8 Helicopter In-Flight Simulator Bo 105 ATTHeS

Bernd Gmelin

8.1 Introduction

The early phase of helicopter development, until about the end of Second World War, was characterized by the technical realization of individual components (for example, rotor, flight control, engine), by developing theoretical fundamentals (such as aerodynamics, rotor dynamics), and by the search for suitable configurations of the new flying device. The rapid further developments during the following decades led to higher speeds, improved maneuverability, enhanced efficiency, and at the same time to numerous ideas of exploiting the versatile applicability of this flying device. It became more difficult for pilots to fly the mostly unstable helicopter since the desire for better flying qualities was

B. Gmelin (✉)
Braunschweig, Germany
e-mail: bernd.gmelin@t-online.de

P.G. Hamel (ed.), *In-Flight Simulators and Fly-by-Wire/Light Demonstrators*,
DOI 10.1007/978-3-319-53997-3_8

often subordinated to the demands for higher flight performance and more complex missions. This was particularly evident during instrument flying under poor visual and adverse weather conditions.

One way out of this situation is the introduction of innovative flight control systems. This is only possible for helicopters if the mechanical/hydraulic control components are replaced by digital Fly-by-Wire (FBW) technology. FBW not only enables the use of stability and control augmentation, but, at the same time, it leads to reduced mechanical complexity, weight reduction, simplification of maintenance, and increased reliability. The introduction of Fly-by-Wire/Light (FBW/L) technology is a crucial step for a successful future of the helicopter because, by enabling the use of full authority stability and control augmentation, more precise flight maneuvers and flight envelope expansion can be realized with reduced pilot workload.

This chapter provides an account of modifications and equipping of the Bo 105-S3 helicopter and of the utilization of the in-flight simulator ATTHeS to address diversified aspects of FBW/L in helicopters.

8.2 History of Bo 105 (Serial Number 3)

The Bölkow Bo 105 is a light multi-role helicopter of the German manufacturer Messerschmitt-Bölkow-Blohm—MBB (then: Eurocopter, today: Airbus Helicopters). Its development began in 1961 and the first flight was on February 16, 1967 with the prototype V2 (see Fig. 8.1). This helicopter is deployed even today for governmental tasks, including the police, the military, civil defense and disaster control, as well as for air rescue in particular, and for various other tasks by civilian operators. For the first time the two gas turbine propulsion concept was introduced with Bo 105 in civilian helicopters of the 2-tons-class, and also a hingeless rotor head with fiberglass reinforced plastic (FRP) rotor blades. The 4-blade rotor "System Bölkow" features a rigid titanium rotor hub. The obligatory flapping and lagging motion of rotor blades, which is enabled in other helicopters through individual rotor hinges, is realized in this case through elastic FRP elements in the roots of the rotor blades. The rotor does not require any lead-lag damper. Altogether it consists of a substantially less number of components than the previous rotors. The construction enables high control power, quick control response and high effectiveness, and thereby a very good maneuverability of the helicopter.

Starting 1970, the Bo 105 was produced in different variants; a total of 1404 helicopters in Germany until 2001 [1]. The helicopter was also manufactured under license in Spain, the Philippines, Indonesia, and Canada. Altogether more than 1640 Bo 105 helicopters were built, of which many are in use even today.

The Bo 105-S3 was produced as Series A in July 1971 by MBB in Manching and registered as D-HEBV (see Fig. 8.2). Immediately after routine tests, the Bo 105 was exported to the USA and was operated by Boeing Vertol Co. with the registration N1149B. The cooperation between MBB and Boeing Vertol at that time had the following objectives: (1) to support type certification of Bo 105 by the FAA (Federal Aviation Administration) (April 1972) and (2) to

Fig. 8.1 First flight of Bo 105 helicopter (*Credit* Airbus Group)

Fig. 8.2 Bo 105-S3 D-HEBV (*Credit* Airbus Group, NA3T)

demonstrate the features of the hingeless rotor in the US and to recommend this technology for the project UTTAS (*Utility Tactical Transport Aircraft System*) of the US Army. The proposal of a prototype YUH-61A developed on this basis by Boeing Vertol was, however, defeated in the procurement process by the competitor YUH-60 of Sikorsky company, who received the development contract for the standard transport helicopter UH-60 of the US Army.

In July 1972, the Bo 105-S3 came back from the USA to MBB in Ottobrunn. After extensive modifications in controls and cockpit (see Sect. 8.3.1) and after upgrade to version C23 of the C series, the S3 flew from 1974 with 2 Allison 250-C20 engines and an all-up weight of 2.3 t. It was operated at MBB with the military registration 98 + 08 on behalf of the Federal Office of Defense Technology and Procurement, BWB (today: Federal Office of Bundeswehr Equipment, Information Technology, and In-Service Support—BAAINBw). As a part of the HSF (German: Hubschrauber-Schlechtwetter-Führung for helicopter adverse weather guidance) project, in the following years, the so-called variable stability helicopter was deployed for design and testing of flight control and guidance systems. In late 1980, BWB decided to sell the helicopter through the Federal Disposal Sales and Marketing Agency (VEBEG).

Based on the initiative of the Institute of Flight Mechanics and the Flight Test Facility, the German Aerospace Research Establishment—DFVLR (Today: German Aerospace Center—DLR)—acquired the helicopter, which finally arrived at Braunschweig in 1982 and was operated with the original registration D-HEBV based on a Permit to Fly of the Federal Aviation Office (Vorläufige Verkehrszulassung VVZ). In the subsequent years, the S3 was converted to the in-flight simulator Bo 105 ATTHeS (*Advanced Technologies Testing Helicopter System*) (see Fig. 8.3). ATTHeS accumulated over 1300 flight hours at DFVLR/DLR in numerous research and development programs (see Sect. 8.4). In a tragic accident due to a fatigue fracture in the tail rotor drive, the helicopter crashed on May 14, 1995, during a ferry flight near Stendal. Thereby the test pilot *Klaus Sanders* and the flight engineer *Jürgen Zimmer* were killed.

8.3 Modifications and Equipment

At the end of 1969, DFVLR, Dornier, and MBB submitted a memorandum "variable stability testbed (VVS), a mid-term program" to the German Federal Ministry of Defense [2]. Besides fixed-wing aircraft projects, realization of a variable stability helicopter based on the Bo 105 was proposed in this document. Theoretical investigation at DFVLR revealed that aircraft with vertical and/or short takeoff and landing capabilities (V/STOL) in low-speed regime could be simulated by a helicopter [3]. Due to its basic characteristics, the Bo 105 helicopter appeared to be particularly suitable for this task [4].

8.3.1 Control System

With the support of the Federal Ministry of Defense, the Bo 105-S3 helicopter was equipped in the years 1973/74 at MBB with a non-redundant electrical flight control system (Fly-by-Wire, FBW) with full authority for the main rotor and the tail rotor control. The test vehicle was designed for a 2-person crew: a simulation pilot and a safety pilot as the operator in command. The safety pilot sat in the rear left part of the cockpit and operated the helicopter through the mechanical control with hydraulic boosters almost similar to that in the production version. The simulation pilot sat centrally in the front part of the cockpit (see Fig. 8.4). His control inputs were converted into electrical signals and fed to the main and tail rotors through electrohydraulic actuators, together with additional signals from the control computer.

Fig. 8.3 Bo 105 ATTHeS

Fig. 8.4 ATTHeS pilots seating arrangement

The movements of the FBW actuators were mechanically fed back to the controls of the safety pilot, who was thereby always informed about the entire control input for the rotors and could monitor the control and assess their plausibility with regard to the planned flight task. The safety pilot could at any time switch off the FBW system or override the actuators and take over the helicopter command with the mechanical control system. The flight safety could be ensured this way even in the event of failure of important components of the non-redundant FBW system. In addition, an automatic safety system was installed, which monitored the bending moment of the main rotor mast and the lead-lag moments. Figure 8.5 shows the concept of the main rotor control modifications.

In the Introduction of the basic technical transcript of MBB [5], development engineer *Hans Derschmidt* describes the design principles as follows:

> The helicopter Bo 105 shall be converted to a test aircraft for VSTOL flight guidance and landing procedures. For this purpose, to increase the quality of simulation flights, the flying qualities and cockpit equipment shall be reproduced as accurately as possible, also for VSTOL aircraft which are likely to be considered. The helicopter has a crew of two pilots for simulation operation. The simulation pilot operates the helicopter with a control station that is equivalent of the aircraft being simulated, but connected only via a computer with the standard Bo 105 control ("Fly-by-Wire"). The onboard computer controls hydraulic actuators so that the Bo 105 motion corresponds to that of a pre-programmed model as best as possible. This deviation from Bo 105 flying qualities would be realized through a system of control simulation, in which the control inputs are converted into electrical signals. These signals and further signals, derived from sensors measuring the flight condition, would be converted by a special simulation computer and by a controller into Bo 105 helicopter control commands, which finally result in the modified flight behavior of the vehicle to be simulated. The differential equations of motion of the flight vehicle to be simulated are programmed in the simulation computer. The safety pilot, who is "program manager" at the same time, monitors the computer performance and can prevent critical flight conditions or limit the effect of controller malfunctions through direct intervention in the Bo 105 mechanical control. Therefore, computers and hydraulic actuators need not be redundant.

The first flight of the modified helicopter took place on July 16, 1974 in Ottobrunn and the successful first flight in FBW mode on August 22, 1974 [6].

The test helicopter could be flown in three modes:

1. Basic mode: The FBW system was turned off, only the safety pilot controlled the helicopter,
2. 1:1 FBW mode: The simulation pilot flew the host helicopter with full control authority, and
3. Simulation or VSS (Variable Stability System) mode: The simulation pilot steered the simulated helicopter with full control authority via the onboard computer.

