Signal flow in core system computer

After the runaway limiters, the input signals pass through automatic fading functions, PIO filter, and rate limiters before they are sent to the hydraulic smart actuators. When the actuator speed is limited there is a slight risk for a PIO (pilot induced oscillation) tendency in the roll axis. Therefore, a PIO filter reduces the phase shift and eliminates this risk. At the end of the control path, a rate limiter restricts the maximum speed of the actuator output to avoid pressure drops in the hydraulic system. Finally, the core system computer also monitors and controls the evaluation pilot's trim system.

Hydraulic System—Smart Actuators

The FHS has four identical smart actuators: three main rotor actuators mounted on the cabin ceiling below the main rotor and one tail rotor actuator in the vertical fin to control the Fenestron®. Figure 10.20 shows the three actuators for the main rotor (longitudinal, lateral and collective control). The upper part (black housing) contains the electronic components and the actuator software. The lower part contains the electro-hydraulic components with electrical rotary torque motors, control valves, hydraulic cylinders, and the actuator shaft. The mechanical linkage seen in front of the figure is connected to the flexball cables of the mechanical control system. According to the actual control modes it switches to the corresponding function of the flexball cables: "safety pilot": the flexball cables have no function, "evaluation

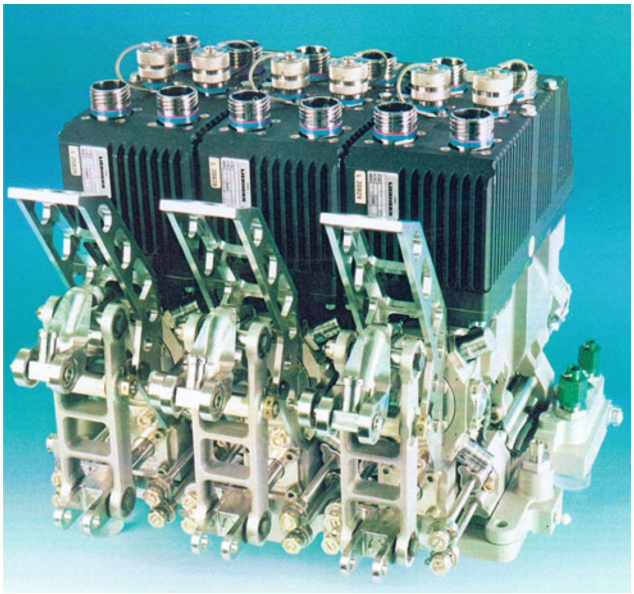


Fig. 10.20 Main rotor smart actuators

pilot": the flexball cable moves the controls of the safety pilot and "safety pilot mechanical controls": the flexball cables connect the safety pilot controls directly to the control rods of the hydraulic actuators.

A functional schematic of the smart actuator is given in Fig. 10.21. The requirements for the actuator control electronics and the software development is practically identical to the design of the core system computer as described above. The quadruplex hardware is dissimilar and the software was written by two different teams. But the components are installed in a single common housing. The actuator electronics receive the set point of the control inputs via the Fly-by-Light connection from the core system computer. First, voting and consolidation are performed. For each channel, the redundant signals are compared, eliminating data failures. Each actuator data lane drives one coil of the quadruplex electrical rotary torque motor. The torque motor is mounted on a single control valve shaft, which controls both valves. The actuator is controlled digitally with a two level cascade loop controller: the outer loop is controlling the actuator position and the inner loop is controlling the direct drive valve position, which is proportional to the actuator rate. The control valve position commands, as well as the measured control valve position signals, are consolidated across all channels to avoid force fighting on the control valve shaft. By limiting the actuator position error before consolidation, undetected hardware or software failures in a single channel can be compensated by the remaining healthy channels. Control of the outer loop is performed with a cycle time of 2 ms; the inner loop control has a cycle time of 400 µsec.

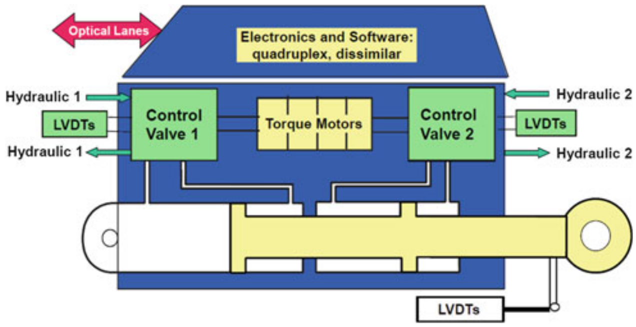


Fig. 10.21 Structure of the electro hydraulic smart actuator

The smart hydraulic actuator was specially designed for the FHS helicopter. It mainly consists of a tandem cylinder assembly driven by a quadruplex direct drive valve assembly. It is controlled by the quadruplex actuator control electronics. The FHS has two independent and segregated hydraulic systems. Each hydraulic system is connected to one of the two control valves and supplies one camber of the tandem cylinder. The motion of the piston rod is measured by four LVDTs and sent to the actuator electronic as feedback information. The signals are also sent to the core system computer and are available in the experimental computer.

The smart actuator assembly is one compact unit. The redundancy concept permits a malfunction of one hydraulic system and simultaneously the loss of two electrical lanes without a major performance deficit. The performance of the smart actuators is comparable to that of the standard EC 135 main rotor actuators.

Optical Data Transfer—Fly-by-Light

A triplex redundant optical data transfer was already installed for the tail rotor control in the Bo 105 ATTHeS (see Sect. 8.3.2). For safety reasons, the standard mechanical control was not removed. Results and experience from ATTHeS, and also those from similar programs in France and the US, revealed the high potential of electronic data transmission. But they also showed the deficits of certain Fly-by-Wire systems that still hinder an increasing industrial application, namely data transfer rate, weight, and immunity to electromagnetic interference.

Data transfer rate: Data transfer rates of actually used data bus standards like ARINC429 (100 kbit/s) or MIL-STD-1553 (100 kbit/s or 1 Mbit/s) are often insufficient. High dynamic control systems often require a much higher data rate. Additional time is needed for synchronization and bus management leading to delays. It was shown that data rates for copper cables are technically limited to about 2 Mbit/s, in particular when electromagnetic compatibility (EMC) requirements are considered. On the other hand, optical data transmission offers significantly higher rates.

Weight: Usually most flight computers are installed in the center of the aircraft in a common housing. From here thick, long, and heavy cable harnesses are distributed to sensors, instruments, actuators, etc. The use of individual decentralized computers, smart devices (like smart actuators), and optical cables can lead to a considerable reduction in weight and needed space.

Electromagnetic Compatibility (*EMC*): Helicopters operating at low altitudes, close to the ground, and close to ships are often within an electromagnetic field with an intensity of more than 200 V/m, with an increasing tendency in the future. To protect a full authority Fly-by-Wire control system with a failure probability of 10^{-9} per flight hour from electromagnetic interferences requires an enormous and expensive effort. Fiber optic cables are immune to electromagnetic interference which is another major benefit of Fly-by-Light solutions.

The present research helicopters with electronic control systems still keep their original mechanical control system for safety reasons. The experimental control system was switched on whenever it was required. Consequently, there was no need to develop the new technology to fulfill the high safety standards for a full authority control system. However, to obtain acceptance and confidence, the electronic control system must prove its reliability and usability as a stand-alone system. Here, the FHS helicopter played a successful role as a technology demonstrator with a primary full authority Fly-by-Light control system [9–11]. The experience gained is a sound basis for future helicopter flight control developments.

10.3.5 Ground Facilities

The FHS system also includes a ground-based system simulator and a mobile data/telemetry ground station to support the flight tests. The ground station consists of two modules, the telemetry station and the data evaluation station. They are installed in two containers, which can be transported to the actual flight testing site to allow FHS operation, including ground support at user sites or at air fields. The telemetry station has an automatic aircraft tracking antenna with a video camera and communication equipment. PCM data, sent by the FHS, are received, recorded, and transferred to the data evaluation station via Ethernet.

The data evaluation station offers work places for three engineers. Each place is equipped with a PC based data station to allow real-time data monitoring by quick-look or appropriate software tools during the flight tests. Communication with the helicopter flight test engineer and evaluation pilot is conducted by the responsible test engineer on the ground. Based on the preliminary data checks he decides whether a test was successful or has to be modified and repeated. Data provided by the telemetry link can be recorded in the ground station. But for a more detailed evaluation, the onboard recorded data will usually be preferred. After landing, the data from the disk is transferred to a computer in the container to allow the full range of project-oriented off-line evaluation. In addition, the PCs can be used to develop and modify the evaluation software. Thus, two major objectives in the FHS flight test data concept were fulfilled. Firstly, the required real-time information to control the tests is provided to the user during the flight tests. And secondly, at the end of the flight, he has access to both his own and DLR developed software tools to conduct a detailed data analysis and evaluation.

The ground-based system simulator is primarily designed as a hardware and software-in-the-loop test facility for the FHS. It replicates the flying environment of the FHS with a real cockpit. It is a fixed base simulator without motion and with a large field-of-view visual system (see Fig. 10.22) [12]. Pilots are provided with a cockpit that is very similar to the one in the FHS. It includes side-by-side seating for the safety pilot and the evaluation pilot and offers the same displays, control units, and pilot controls. All functions of the core system computer are represented including switching between the operational modes. The EC 135 helicopter dynamics, the core system computer, and some sensors are simulated. Here, an emphasis was placed on a precise mathematical model of EC 135 that realistically represents the helicopter dynamics. A hardware duplicate of the actual complete experimental system is installed in the simulator. It also serves as a spare unit for the helicopter, if needed. In addition, further hardware components can be connected, that is, from external users. Before any new hardware or software is installed in the helicopter, it is first tested in the ground-based simulator. The simulator is independent of the

Fig. 10.22 FHS ground-based simulator: approach to DLR research campus Braunschweig

FHS, so it can also be used when the helicopter is deployed in flight tests. It offers a perfect test environment through all phases of a flight test program: (1) development, test, and preparation environment for engineers, (2) tests and verification of new hardware and software components before implementation in the helicopter and before flight and (3) pre-flight training and briefing of the crew, in particular when new pilots are involved.

10.4 FHS Research Programs

10.4.1 Introduction

During the first decade (2003–2012) of operation, the FHS flew 960 h for different programs. In general, the research vehicles usually need larger periods on the ground to prepare new flight tests and to implement and check required modifications or additional components. Therefore, the flight time of almost 100 h per year demonstrates the highly effective FHS utilization. Some earlier DLR projects requiring in-flight simulation, which were discontinued after the Bo 105 ATTHeS accident in 1995, could now be pursued with the availability of FHS.

The global activities are coordinated by the FHS user committee that includes representatives from German ministries, Eurocopter Germany, and DLR. The individual projects are planned, scheduled, and coordinated by the FHS Board, consisting of the involved DLR institutes and the project leaders of the experiments. For the future FHS applications, some standards were defined to specify the interactions between different design approaches, test procedures, and implementation in the helicopter. Here, requirements and interests of both DLR and external users were taken into account. As an example, Fig. 10.23 outlines the steps from the conceptual design of a control system for the realization and evaluation in flight. Interfaces for software and hardware were reviewed and extended to allow an easy and flexible access for external users, who may also provide their own hardware and software.

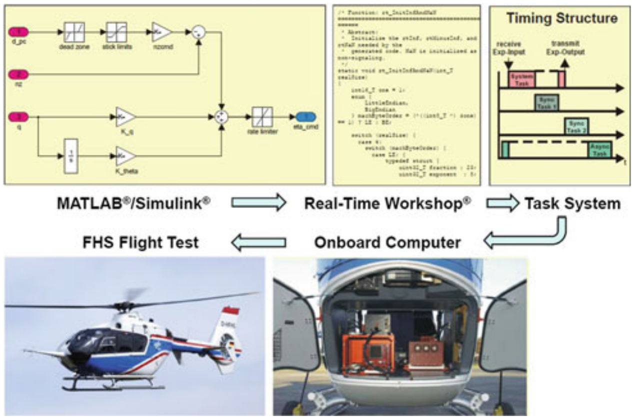


Fig. 10.23 FHS flight control system design chain

The development of nonlinear, generic mathematical helicopter models for simulator applications and flight test preparations was already started during the FHS design phase. The in-flight simulation concept is based on the "model following control system" approach. It requires high fidelity state space models, which were determined by system identification techniques. For this, a comprehensive flight test program from hover to maximum speed was conducted to gather the required data. Classical mathematical models describe the motion of a rigid body in equations for forces and moments for the three axes: longitudinal, lateral and vertical. Such six-degrees-of-freedom models can only represent the low-frequency range of helicopter flight dynamics up to about 10 rad/sec. They neglect the effect of the rotor dynamics. Consequently, the model calculates an immediate linear or angular acceleration response due to a control input. In reality, however, the first reaction is the main rotor tilt due to stick inputs. Then, body accelerations build up with a delay, similar to a second order system response. However, most control laws rely on a correct initial response. Adding an equivalent time delay for the model response is only a very rough approximation. This is why six-degrees-of-freedom helicopter models are often not appropriate for the intended purpose. Therefore, the FHS mathematical model was extended by including rotor degrees of freedom using an implicit formulation for blade flapping and a parametric formulation for the blade regressive lead-lag motion. Through such an extension the model response agreed with flight data for a frequency range of up to about 30 rad/sec, which is adequate for the control system design and application. For a better fit of the vertical response, an implicit formulation of the dynamic inflow (describing the inertia effects of the rotor induced airflow) completed the modeled states. Figure 10.24 demonstrates the quality of different model complexities compared to flight test data. The frequency responses for the vertical acceleration due to collective control inputs are presented for models without and with dynamic inflow effects [13].