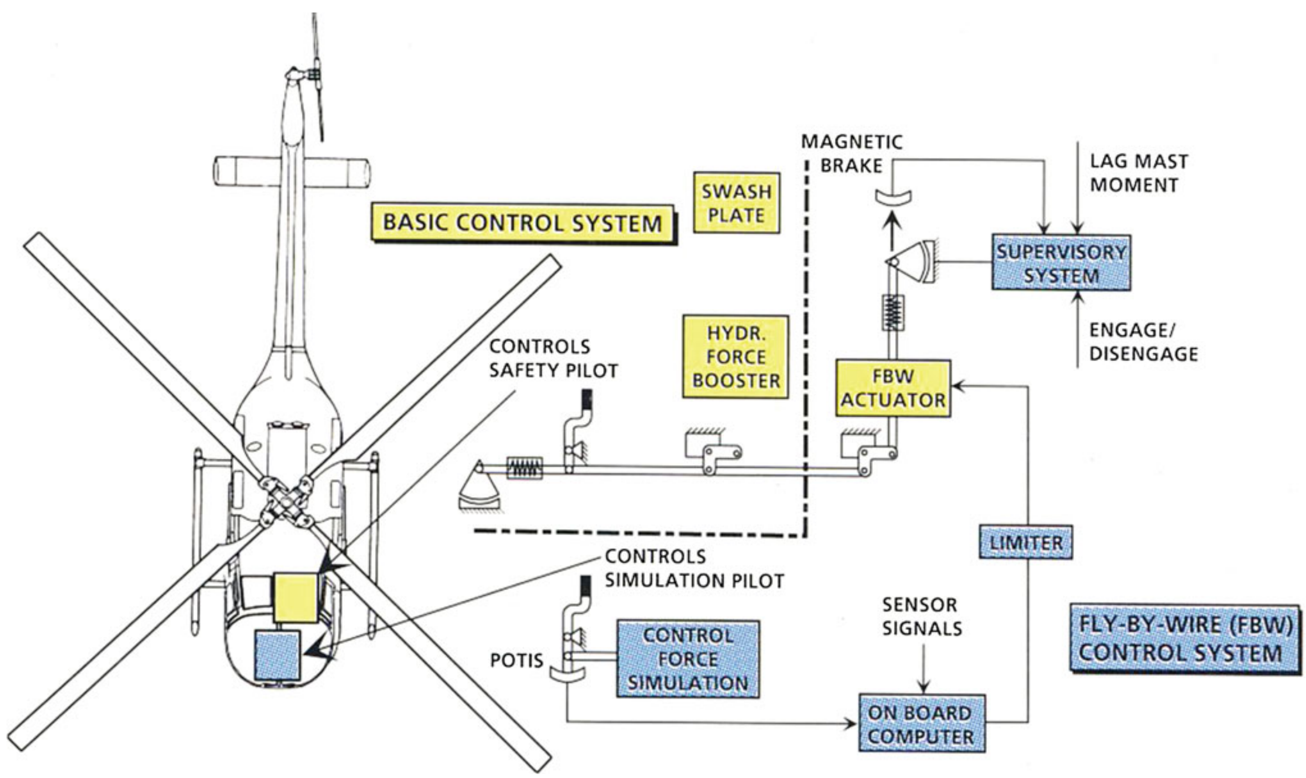

Fig. 8.5 Concept of main-rotor control modifications

In 1:1 FBW and simulation mode the flight envelope was limited to altitudes of at least 50 ft above ground when hovering and 100 ft in forward flight.

After the acquisition of the modified helicopter by DFVLR in 1982, the Bo 105, S/N 3 built in 1971 (Bo 105-S3) served as a host flying device for the helicopter in-flight simulator ATTHeS.

The next generation of civil and military helicopters should enable flight tasks with higher precision and maneuverability. These requirements were to be particularly considered in the development of ATTHeS. As the in-flight simulator capabilities depend highly on the dynamic performance of the basic flying vehicle, the high control effectiveness and fast response to control inputs of the hingeless rotor of Bo 105 were important prerequisites for the utilization of this helicopter as an in-flight simulator.

8.3.2 Tail Rotor Control with Optical Signal Transmission

From 1986, the project OPST1 (Optical Control, Phase 1) was pursued as part of a technology program of the Federal Ministry of Defense [7]. The FBW control system of the Bo 105-S3 tail rotor was replaced by an electro-optical flight control system (Fly-by-Light—FBL) and tested in flight jointly by MBB, LAT (Liebherr-Aero-Technik, today: Liebherr Aerospace) and DFVLR/DLR (see Fig. 8.6). On the basis of an existing duplex actuator of suitable dimensions, LAT designed an optically controlled "smart" actuator with integrated control electronics. The duo-duplex electronics could implement all functions in software and thereby could be changed without modifying the hardware. Besides the computations for the controller, the locally available computing power was utilized also for redundancy management and self-diagnosis purposes. Thereby the electro-magnetic compatibility was also improved and the amount of cabling considerably reduced compared to the central arrangement of actuator electronics. The smart actuator was developed and manufactured by LAT and could be driven by a triple redundant computer (see Sect. 8.4.3). The control variables generated in the triplex computer were converted into optical signals and transmitted via fiber optic cable to the electro-hydraulic actuator in the tail boom (see Fig. 8.7). The advantage of the optical signal transmission is its high immunity to electromagnetic interference, an important aspect for helicopter deployment, including those close to the ground and thereby in the vicinity of diverse transmitters [8, 9].

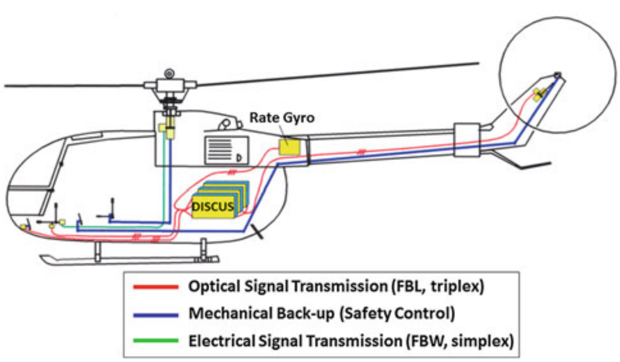

Fig. 8.6 Fly-by-Light (FBL) yaw axis control

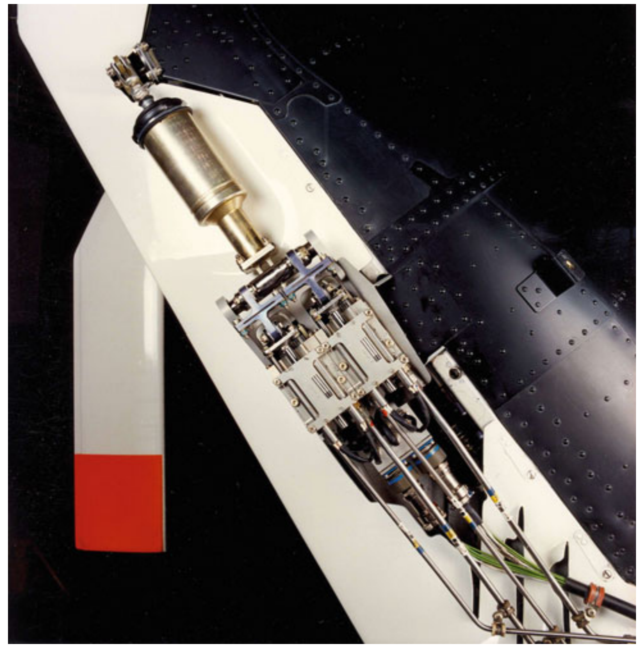

Fig. 8.7 Optically controlled actuator in tail boom

The system "smart actuator with optical transmission" was tested during 1988/1989 in conjunction with a yaw controller for heading hold (see Sect. 8.4.4) and then introduced successfully in several research programs [10].

8.3.3 Model Following Control System

The most promising and also most challenging approach to simulate the desired flying qualities, those that may differ from the host helicopter, is the development of a model following control system. In this process, the controller forces the host helicopter to follow the dynamic flight behavior of an explicit command model which is mathematically formulated in the onboard computer. The simulation pilot then flies a helicopter with properties of the mathematical model (see also Sect. 3.3).

The response of the command model due to pilot control inputs is calculated in real-time and fed to the control system. The dynamic feedforward controller, consisting of the known "inverted" model of the host helicopter, calculates the actuator inputs for the host helicopter with the aim that the host helicopter now responds like the command model. Figure 8.8 shows the basic structure of an explicit model following control system (MFCS). Theoretically, a perfect simulation in flight is achieved through the dynamic feed-forward. In the practical realization, however, a proportional-integral regulator is required in addition to the state feedback (PI feedback controller) to compensate the deviations between the command model responses and the host helicopter due to external disturbances, such as gusts or model inaccuracies and long-term drift. The feedforward and PI controllers are independent of the command model and of the current flight conditions of the helicopter. This method is particularly useful when high flexibility is required in the commanded models, which is particularly of great importance for a research vehicle. Even in modern operational flight devices equipped with a FBW/L control, this type of control system is used increasingly with the aim of realizing optimal flying qualities at different flight conditions [11].

The development of explicit model following control system began during 1983/84 in the *Vertical Motion Simulator* (VMS) at NASA Ames research center in the USA (see Fig. 8.9) as part of a joint transatlantic research program "US/German Memorandum of Understanding on Helicopter Flight Control" between US Army/NASA and DFVLR (see Sect. 12.3.3) [12]. The first simulator results showed a strong dependency of the model following quality on the command model dynamics. Improvements in the model bandwidth (the frequency range of the model response) led to higher demands on the controller. It was, therefore, necessary to account for the dynamic response of the actuators and their position and/or actuation rate limits in particular. The control system was developed for the helicopter Bo 105 and for UH-1H V/STOLAND (see Fig. 8.10) and tested in the simulator [13]. The results showed for both helicopters significant performance improvements at reduced pilot workload for specially defined dynamic flight maneuvers, namely fly over and around obstacles.