Calm atmospheric conditions occur only infrequently. Usually, gusts and winds are encountered during flight testing. Therefore, an emphasis was placed on the development of empirical turbulence models, which can be used in both ground-based and in-flight simulations, with the aim of giving the pilot a realistic feeling of flying in real turbulence for hover and low speed. Additionally, these models are used to present deterministic disturbances for the control system design. The models were derived from flight test data collected under different turbulence conditions, which were recorded by anemometers at the test location. A predicted response of the helicopter due to the pilot stabilization inputs

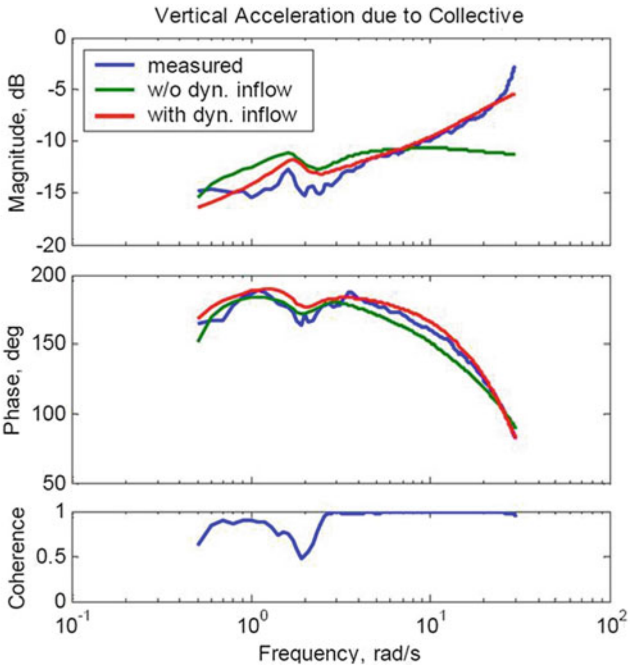


Fig. 10.24 Improved mathematical model accuracy through dynamic inflow modeling

was subtracted from the actually measured one. The remaining random response signals were converted to equivalent control input signals. During a flight in a calm air or piloting a ground-based simulator, these equivalent inputs can be added to the actual pilot control inputs, giving the pilot the impression of flying in turbulent air. Hence such models are denoted as "*control equivalent turbulence input models*" [14].

Helicopters are often used to transport larger payloads to remote locations. The loads are either attached to a load hook by a rope or a sling system beneath the aircraft, or they are carried by a hook or a winch on the side of the helicopter. However, the load can reveal an uncontrollable dynamic behavior and can reduce the helicopter's overall stability. The interaction between aircraft and load depends on various factors like weight, shape of the load, airspeed, and rope length. The pilot must react quickly to the motion of the sling load in order to keep the entire helicopter/sling load system stable. It can lead to dangerous situations, where sometimes the load has to be dropped to avoid an accident. To help the pilot maintain control over the helicopter, a flight director display was developed. It indicated the required control inputs to effectively damp the load pendulum motion and to allow maneuvering without exciting oscillatory load modes. The display was successfully tested in flights. Based on the experience with the flight director, the development of an automatic control system for load carrying and positioning was first started in ground simulations and then consequently prepared for flight tests. Two different alternatives for the implementation of a load stabilization algorithm were evaluated: (1) as an add-on to classical stability augmentation systems or autopilots with limited authority and (2) as a fully integrated component, interacting with the aircraft control system (see Sect. 10.4.5) [15, 16].

Fig. 10.25 FHS and ACT-IME crew

In 2004, the first demonstration of a successful FHS test program by an external user was the comprehensive flight test program ACT-IME (Active Control Technology to Improve Mission Effectiveness). It was conducted by Eurocopter France. Advanced mission adapted control strategies, developed by Eurocopter, were evaluated. The complete program including software development, implementation in the FHS ground-based simulator, and flight test and evaluation, was fully under the control and responsibility of the external user. Interface definitions and implementation support were provided by DLR so far as needed. Essentially, it was demonstrated that an external user can independently and under his own responsibility conduct tests with the FHS, without sharing any information, recorded data, evaluations or results with DLR. Figure 10.25 shows the joint flight test crew after the last flight.

DLR also continued some research programs with FHS that were started with the Bo 105 ATTHeS, for example, techniques for variable flying qualities, control system development, and the test pilot and flight test engineer training. Typical examples of such applications are presented in some details in the following, namely (1) control system, (2) active inceptors (sidesticks), and (3) pilot assistance.

10.4.2 Model Following Controller

Based on the experience gained from the Bo 105 ATTHeS testbed, the main emphasis was placed on the design and

Fig. 10.26 Principle of in-flight simulation

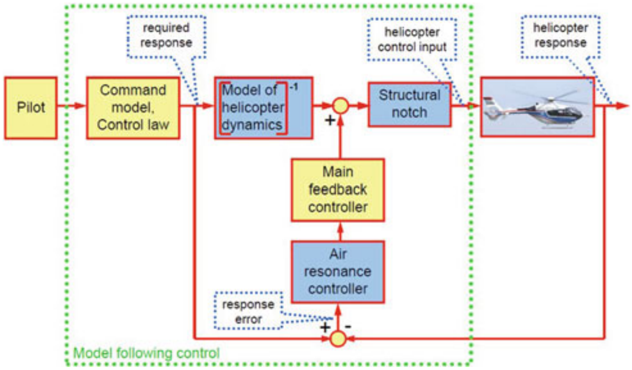


Fig. 10.27 Block diagram of FHS model following control system

optimization of the model following control system for the in-flight simulation (see Fig. 10.26). It gives the FHS the potential to change its inherent EC 135 dynamic flight characteristics. The principle approach for the control system is shown in Fig. 10.27 [17]. Here, the key element is the “model of helicopter dynamics” representing a mathematical model for the FHS dynamics. If the mathematical model exactly describes the helicopter behavior, the inverted model neutralizes the original EC 135 dynamics. The pilot flies the command model as defined in the forward loop. Deficiencies due to model inaccuracies and external disturbances are corrected by a feedback loop. A number of parameterized command models are available in the experimental system computer. They can easily be retrieved during flight by the evaluation pilot or the flight test engineer. In comparison to helicopters with articulated rotors, helicopters with a bearingless main rotor like the EC 135 are more sensitive to the so-called air resonance phenomenon. Principally, it is a coupling effect between the lead-lag motion of the main rotor blades and the body modes. For the EC 135, it can occur in flight, when the regressive lag mode couples with the fuselage roll motion mode. It is noticed by oscillations in the roll motion. To avoid resonance problems, in particular with higher feedback gains, an air resonance controller was added to the feedback loop (see Fig. 10.27) [18].