After implementation and evaluation of this concept in the variable stability research helicopter CH-47 of NASA (see Fig. 8.11) [14] (see also Sect. 5.2.3) and in the helicopter Bo 105 ATTHeS of DFVLR (see Fig. 8.12), it became apparent that further improvements in the original MFCS design were necessary. As a result of higher order effects, such as the rotor flapping motion dynamics as well as of the sensor filters and the time delays in the computers, large delays were observed between the control inputs and the helicopter reaction. It turned out that the efficiency and accuracy of the model following control system depend highly on the accuracy of the mathematical model of the host helicopter. The better the dynamics of the host helicopter and its systems are known, especially the short-time response, the more accurately the elements of the feedforward gain matrix can be calculated [15]. Additional factors are also of importance for the performance and the accuracy of the entire system, namely the dynamics of the pilot control devices, the shape of the pilot control inputs, the dynamics of actuators and sensors, and the processing of the electrical signals.

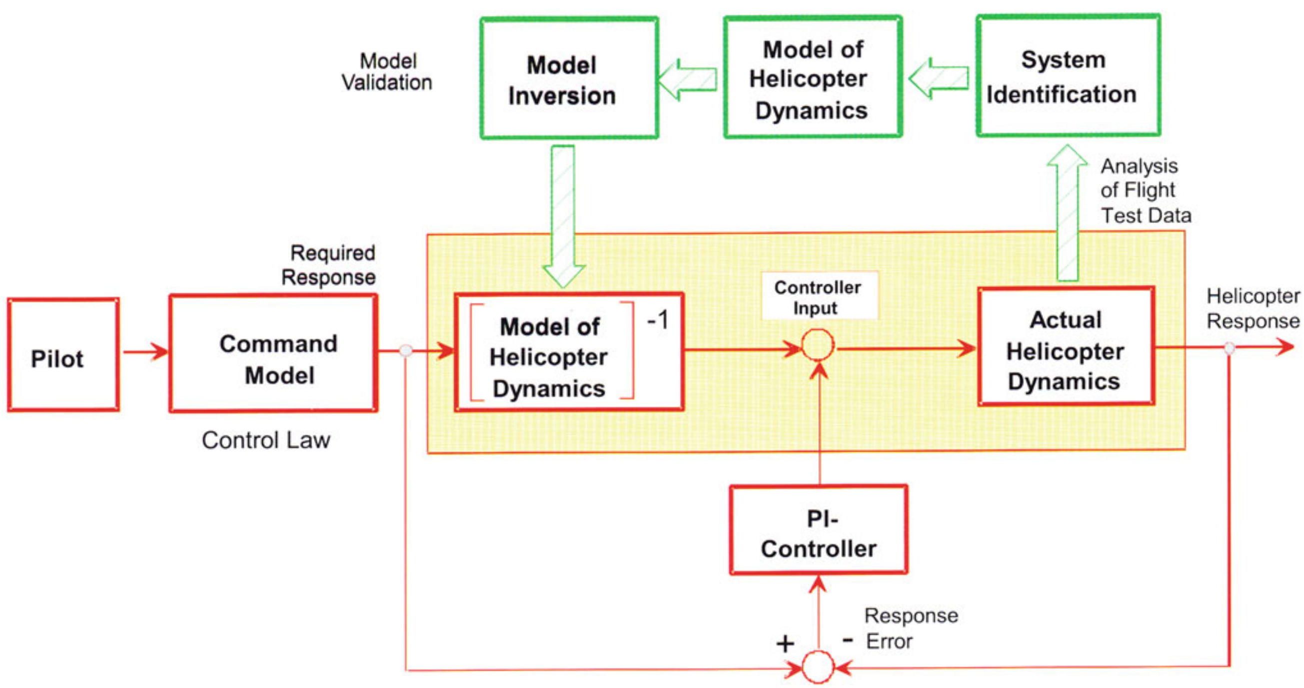

Fig. 8.8 Structure of an explicit model following control

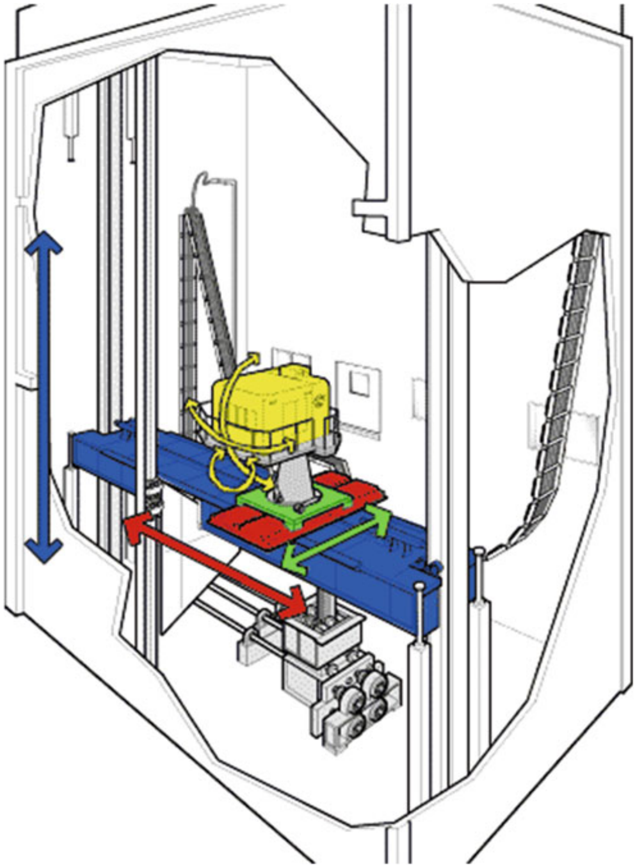

Fig. 8.9 Vertical motion simulator (VMS) of NASA (*Credit* NASA)

Fig. 8.11 Test helicopter CH-47B (NASA 737)

Fig. 8.12 NASA test pilot *Ron Gerdes* (*left*) and flight test expert *Ed Aiken* in front of Bo 105 ATTHeS (Manching, May 1984)

Fig. 8.10 Test helicopter UH-1H V/STOLAND (NASA 733)

The effect of unmodeled rotor dynamics is shown in Fig. 8.13. The three time-history plots on the top show for the in-flight simulator ATTHeS a comparison of the behavior demanded by the command model and the measured behavior in the roll axis due to lateral stick input for a 6 degrees of freedom rigid-body model of the host helicopter (Bo 105). The deviations between the desired and measured responses are significantly reduced by accounting for the rotor dynamics in the model of the host helicopter (8 degrees of freedom) and for the corresponding adaptation of the feedforward gain matrix as seen from the lower diagrams in the same figure [16].

After further improvements, for example, through powerful system identification methods to improve model fidelity using flight test data, an explicit model following control system was developed for the in-flight simulator ATTHeS that was tuned for airspeeds between 40 and 100 knots and for hovering [17–20].

The design of the model following control system was carried out substantially in four steps:

1. Definition of the mathematical model structure of the host aircraft including rotor dynamics at high frequencies,
2. Determination of the parameters of the defined model applying system identification methods or by simulation programs,
3. Determination of the feedforward structure through formal inversion of the defined model of the host flying vehicle, and
4. Definition of the feedback controller structure, optimization of the overall performance in simulation and confirmation in flight test.

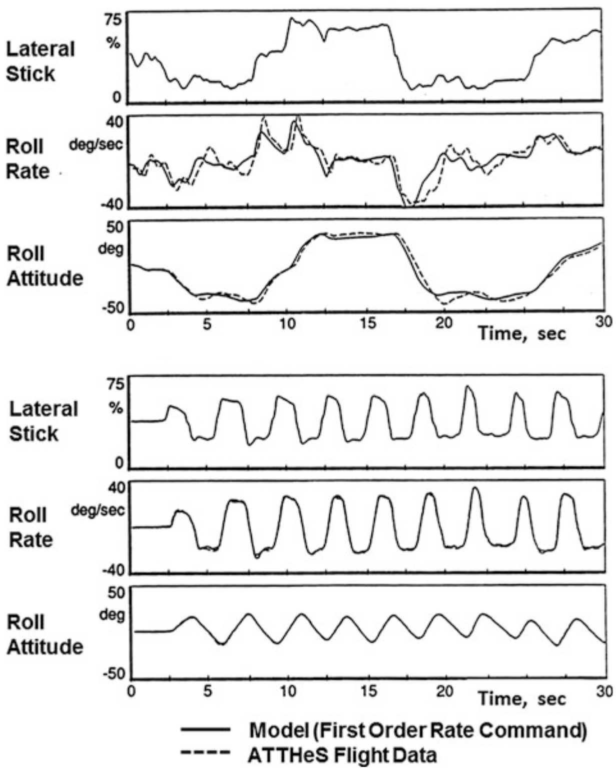

Fig. 8.13 Influence of rotor dynamic modeling on the simulation accuracy (*top*: 6° of freedom rigid-body model of Bo 105, *bottom*: 8° of freedom model accounting for rotor dynamics

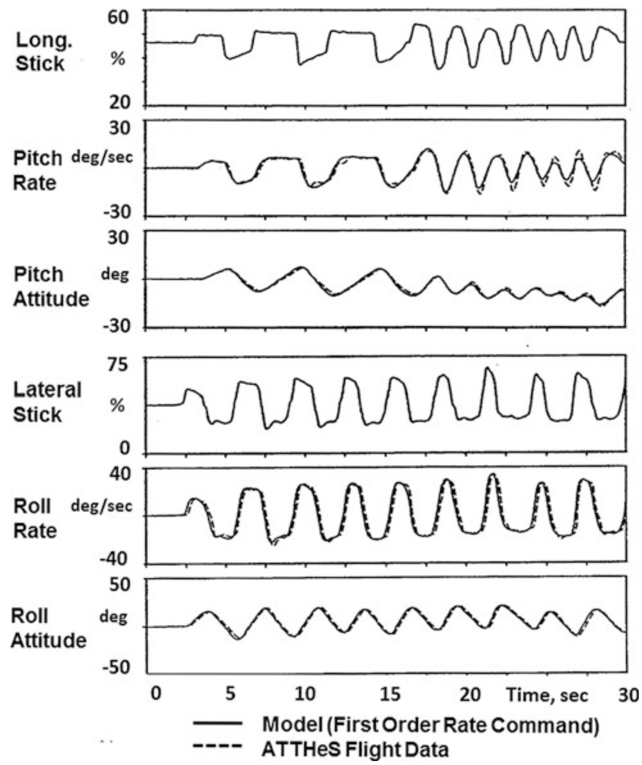

Fig. 8.14 ATTHeS model following quality

Poor model following quality results in differences between the actual behavior of in-flight simulator and the reaction demanded by the command model. The achieved model following quality is shown in Fig. 8.14; both flight-measured rotational rates, as well as the attitude angles in the roll and pitch axes, show satisfactory match with the model. The achieved decoupling between the roll and pitch axis compared to Bo 105 without control system is depicted in Fig. 8.15; here too the good controller performance is obvious [21].

To assess the required model following quality, a criterion was defined in the frequency domain that was based on the flight dynamics not perceived by pilots (unnoticeable dynamics). As an example, Fig. 8.16 shows the ratio of the roll rate of ATTHeS to the command model for dynamic pilot control inputs (transfer function). In an ideal model following case, the amplitude of the so-called error function will be 0 dB and the phase angle 0° over the entire frequency range. The boundary curves show ranges in which the pilot discerns significantly or does not notice respectively the differences in the flying qualities. For a good model following performance, the ratio of the roll rates has to be within the defined range for the unnoticeable dynamics. The controller based on the model taking into account the rotor dynamics fulfilled this requirement [22].

8.3.4 Onboard Computer and Measurement System

An onboard computer and a data acquisition system were constructed and installed in the helicopter to enable implementation of a flight controller for in-flight simulation. Considering the limitations of existing technology available during 1980 and subsequent years, the following requirements had to be accounted for: (1) available space in the helicopter is very limited, (2) software changes in control system had to be carried out on a so-called host computer on ground, (3) software modifications were to be introduced in flight only after verification in a system simulation on ground compatible to the onboard system, (4) controller tasks of the onboard system and the evaluation of the system performance must be clearly separated, and (5) flight tests are to be tracked and managed from a ground station. A block diagram of the onboard system is shown in Fig. 8.17. Two computers, which were “hardened” for the conditions during flight tests, were assigned to the data acquisition and the control/regulation tasks and permitted a largely independent data transfers of both the tasks. The control inputs by the simulation pilot and the necessary state variables for the control system were generated directly from the sensor signals with a sampling rate of 25 Hz. The total processing time for the command model and the control laws was 7 msec. The computer for data gathering was equipped with a 64-channel analog/digital converter, and all

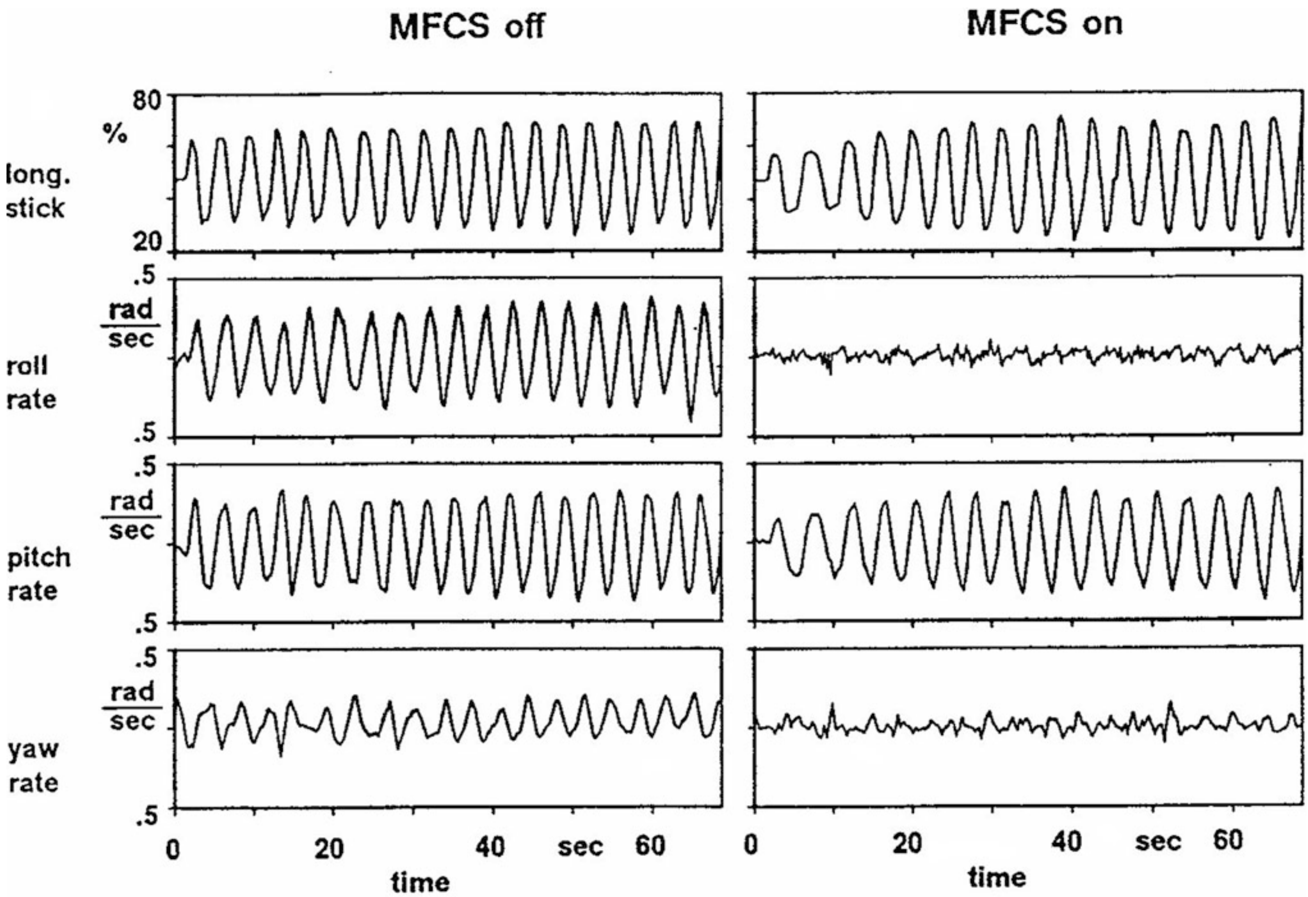

Fig. 8.15 ATTHeS decoupling between roll and pitch axis (*MFCS* model following controller)

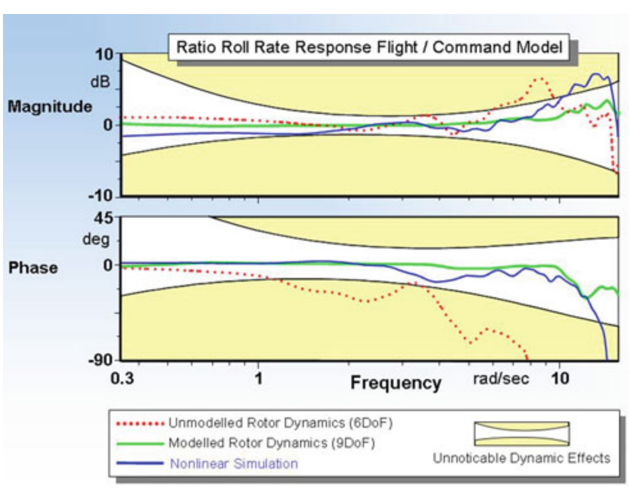

Fig. 8.16 Influence of modeling on the model following quality

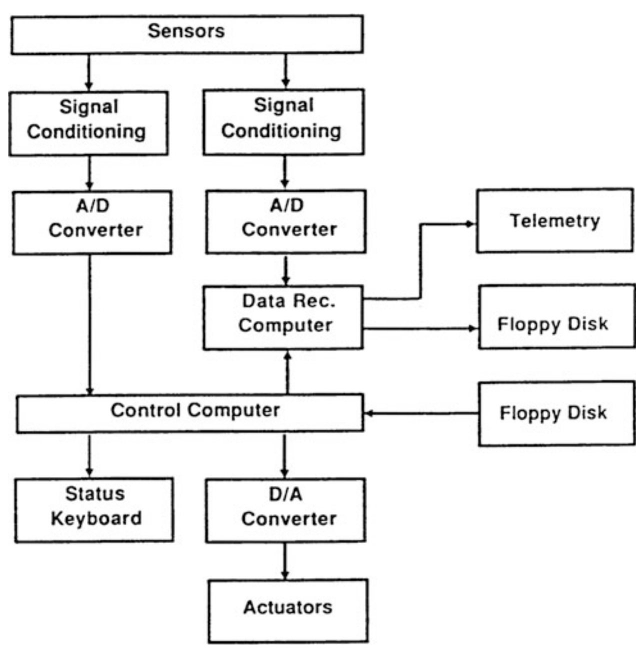

Fig. 8.17 Onboard computer system for data recording and flight control

sensor signals sampled at 100 Hz. The much higher sampling rate compared to the control computer was chosen to enable a more precise evaluation of overall system performance.