According to the development contract, the FHS had some constraints in the flight envelope when it was delivered in 2002. Flights in the “evaluation pilot experimental” mode were not allowed at low heights (below 20 feet over ground) and at low speed. Extensive tests were conducted to document the time needed for the safety pilot to gain control after full control inputs (e.g. from the evaluation pilot or external perturbation). Based on the measurements from these so-called runaway tests, the certification for the flight envelope was extended (see Fig. 10.28). On May 23, 2008, the first landing of the FHS with an engaged experimental system was performed [19].

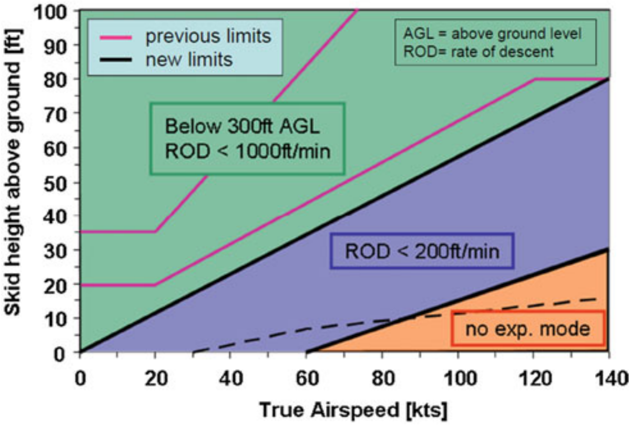


Fig. 10.28 FHS flight envelope for flight in experimental configuration

10.4.3 Active Inceptors (Sidesticks)

In modern aircraft, a wide selection of information about the vehicle and the flight conditions is available. For an optimal support of the pilot, it is essential to select the information he needs for the actual flight situation and present it to him in a most effective way. It can be considered as an interface between the aircraft, the environment, and the pilot. Two factors play an important role for the pilot in assimilating the information, namely (1) he has a very sensitive feeling of accelerations (this is particularly important as helicopters show strong linear and rotational acceleration responses) and (2) he can immediately react to changes in his field of view (horizon). Both of these actions are performed intuitively and subconsciously, in other words at no extra cost. On the other hand, additional information required by him for controlling the helicopter has to be generated and provided explicitly, which involves additional measures such as hardware and software. This is the field of a new generation of pilot controls. With the classical mechanical inceptors, the pilot is controlling the vertical motion using the collective lever in his left hand. He corrects the yawing motion with the pedals at his feet. Furthermore, the pitch and roll motions are controlled by the right hand with the cyclic stick between the

Fig. 10.29 FHS-cockpit with 2 sidesticks, side-by-side configuration

pilot's knees. Helicopter motions are highly coupled. An input in one control generates responses in all axes so that the pilot is always simultaneously working with all his controls, which means with both hands and his feet.

Advanced helicopter flight control systems will feature active inceptors (for example side-sticks), where the forces felt by the pilot are generated by electric motors. They expand the classical, vision-centered human-machine-interface using haptic information. By local variation of their force-feel characteristics, additional information can be transferred to the pilot in an intuitive and effective way. In its role as technology demonstrator, the FHS is ideally suited for the assessment of new inceptors because they can be installed as controls for the evaluation pilot. The upgrade of the FHS and the integration of a sidestick began in 2004 with a feasibility study together with Airbus Helicopter Germany. In 2007, the FHS cyclic control stick was replaced by a 'Goldstick' from Stirling Dynamics Ltd. [20, 21]. After an experimental acceptance study, a second sidestick for the heave axis was obtained from LAT. It was flown successfully in September 2009. The new cyclic stick is now on the right side of the pilot and the classic long pole stick was replaced by a short pole stick, capable of adapting and changing its force profile based on mission requirements. The standard collective lever was removed. The vertical motion (up-down) is now controlled by a short pole active stick at the left side of the pilot. The obvious ergonomic advantage is that the pilot can sit more upright. It also results in several further improvements. In addition, the left-hand sidestick allows the control of two degrees of freedom (forward-backward and left-right) and can optionally be used for yaw control. In flight tests, it was rated as an "intuitive control". Furthermore, this 'side-by-side' configuration improves the ergonomics, the comfort, and the crash safety (see Fig. 10.29).

Active inceptors offer many advantages, among them the ability to adapt the control forces to the actual flight condition and to the status of the flight control system. The sticks can be designed to always provide an optimal control force, leading to improved handling qualities and higher mission effectiveness. The haptic feedback, the so-called 'tactile cueing', is a significant feature of the active sticks. By carefully shaping the profile of the control forces, the pilot can be informed on flight envelope limits, helicopter load limits, or obstacles without having to monitor continuously the limit displays on the cockpit panel. This is essential for flights under visual conditions, where the aerial surveillance is an additional pilot task. So the sidestick helps to improve the situational awareness. When the pilot applies a force to the active inceptor it responds dynamically and the inceptor displacement controls the augmented helicopter. By closing the feedback loop in the inceptor control system, it is possible to indicate the limits mentioned above to the pilot by adding cues or varying force gradients (see Fig. 10.30). An overview of the features of active inceptors and their usage in the feedback-block is outlined in Fig. 10.31. It has to be pointed out that all characteristics and details are freely programmable. They can be adapted to the specific helicopter configuration and actual flight situation. This possibility opens a large variety of solutions and needs criteria for optimization.

For activities pertaining to tactile cueing, so-called demonstrator functions were developed and tested in flight in 2007. These demonstrator functions included load-factor

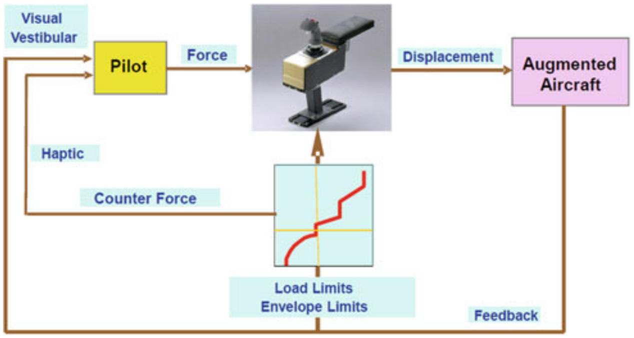
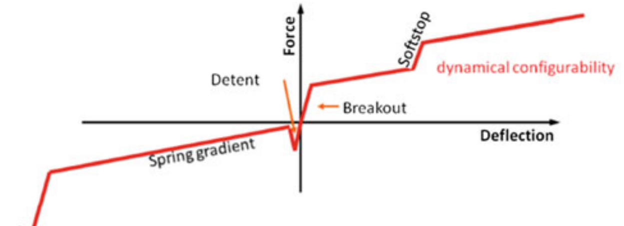