Furthermore, the so-called aliasing errors were thereby eliminated, which arise due to the digitization of higher frequencies at too low a sampling frequency. Both computers were connected through a memory with two inputs (*dual ported memory*), through which all data were gathered and recorded on an onboard floppy disk. Moreover, data were transmitted via telemetry and used in the ground station for quicklook. A computer compatible with the onboard control computer was available in the ground station on which all software modifications could be carried out and then transferred to the onboard computer using a floppy disk.

The software of the control computer consisted of two parts, the system level and the user level. The system software with real-time control, the input-output operations and pilot information was programmed in assembler programming language to minimize the computing time. The user software with the control laws, the command model and signal conditioning required for the controller was programmed in Fortran and C languages [23].

8.3.5 Ground-Based Simulator and Ground Station

Before the software could be used in flight, it had to be tested on the ground in real time to ensure the compatibility and to avoid extreme control amplitudes. A real-time simulator was, therefore, designed for the complete ATTHeS system, including the actuators and sensors, see Fig. 8.18. A nonlinear helicopter simulation program was implemented on a special simulation computer (Applied Dynamics International AD100), that computed all model elements in a cycle time of 2.5 msec. Thereby simulated signals of sensors and actuators were generated and used as input for a duplicate of the onboard control computer, on which the same software was run as that on the onboard computer.

The ground-based simulator was mainly used for functional testing of the software for the in-flight simulator. Therefore, it was adequate to use a simple cockpit with conventional helicopter controls and a display for the information to the pilot [24]. With this simulation on the ground, engineers and pilots could be trained to handle the in-flight simulator and could check the proper functioning of the software. After successful ground tests, flight testing was envisaged.

The limited space in the helicopter necessitated the construction of a ground station for the engineers as an integral part of ATTHeS system. The ground station contained the following facilities: (1) host computer for onboard systems, (2) PC for continuous recording of telemetry data and presentation of the helicopter position on a local map, (3) two PCs for quicklook representation of ten signals on each, (4) 3-dimensional visualization of the helicopter motion,

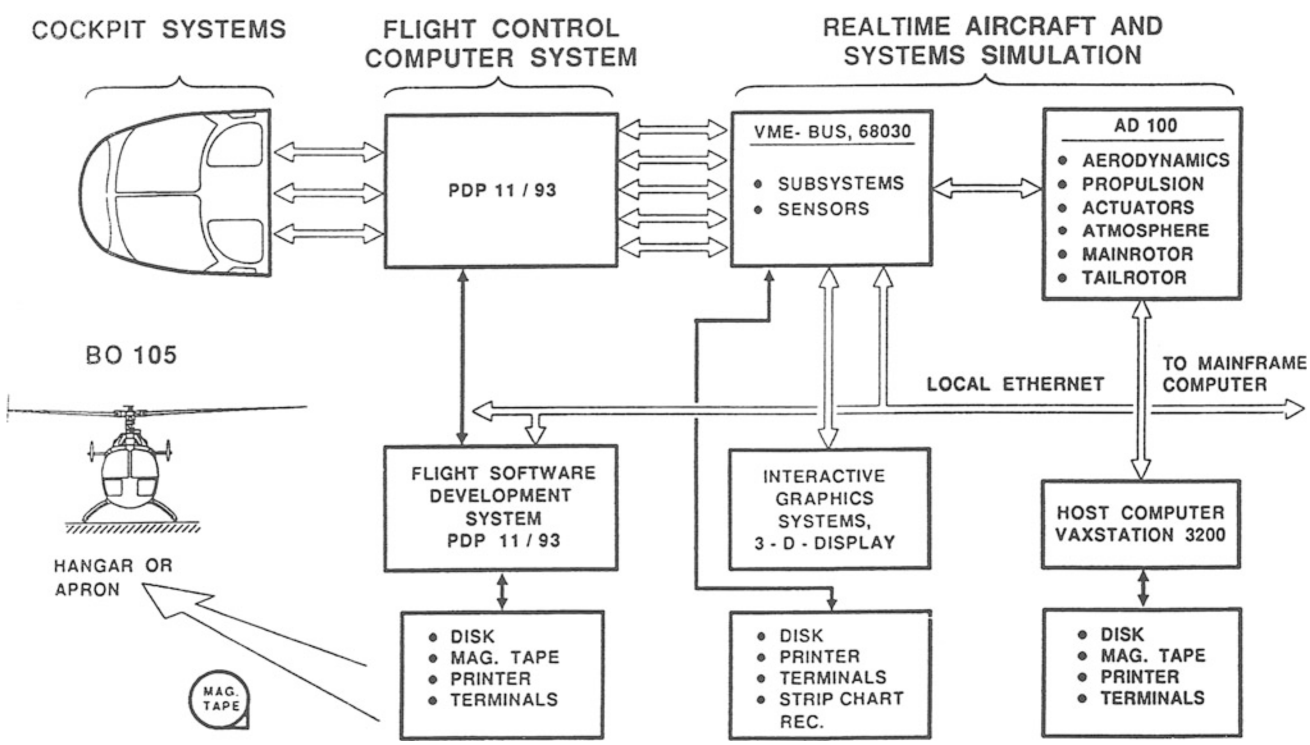

Fig. 8.18 Real time ground based simulation

calculated from the telemetry data, (5) terminal for real-time display of the helicopter position above ground from the laser tracking data, (6) TV monitor to display images from a camera mounted on the tracking antenna, and (7) computer for off-line analysis of flight data. The engineers were able to observe and guide the flight tests from the ground station. Furthermore, the mobile equipment facilitated flight tests at different places outside DLR [25].

The ATTHeS equipment and layout of the ground facilities was implemented at DLR in several successive stages from 1983. Corresponding to the achieved state of these facilities, different utilization programs were planned and carried out, which delivered the first important results, and were also fundamental for the further ATTHeS system expansion. An international symposium on in-flight simulation was held in July 1991 at DLR in Braunschweig, during which the experts shared their experiences, and various test aircraft and their applications were presented and discussed [26]. A special highlight during this period was the first flight over the Brocken in Harz mountains, shortly after the German reunification (Fig. 8.19).

Fig. 8.19 ATTHeS over Brocken in Harz mountains

8.4 Utilization Programs

8.4.1 Flying Qualities Investigations

8.4.1.1 Variation of Control Characteristics

After equipping the Bo 105-S3 with the necessary sensors, data processing, and digital computer for actuators control (see Sect. 8.3), first flights with digital control were conducted starting March 1983. Thereby the influence of the control characteristics on pilot workload was investigated during certain flight tasks. For example, the damping and control sensitivity in the roll axis were varied to assess the helicopter dynamic properties during flying close to the ground around obstacles ("*slalom task*"). Figure 8.20 shows results of this evaluation compared to previous studies [27]. Heretofore, appropriate data with high control sensitivity were not available for helicopters.

8.4.1.2 Contributions to Flying Qualities Criteria

One of the key objectives of flight mechanics research is to provide reliable data for the definition of flying qualities guidelines. The certification criteria for civil helicopters, for example, the documents CS-27 and CS-29 of EASA (*European Aviation Safety Agency*), contain general requirements pertaining to control and stability in order to ensure flight safety at all flight conditions. In the current guidelines for military helicopters, for example, ADS-33E-PRF of the US Army [28], detailed quantitative and qualitative criteria for the completion of a particular task or mission are defined in addition, the so-called mission-oriented flying qualities criteria. They also account for the integration of modern cockpit equipment and control systems, as well as flights under limited visibility conditions [29].

Development of new flying qualities guidelines was pursued by the US Army/NASA from roughly 1980 onwards, once the shortcomings of the flying qualities requirements

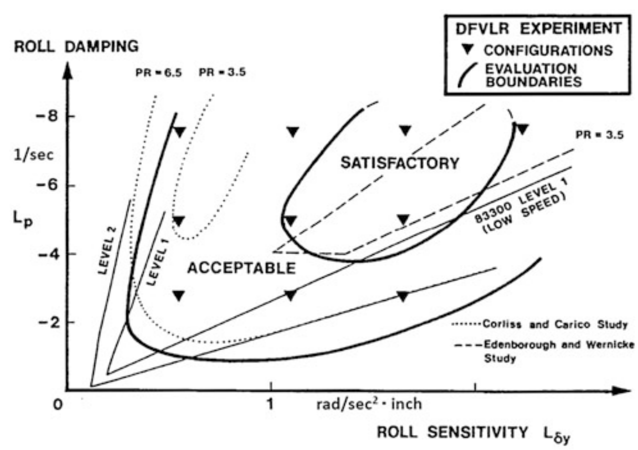

Fig. 8.20 Assessment of roll control sensitivity

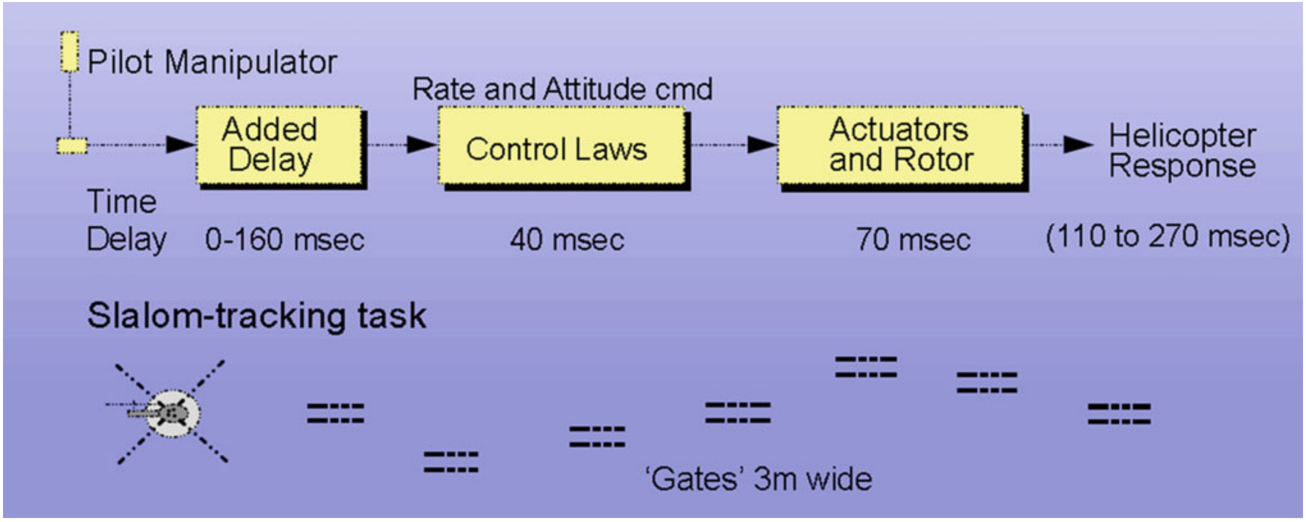

Fig. 8.21 Slalom tracking course

MIL-H8501, which were applied to military helicopters since 1952, were discussed sufficiently and established. An essential prerequisite for this purpose was the availability of an adequate, systematic and reliable data base. In order to generate this, collaboration was sought with other research organizations and institutions. The Flight Research Laboratory of National Research Council (NRC) in Canada (see also Sect. 5.3), the Royal Aircraft Establishment (RAE) in the UK and the Institute of Flight Mechanics of DFVLR supported the proposition in the subsequent years through flight test data and scientific contributions [30].

In collaboration with the US Army, systematic tests were carried out to verify and optimize the new flying qualities criteria. For this purpose, the ground-based simulator VMS (*Vertical Motion Simulator*) of NASA and the in-flight simulator ATTHeS were deployed complementarily (see also Sect. 12.3.3). As an outcome of this effort, important key data were generated and insights gained for the new *Aeronautical Design Standard* ADS-33. Flight tests with ATTHeS have significantly contributed to this joint venture [31].

Time delays appearing in helicopter response to pilot control inputs, for example, due to computational times in the control computer or by run-times in the control system, can lead to undesirable and dangerous couplings between the pilot and the helicopter (*Rotorcraft-Pilot-Coupling* - RPC) during difficult maneuvers [32]. To investigate these effects, a flight test was planned in which several pilots flew a slalom course defined by markings on the ground (see Fig. 8.21). The suitability of the helicopter characteristics for this particular task was rated based on the standardized *Cooper-Harper* scale. Along the marked course so-called tracking phases through the 3-meter-wide gates alternating with transition phases, which required rather lower frequency control inputs. The deviations from the prescribed flight path were measured with a laser tracking system. Following each evaluation phase, the properties of ATTHeS were systematically varied. Additional delays in the helicopter response up to 160 msec could be inputted and different controller characteristics were programmed. Figure 8.22 shows the time histories of a test flight with an attitude command controller and an additional time delay of 160 msec. The individual phases can be clearly observed in the pilot control and in the roll attitude, also the strong dynamic in the control while flying through the gates due to RPC ("*pronounced RPC situation*"). The pilot commented on the flight as follows: "roll, pilot induced oscillation" and "very poor configuration". He assessed the flying qualities as objectionable with tolerable deficiencies, whereby adequate flight operation could be achieved only with considerable pilot compensation.

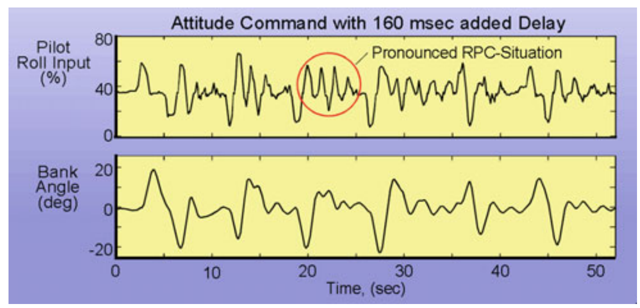

Fig. 8.22 Flight tests with additional time delay

For such high precision tracking flight tasks, for example during landing, or during target tracking, two parameters are of prime importance, namely phase delay and bandwidth of the helicopter response to pilot control inputs. The correlation of both parameters could be determined from the systematic ATTHeS flight tests for this flight task. The DLR

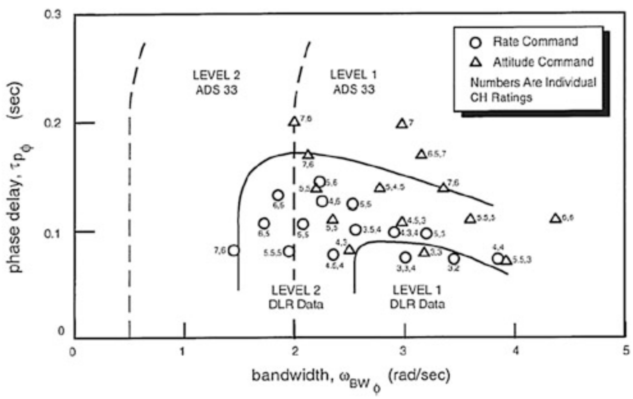

Fig. 8.23 Flight test data for new flying qualities criteria

data and the changed boundary curves between the flying qualities levels "satisfactory without improvement" (Level 1), "acceptable, warrant improvement" (Level 2), and "unacceptable, improvement required" are depicted in Fig. 8.23 [33]. The criteria in *Aeronautical Design Standard ADS-33* were modified based on these results.

Because of the specific properties of the Bo 105 and because of the flexible model following control system and the modular equipment, the in-flight simulator Bo 105 ATTHeS played a significant role in the formulation and verification of the new criteria, which are meanwhile applied worldwide to define and assess the mission-oriented flying qualities of military and also civil helicopters [34, 35].

8.4.2 In-Flight Simulation of Other Helicopter Types

The essential purpose of a simulator is manifold, for example, a verification of flying qualities of a helicopter in its design stage or after modifications, optimization of controller and equipment components of existing helicopter, and familiarization and training of pilots. For this purpose, often different simulators are successfully utilized, which are specifically customized for a particular task. In spite of high technical efforts, however, it is not always possible to reproduce realistically all factors in ground-based simulators, in particular the high-stress situation for a pilot in difficult flight phases. This aspect can be investigated more readily with in-flight simulators under realistic flight conditions. But, in fact, the more dangerous and highest stress scenarios at the edges of the flight envelope are best tested first in the ground-based simulator before they are finally evaluated in flight.

For the simulation of different helicopters with ATTHeS, a special linear mathematical model was developed, whose parameters were determined from generic simulation models or from flight tests, applying system identification methods. The nonlinear terms required for a continuous flight with large variations in flight conditions were explicitly programmed. These terms come from coordinated turns, gravitational terms, changes in the trajectory and Euler angles defining the helicopter position in the airspace. In addition, a 4-axis flight controller (*Stability Command Augmentation System*—SCAS) was programmed, with which the investigation of SCAS failures was possible.

As an example, the in-flight simulation of the helicopter Westland Lynx is presented. Due to the opposite direction of rotor rotation (clockwise as seen from the top), this helicopter has different coupling properties compared to the Bo 105 host helicopter of ATTHeS. Figure 8.24 shows an acceleration/deceleration maneuver at a constant altitude and constant heading. The speed was varied by changing the pitch attitude. The control inputs of the simulation pilot and the ATTHeS-actuator activity (= output of MFCS) show significant deviations, except for the collective control (graphs on the right). The reason for this deviation is attributed to opposite coupling of pitch rate due to collective input in the case of Lynx helicopter compared to the Bo 105. All the ATTHeS flight variables agreed well with those commanded of the Lynx model (graphs on the left-hand side). The pilots assessed the ATTHeS in-flight simulation as a representative of the Lynx helicopter [36].

Figure 8.25 depicts a case of control system failure in the simulated helicopter. In a right turn, after 10 sec in Fig. 8.25, the longitudinal SCAS malfunctions, and as a consequence the pitching motion is now unregulated and unstable, as is the case with most helicopters. After another 10 sec, the activity of the simulation pilot in the longitudinal control increases considerably, the Lynx helicopter starts to oscillate about the pitch axis. Even this situation could be replicated exactly with ATTHeS and was assessed by the pilots as representative of the real flight case.

8.4.3 Fault Tolerant Computer System (DISCUS)

The future demands on the spectrum of helicopter operations necessitate integrated digital flight guidance/flight control systems with full control authority. Such systems have to meet the same or higher demands on operational safety as in the case of conventional mechanical-hydraulic controls. Safety in this context implies fault tolerance, which can be achieved by multiple duplications with appropriate redundancy management for failure detection and elimination. In the DISCUS project (*Digital Self-healing Control for Upgraded Safety*), MBB and Liebherr-Aero-Technik, together with DLR, have developed systems with fault-tolerant features. These were implemented and flight tested with ATTHeS [37].