Fig. 10.30 Extended pilot-inceptor-aircraft loop



Breakout	helps the pilot to hold the control in trim
Detent	indicates a certain control position (i.e. 70% coll.)
Spring gradient	helps the pilot to cue by the force his control deflection
Vibration	indicates the *approach* to a limit
Soft stop	indicates the *appearance* of a limit (load or flight envelope), but is overrideable by pilot decision
Hard stop	*fixed* control limit, not overrideable even in case of emergency

Fig. 10.31 Features of active inceptors (stops, forces diagram)

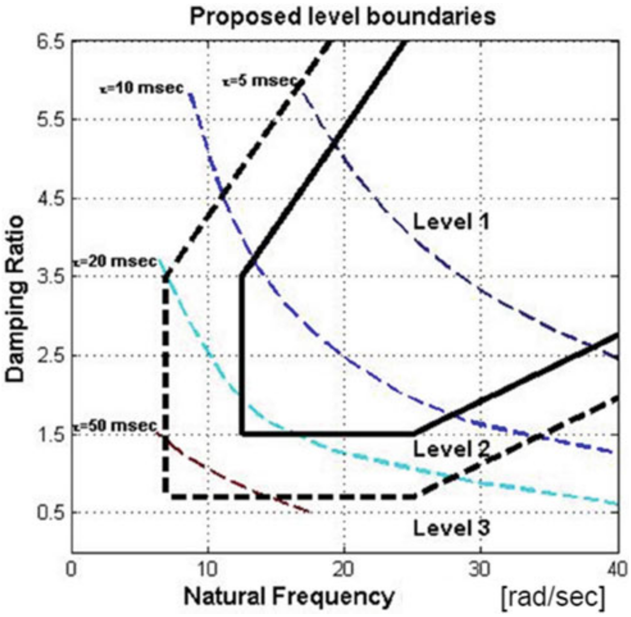


Fig. 10.32 Proposed level boundaries for active inceptors

limitations, mast bending limitations, and tactical guidance to fly a standard 360 degree turn by using a soft stop. In critical situations, soft stops can be overridden by the pilot. A haptic vortex ring state protection (sink rate limitation) developed in cooperation with the ONERA was successfully demonstrated in flight in 2010. As a further application, a torque protection cue was developed in cooperation with Eurocopter and demonstrated in flight. Another activity is related to obstacle avoidance. It supports the pilot flying in obstacle scenery close to the ground. Considering the active inceptor technology as part of the overall active control technology, and using an integrated approach, these functions can be imbedded into more comprehensive pilot assistance systems.

Under the umbrella of the US-German Memorandum of Understanding for Cooperative Research on Helicopter Aeromechanics, a task considering 'Handling Qualities for Actively Controlled Rotorcraft' was formulated (see also Sect. 12.3.3). DLR and the U.S. Army Aeroflightdynamics Directorate performed common and complementary in-flight and ground-based simulator studies. The objective was gaining insight into the influence of the dynamic inceptor parameters (damping and natural frequency) on the handling qualities of helicopters. For the evaluation in flight, the considered mission task elements were "hover" and "forward flight slalom". Objectives were to provide design guidance for rotorcraft with active inceptors and to identify a methodology for integrating inceptor characteristics into the optimization process of the entire system to improve handling qualities. The used test vehicles were the FHS equipped with two active sidesticks and the JUH-60 RASCAL (see Sect. 5.2.2.17).

Several flight test campaigns were performed. The dynamic inceptor parameters (damping and natural frequency) were systematically changed and handling qualities were evaluated to define the requirements for active inceptors [22, 23]. The pilots stated that they preferred (1) short delay between their control inputs and the initial response of the aircraft and (2) high damping to allow a quick and precise control of the stick position without any danger of overshooting. With the general requirement for higher damping values, the first proposal for level boundaries was generated. They are given as bold lines in Fig. 10.32. To show the influence of time delays, selected contour lines are added to the diagram. Level 1 indicates the region of satisfactory and level 2 for acceptable handling qualities.

10.4.4 Pilot Assistance Systems

The objective of helicopter pilot assistance is to support the pilot with suitable technologies to reduce his workload and increase the probability of a successful mission. The challenge in the definition of an assistance system is that it has to

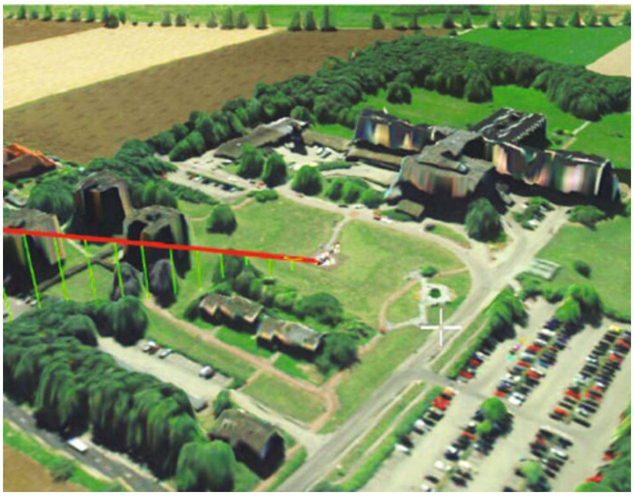


Fig. 10.33 Example of a high resolution stereo image with embedded departure route

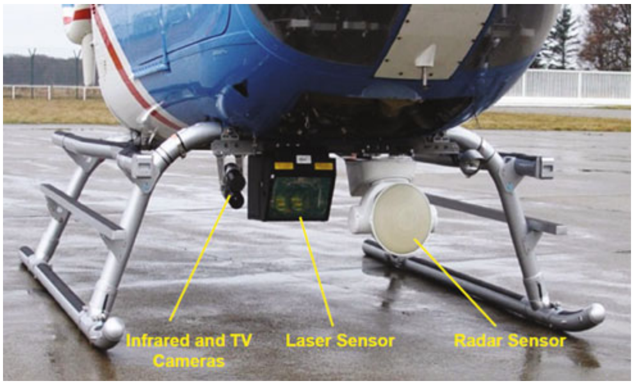


Fig. 10.34 Sensors for the All Flight program

be adapted to (1) the helicopter configuration, (2) the actual flight task, and (3) the pilot capability. In April 2003, a common DLR/ONERA project called PAVE (pilot assistant in the vicinity of helipads) was initiated. It concentrated on automatically and manually flown landing approaches and departures, emergency procedures, as well as noise abatement flight profiles. For increased situation awareness, high-resolution stereo images were integrated into a virtual landscape. An example for a high-resolution stereo image with embedded departure route is given in Fig. 10.33. Various supporting modules were developed including an intuitive planning module for easy flight plan changes and a guidance module for automatic flight modes. A flight director display showed the deviations from the pilot-defined trajectory. Flight testing started in 2006 and the PAVE project was finished in 2007 by a successful demonstration of an automatic flight for an emergency medical services mission [24–26].

A follow-on project was ALLFlight (Assisted Low Level Flight and Landing on Unprepared Landing Sites). It aimed at operating a helicopter under degraded visual environment conditions with optimal handling qualities for the entire flight from start to landing. The required hardware for the tests included a high landing skid equipped with sensors to detect ground contact, a beam for sensor installations, and four external sensors (ladar, radar, TV camera, and infrared camera). Figure 10.34 shows the additional sensors on the FHS. An additional computer was installed as part of the FHS experimental system. It was needed for the extensive navigation task and for the calculation and presentation of maps, terrain, obstacles, and possible landing trajectories. Flight tests began in November 2011. The measured data were used for an online obstacle free trajectory planning. Individual algorithms for the three flight segments start, en-route, and landing were derived. The algorithms consider all helicopter limitations and typical procedures (for example, CAT A start and landing) of piloted operations. To improve pilot acceptance of the automated trajectory planning, 68 pilots from various operators were interviewed for their trajectory planning preferences. As an example, Fig. 10.35 shows a map of obstacles and the terrain profile with suggested landing flight paths.

In addition to infrared and TV data, radar and ladar measurements were obtained (see Fig. 10.34). In principle, the two last sensors provide redundant information. Both are detection and ranging systems, where signals are sent out and their reflections from any objects are received and processed. The more familiar radar is based on electromagnetic waves. It is best suited for the detection of larger objects. Ladar is an optical system and uses laser technology. The main difference is that it operates in higher frequency bands. It has a higher resolution and is able to detect smaller objects like electrical wires. By the so-called “data fusing” procedure, the measurements of both sensors are combined to take advantage of the benefits of the two systems and to give the pilot the best possible image (see Fig. 10.36) [27–29]. In 2012 the displayed fused data in combination with the selectable flight control parameters were tested in flight [29–31].

Another approach to support the pilot when flying in low visibility conditions like fog, brown out and white out, or even in dawn or during the night is based on a helmet-mounted display (HMD). Therefore, the Elbit’s JedEye™ helmet mounted display system (see Fig. 10.37) was installed in both the FHS and a ground-based simulator, the DLR Generic Cockpit Simulator GECO with a collimated vision system. The integration of such a helmet in the research helicopter offers the possibility to increase the situation awareness especially under degraded visual condi-

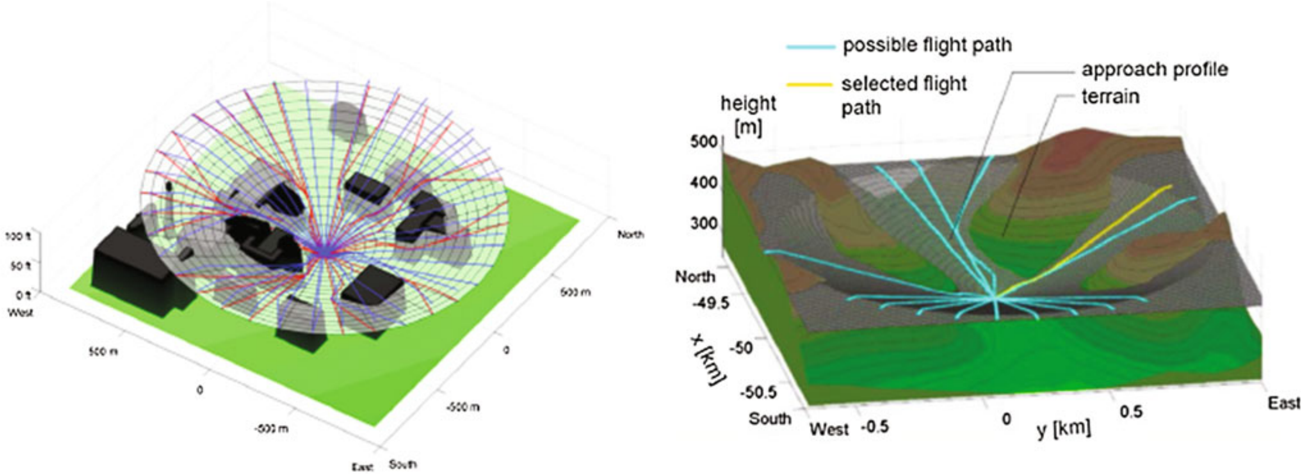


Fig. 10.35 Map of obstacles (*left* buildings, *right* terrain) and possible landing trajectories