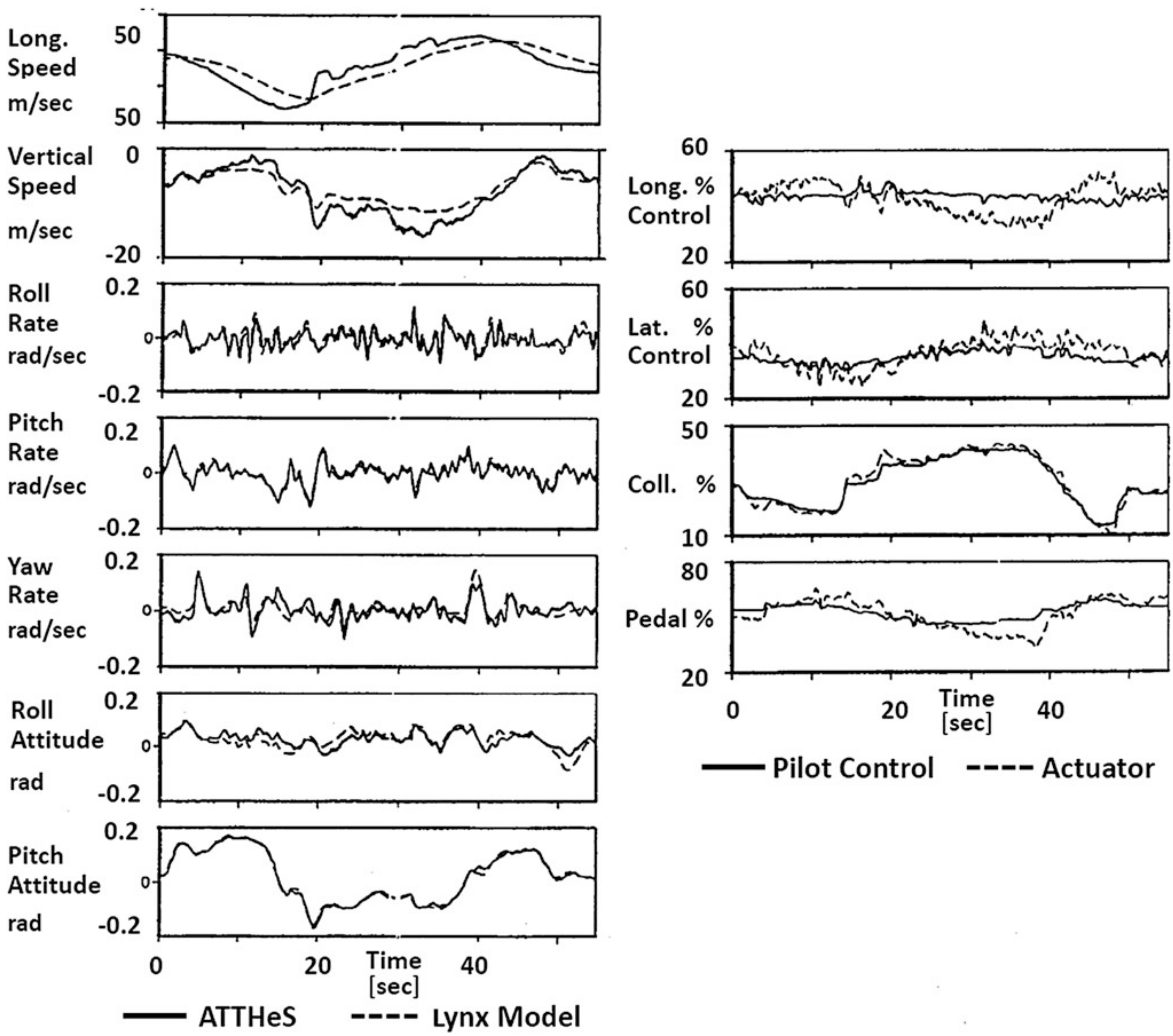

Fig. 8.24 ATTHeS simulation of Lynx helicopter

One of the essential building blocks of the system was the DISCUS computer, a fault-tolerant modular multiprocessor system (see Fig. 8.26). The ability of the computer to detect a first fault or failure, to isolate, to display and to overcome them (*One-Fail-Operational capacity*) could be accomplished by a triplex structure. Each computer channel was housed in its own casing, and the failure detection was ensured by a majority decision between the three identical channels (see Fig. 8.27). The data exchange between the parallel computer channels was by means of optical communication. Thereby the interferences due to other electromagnetic signals could be eliminated [37].

The realization of the flight control computer DISCUS featuring the required degree of redundancy and its testing in flight broke new ground at that time (before 1990). Thereby important insights could be obtained into the redundancy structure, fault tolerance and failure detection of flight critical systems [9].

8.4.4 Design of Flight Controllers

8.4.4.1 Yaw Controller for Pilot Workload Reduction

Using the tail rotor control modifications in the Project OPST1 (see Sect. 8.3.2) and the DISCUS computer (see Sect. 8.4.3), a yaw controller was developed, integrated and tested in ATTHeS jointly by MBB, LAT, and DLR. The objectives of the project were: (1) to improve the accuracy of helicopter control, (2) to reduce the interferences, for

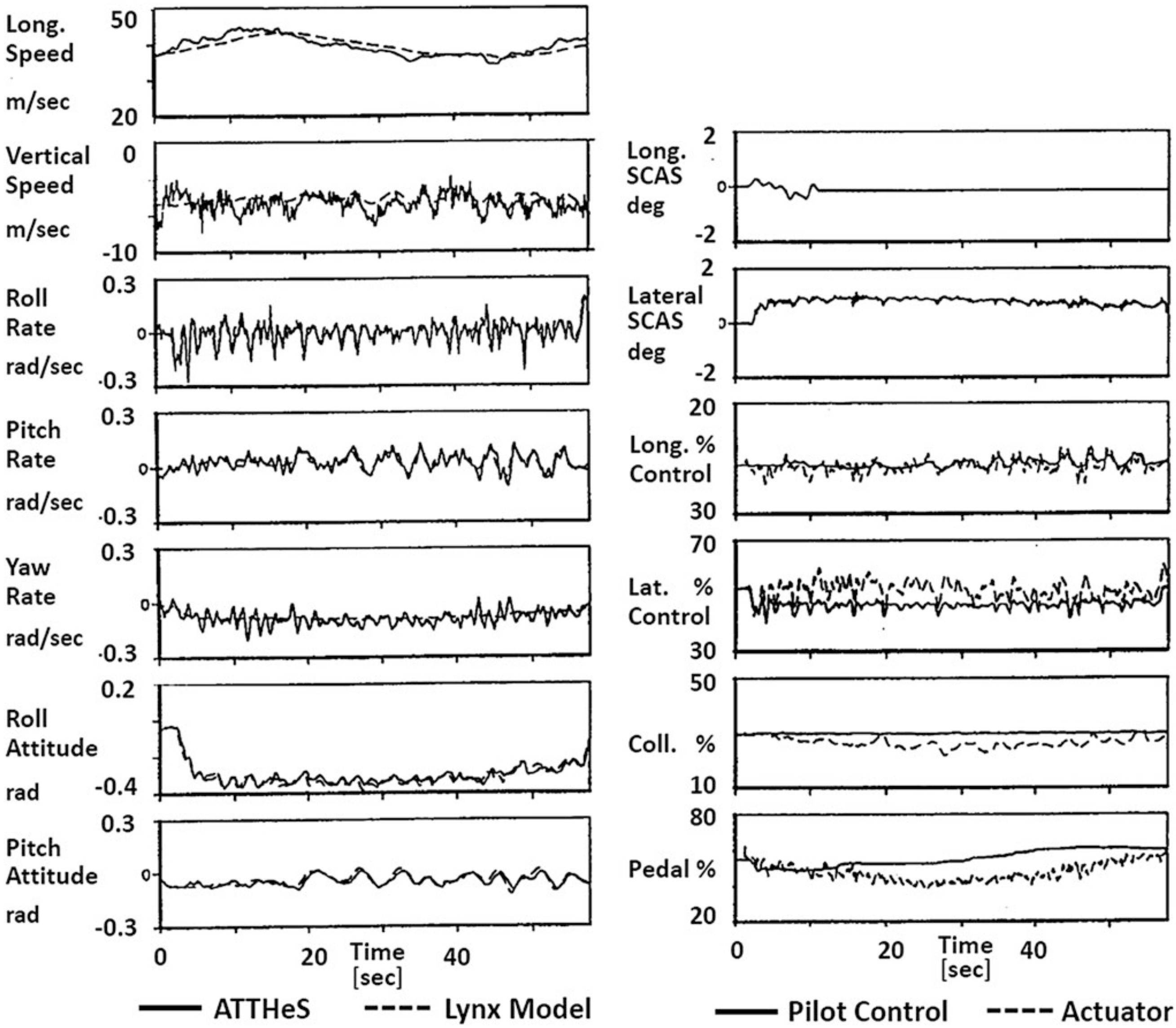

Fig. 8.25 SCAS failure in Lynx Model

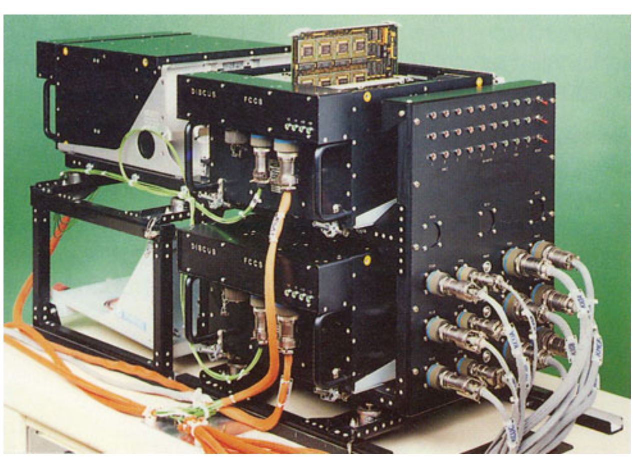

Fig. 8.26 Airworthy hardware of fault tolerant DISCUS computer

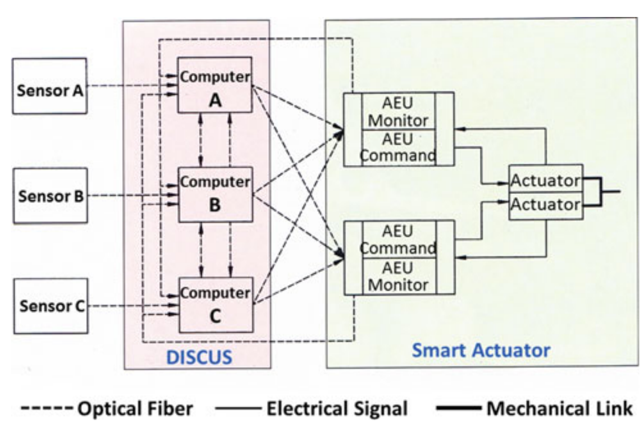

Fig. 8.27 Redundancy structure of DISCUS system

example, caused by strong gusts, and (3) to minimize the coupling between pilot collective control inputs and the helicopter yawing motion. Thereby the pilot could be significantly relieved, especially in difficult flight tasks and under bad weather conditions. The high actuation authority for the yaw controller, necessarily required to meet these objectives, demanded adequate fault tolerance of the entire yaw control system. According to the redundancy structure shown in Fig. 8.27, with the exception of the actuator and the hydraulic energy supply, all elements of the yaw control were tripled. They included the position encoders for actuation commands for the collective blade pitch angle on the main rotor, pedal position encoder for blade angle of the tail rotor, rate gyro to measure the yaw rate, control computer, and electric power supply.