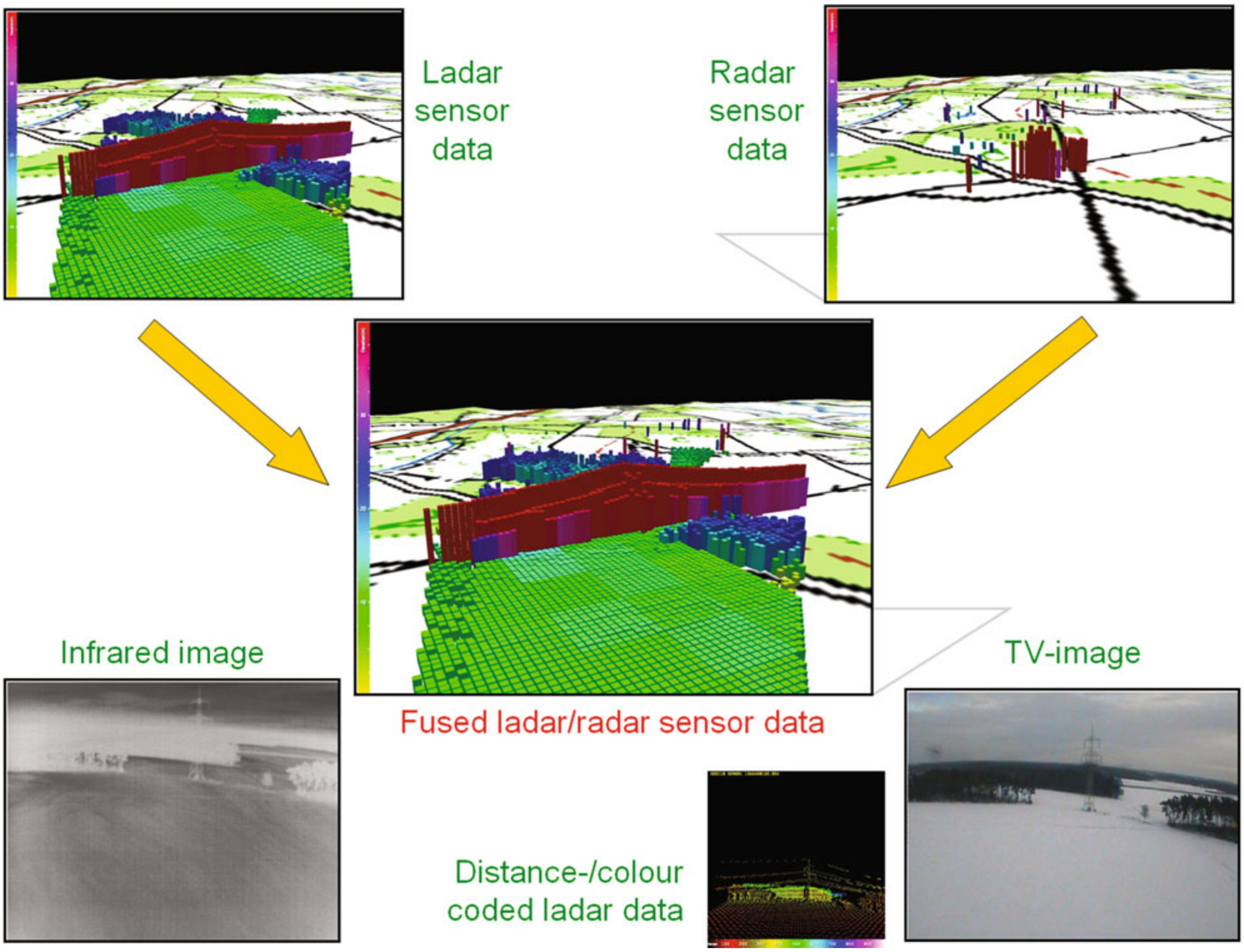


Fig. 10.36 Sensor data fusion for 3D image generation

Fig. 10.37 FHS Evaluation with JedEye™ helmet

tions by displaying mission dependent symbologies. The main focus concentrated on the extraction of relevant information (e.g. obstacles) out of the adequate visual conformal symbology. The presentation on the helmet allowed following predefined 3D trajectories, such as noise abatement flight procedures. This symbology was validated in FHS flight tests [32].

10.4.5 Automatic Stabilization and Positioning of Sling Loads

For demonstrating sling load assistant systems and for reducing the tremendous workload of pilots during sling load transport, the FHS was equipped with a rescue hoist (see Fig. 10.38). Challenges of the rescue hoist derive from the variable cable length and the disturbing rolling moment that is generated by the side installation. Main project objectives were an additional automatic stabilizing and positioning mode connected to a modern automatic flight control system (AFCS). Sling load motions are detected by an infrared camera (see Fig. 10.39). Control algorithms were derived to dampen load oscillations and to support a precise load delivery. This algorithm could become part of an AFCS for advanced utility and transport rotorcraft [33–35].

10.5 Pilot and Test Engineer Training

Following the tragic Bo 105 ATTHeS accident, the pilot training with this helicopter had to be discontinued in 1995 (see Chap. 8). However, due to the highly positive experience with the Bo 105 ATTHeS, the English Empire Test Pilots' School (ETPS) was further interested in the utilization of a helicopter in-flight simulator for pilot and flight test engineer training. Accordingly, ETPS visited DLR Flight Test Facility in Braunschweig during spring 2005 to explore the resumption of these opportunities with the FHS. Once again the ETPS was convinced of the overall set up consisting of the experimental system, data recording, monitoring, and ground-based simulator, as FHS offered flexibility and efficient hands-on training.

The first training campaign for the ETPS with FHS started in autumn 2005. As a part of their thesis work, a pilot and a flight test engineer were allowed to test and evaluate FHS. Because of the complexity of the overall system, this was a challenge for the trainee students, which they successfully absolved. In the following year, FHS was deployed on a regular basis in the EPTS test pilot courses for flying qualities training. 6–8 trainees from ETPS visited Braunschweig for training purposes (see Fig. 10.40). The task comprised of optimizing the flight control laws for a given mission and then to assess the helicopter suitability. A typical mission could be, for example, rescue operation at night under poor visibility conditions. After installation of an active sidestick in the year 2010, it opened up new areas of pilot training for ETPS. As already elaborated, the damping or force-displacement characteristics of the sidestick could be changed easily via the onboard computer. Optimization of control characteristics together with flight control laws was thus part of the training program.

The test campaigns also provided valuable insights into test vehicle and flight control law design. As such it was interesting to note that some teams preferred attitude control, whereas others the rate control for the same task. It turned out that the prior exposure to flying transport or combat helicopters had a significant impact on the pilot ratings. Another insight was that the interaction between the different flight control laws and the force-displacement characteristics of an active control device was quite important. For example, a combination of two components, individually assessed to be good, however, resulted in poor ratings for the overall

Fig. 10.38 Flight test for sling load assistance system with load motion sensor

Fig. 10.39 Sensor installation for sling load assistance system

system. Even more interesting was the case when the combined overall system was rated to be good when the individual components were rated poor.

The importance of in-flight simulators for pilot and flight test engineer training was repeatedly confirmed [36, 37]. The French Test Pilot School EPNER also showed interest in its utilization and joint work. Accordingly, an EPNER team visited DLR Braunschweig in December 2013 to explore the possibilities of future utilization of FHS for the training of flight personnel.

Fig. 10.40 ETPS trainees in the year 2013 (from *left* test and safety pilot *U. Göhmann* together with *M. Mühlhäuser*, *A. Delaney*, *O. Higgins*, *I. West*, *D. Lee*, *J. Wolfram*, *M. Barnett*, *W. Krebs*, *S. Soffner* and *M. Bernhardt*)

References

1. Butter, U., Schimke, D.: Pausder, H.-J., Gollnick, V.: ACT-Demonstrator/Fliegender Hubschrauber Simulator—Projektdefinitionsstudie—Abschlußbericht, DLR IB 111-95/26 and ECD-0045-95, July 1995 (in German)
2. Pausder, H.-J., Butter, U., Gollnick, V.: ACT-Demonstrator/flying Helicopter Demonstrator—A New Demonstrator Tested for Flight Control and Cockpit Technologies. American Helicopter Society 52nd Annual Forum, Washington D.C., USA, June 1996

3. Pausder, H.-J., Butter, U., Gollnick, V.: ACT-Demonstrator/flying helicopter demonstrator—an airborne testbed development project. In: 22nd European Rotorcraft Forum, Brighton, UK, Sept 1996
4. Kaletka, J., Kurscheid, H., Butter, U.: FHS, the new research helicopter ready for service. In: 29th European Rotorcraft Forum, Friedrichshafen, Germany, Sept 2003
5. Pausder, H.-J., Butter, U., Steinmaier, F.: ACT/FHS for the next generation technologies evaluation and demonstration. In: 25th European Rotorcraft Forum, Rome, Italy, Sept 1999
6. Ockier, C., Butter, U.: ACT/FHS—an airborne rotorcraft simulator for technology development and research. In: AIAA Modeling and Simulation Technologies, Denver, USA, AIAA-2000-4575, Aug 2000
7. Butter, U., Pausder, H.-J., Steinmaier, F.: Safety concept of technology demonstrator ACT/FHS. In: American Helicopter Society 56th Annual Forum, Virginia Beach, USA, May 2000
8. Gelhaar, B., Oertel, H., Alvermann, K., Bodenstein, M., Gandert, R., Graeber, S., Schwaneck, H.-P.: FHS—experimental system for flying helicopter simulator put into operation. In: American Helicopter Society 59th Annual Forum, Phoenix, USA, May 2003
9. Steinmaier, F., Bickel, N., Pausder, H.-J.: Survivable fly-by-light control system. In: ACT/FHS, RTO MP-047, Paper 10, April 2000
10. Bickel, N., Steinmaier, F.: Design of a primary fly-by-light control with a dissimilar redundant architecture. In: American Helicopter Society 54th Annual Forum, Washington D.C., USA, May 1998
11. Bickel, N., Butter, U., Hammerlindl, M., Eichberger, W.: Getting a primary fly-by-light system into flight. In: American Helicopter Society 59th Annual Forum, Phoenix, USA, May 2003
12. Hamers, M., Bouwer, G., von Grünhagen, W.: System Simulator for the DLR's in-flight simulator ACT/FHS—software and hardware realization. In: AHS Vertical Lift Aircraft Design Conference, San Francisco, USA, January 2000
13. Hamers, M., von Grünhagen, W.: Advanced modelling approach for ACT/FHS controller development. In: 27th European Rotorcraft Forum, Moscow, Russia, Sept 2001
14. Seher-Weiß, S., von Grünhagen, W.: EC 135 system identification for model following control and turbulence modeling. In: CEAS Conference, Berlin, Sept 2007
15. Hamers, M., Bouwer, G.: Flight director for helicopter with slung load. In: 30th European Rotorcraft Forum, Marseille, France, Sept 2004
16. Hamers, M., Bouwer, G.: Helicopter slung load stabilization using a flight director. In: American Helicopter Society 61st Annual Forum, Gaylord Resort Grapevine, USA, June 2005
17. Hamers, M., Lantzsch, R., Wolfram, J.: First control system evaluation of the research helicopter FHS. In: 33rd European Rotorcraft Forum, Kazan, Russia, Sept 2007
18. Lantzsch, R., Wolfram, J., Hamers, M.: Increasing handling qualities and flight control performance using an air resonance controller. In: American Helicopter Society 64th Annual Forum, Montreal, CA, April 2008
19. Hamers, M., et al.: Extension of the ACT/FHS experimental flight envelope. In: American Helicopter Society 65th Annual Forum, Gaylord Resort Grapevine, TX, USA, May 2009
20. Abildgaard, M., von Grünhagen, W.: Demonstration of an active sidestick in the DLR flying helicopter simulator (FHS). In: 34th European Rotorcraft Forum, Liverpool, UK, Sept 2008
21. von Grünhagen, W., Müllhäuser, M., Abildgaard, M.: Active inceptors in FHS for pilot assistance systems. In: 36th European Rotorcraft Forum, Paris, France, Sept 2010
22. von Grünhagen, W., Schönenberg, T., Lantzsch, R., Lusardi, J., Fischer, H., Lee, D.: Handling qualities studies into the interaction between active sidestick parameters and helicopter response types. In: 38th European Rotorcraft Forum, Amsterdam, The Netherland, Sept 2012
23. von Grünhagen, W., Müllhäuser, M., Höfinger, M., Lusardi, J.: In-flight evaluation of active sidestick parameters with respect to the handling qualities for rate command and attitude command types. In: AHS Rotorcraft Handling Qualities Specialists' Meeting, Huntsville, USA, Feb 2014
24. Lüken, T., Korn, B.: PAVE: assistance system to support pilots for IFR rotorcraft airport operations. In: 25th ICAS Congress, Hamburg, Sept 2006
25. Döhler, H.-U., Lüken, T., Lantzsch, R.: ALLFlight—a full scale enhanced and synthetic vision sensor suite for helicopter applications. In: SPIE Defense, Security + Sensing 2009, Orlando, USA, April 2009
26. Stromaier, T., Lantzsch, R., Greiser, S.: Assisted landing for helicopters in confined areas. In: 36th European Rotorcraft Forum, Paris, France, Sept 2010
27. Lüken, T., Döhler, H.-U., Lantzsch, R.: ALLFlight—fusion sensor information to increase helicopter pilot's situation awareness. In: 36th European Rotorcraft Forum, Paris, France, Sept 2010
28. Lüken, T., Döhler, H.-U., Lantzsch, R.: ALLFlight—fusion sensor suite with "see through" capability for helicopter applications. In: American Helicopter Society 66th Annual Forum, Phoenix, USA, May 2010
29. Lüken, T. et al: ALLFlight—helicopter flight trials under DVE conditions with an AI-130 mmW radar system. In: 37th European Rotorcraft Forum, Gallarate, Italy, Sept 2011
30. Lantzsch, R., et al.: AllFlight—helicopter pilot assistance in all phases of flight. In: 38th European Rotorcraft Forum, Amsterdam, NL, Sept 2012
31. Lantzsch, R., et al.: ALLFlight—a full scale pilot assistance test environment. In: American Helicopter Society 68th Annual Forum, Fort Worth, USA, May 2012
32. Lüken, T., Döhler, H.-U., Schmerwitz, S.: Helmet mounted display supporting helicopter missions during en route flight and landing. In: Degraded visual environments: enhanced, synthetic, and external vision solutions 2016, 9839 (11). SPIE Press. SPIE Defense + Commercial Sensing 2016, 2016, Baltimore, USA, April 2016
33. Kim, H.-M., Nonnenmacher, D., Götz, J., Weber, P., von Hinüber, E., Knedlik, S.: Initial flight tests of an automatic slung load control system for the ACT/FHS. In: 40th European Rotorcraft Forum, Southampton, UK, Sept 2014
34. Nonnenmacher, D. Jones, M.: Handling qualities evaluation of an automatic slung load stabilization system for the ACT/FHS. In: 41th European Rotorcraft Forum, Munich, Germany, Sept 2015
35. Kim, H.-M.: Design of an automatic load positioning system for hoist operations. In: American Helicopter Society, 72st Annual Forum, West Palm Beach, FL, USA, May 2016
36. Lewis, P., et al.: Learning to test. In: Flight International, pp. 39–43, Nov 28–Dec 4 2000
37. Osborne, T.: Training times. In: Aviation week and space technology, pp. 47–48, 2 Dec 2013

Author Biography

Jürgen Kaletka was a research scientist at the Institute of Flight Systems at DLR in Braunschweig (1973–2009). He received his Dipl.-Ing. degree in Aeronautical Engineering from the Technical University of Braunschweig. His main research interest are flight dynamics, in-flight simulation, modeling and system identification (helicopter). From 1987 to 1991 he was the manager of the AGARD FMP Working Group WG 18 Rotorcraft System Identification, from 1979 to 1994 the task manager for system identification in the US-German Memorandum of Understanding (MoU) Helicopter Aero Mechanics. From 1999 to 2003 he was the technical project manager for the development of ACT/FHS (helicopter in-flight simulator based on EC 135).