The flights for testing and optimization of the systems took place during 1989 in Braunschweig. Several pilots evaluated the flying qualities in terms of the desired reduction of workload during difficult flight phases and maneuvers. The helicopter cockpit was equipped with electronic displays so that commands could be easily displayed, which the test pilot had to follow in accordance with the defined task (see Fig. 8.28).

The flight test data in Fig. 8.29, pertaining to a hover while maintaining the heading in the presence of crosswinds from left (wind 17 knots from 190°), clearly illustrate that the pilot required significant pedal control inputs to maintain the course with the unregulated helicopter. After switching on the yaw controller, pedal inputs were not required. The controller takes over the tasks of minimizing the course deviations and reducing the yaw rates resulting from disturbances. The targeted pilot workload reduction was confirmed by their comments [38].

Fig. 8.28 ATTHeS Cockpit with primary-flight-display and NAV-display

8.4.4.2 Autopilot Functions

Control systems with autopilot functions are increasingly installed in modern, especially the larger helicopters. For research in this field with ATTHeS, a corresponding navigation task was defined, namely to fly autonomously, at constant altitude and airspeed, a predefined course marked by fly-over-points.

The existing explicit command model, including speed command and attitude hold in forward flight, was extended by controllers for altitude, airspeed, and heading. A software module was programmed and integrated in the onboard computer, that computed the heading command as a function of the current and desired position and the actual wind using a wind estimator and GPS data. The fly-over-points and the resulting flight path in the vicinity of Braunschweig are illustrated in Fig. 8.30. The flight was carried out autonomously (with safety pilot) at constant altitude and airspeed, without pilot intervention, except pressing a button to initialize the system. The flight tests took place in 1993 [39].

8.4.4.3 Position Hold

The design of flight controllers for helicopters in hover or at low speeds is an essential prerequisite for expansion of flight operations, such as the police operation, rescue flights or offshore supply flights. A specific task is maintaining the helicopter position over a fixed or moving target in the presence of wind and gusts, such as over a ship deck or a lifeboat in stormy seas.

For these investigations, ATTHeS was equipped with an innovative measurement system for hovering over a target. A video camera and a computer for processing the optical information was used as an integrated sensor to determine the helicopter position relative to the target. The existing ATTHeS model following control system was modified for the requirements of position hold. In a helicopter in hover, the longitudinal and lateral accelerations can be controlled by variations in the pitch and roll attitude. Additional terms were necessary in the MFCS equations for position hold, which formulated the relations between the commanded pitch and roll attitude changes, the helicopter position relative to the target, and the corresponding speeds.

Before the first flight tests for position hold, the hardware and software were integrated and tested under real-time conditions in the ground-based simulator (see Sect. 8.3.5). The video camera on the helicopter pointing downwards captured the target, which was represented by a moving car.

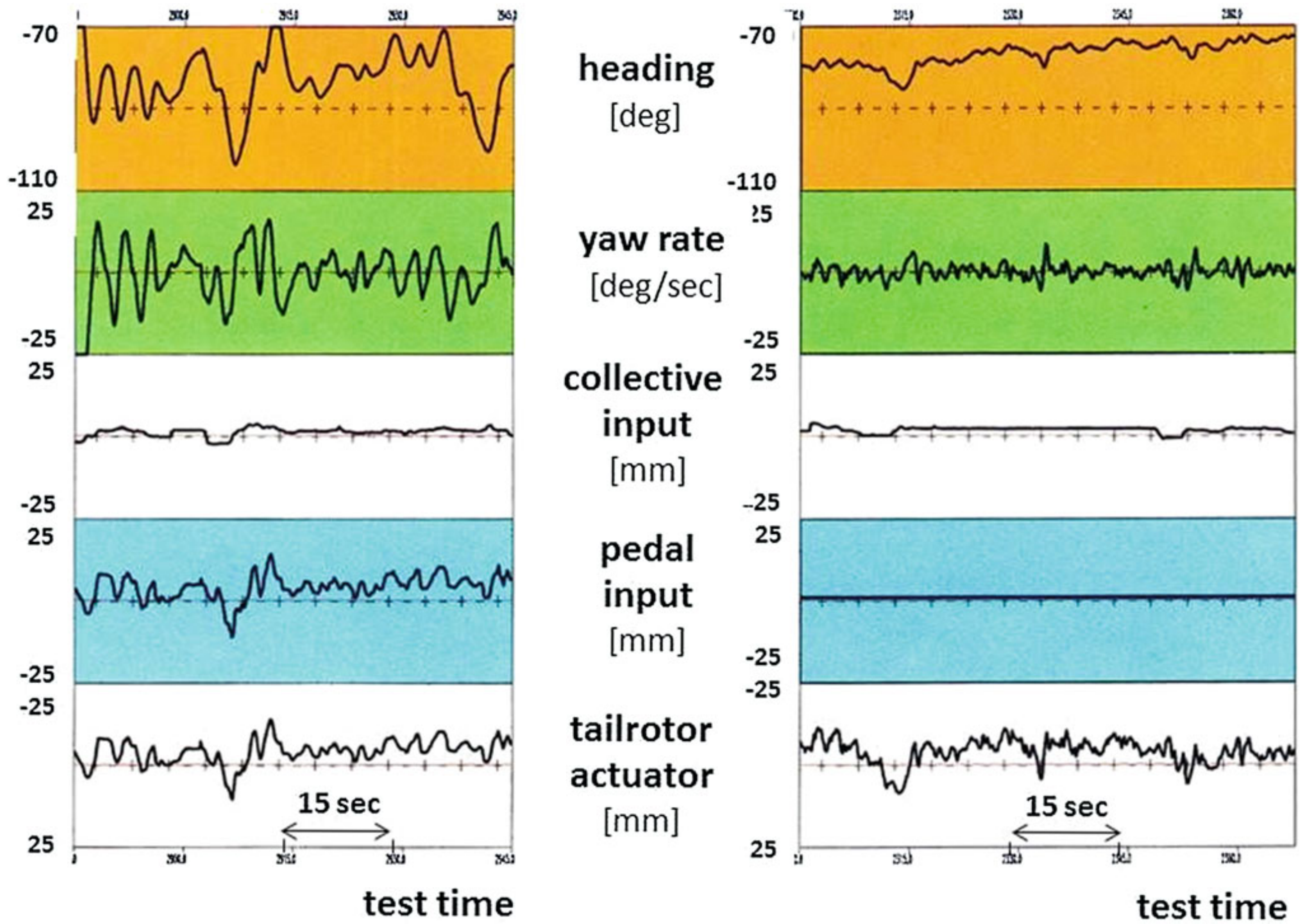

Fig. 8.29 Course hold in hover during wind from left; without controller on *left side*, and with controller on *right*

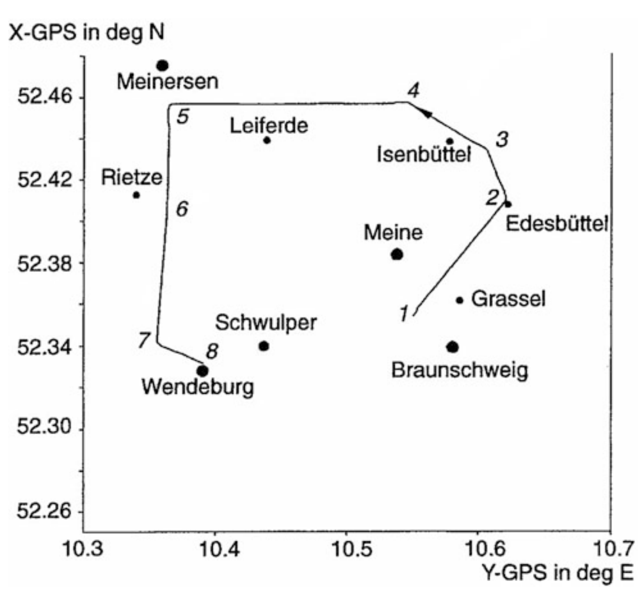

Fig. 8.30 Autonomous flight path control (fly-over points and track)

The camera signals were analyzed in the onboard computer, which then provided the control computer with position data of the vehicle. The control system steered the "observing" helicopter so that it flew directly over the target and followed the target movements at constant height and constant heading, without any pilot intervention (see Fig. 8.31). The flight tests took place in March 1994, with a public demonstration on March 16, 1994, partly under stormy weather conditions (15 knots of wind with gusts up to 30 knots, see Fig. 8.32). The vehicle on the ground drove in circles of about 40 m radius at a constant speed. Once the pilot had activated the system, ATTHeS followed autonomously the target with a standard deviation of not more than 1.6 m. Figure 8.33 shows the time histories of the x and y position coordinates and the pilot controls dx and dy, which were not operated manually during the test flight [40]. Corresponding flight tests with autonomous flying were unknown until then, and as such, the demonstration with ATTHeS attracted attention worldwide.

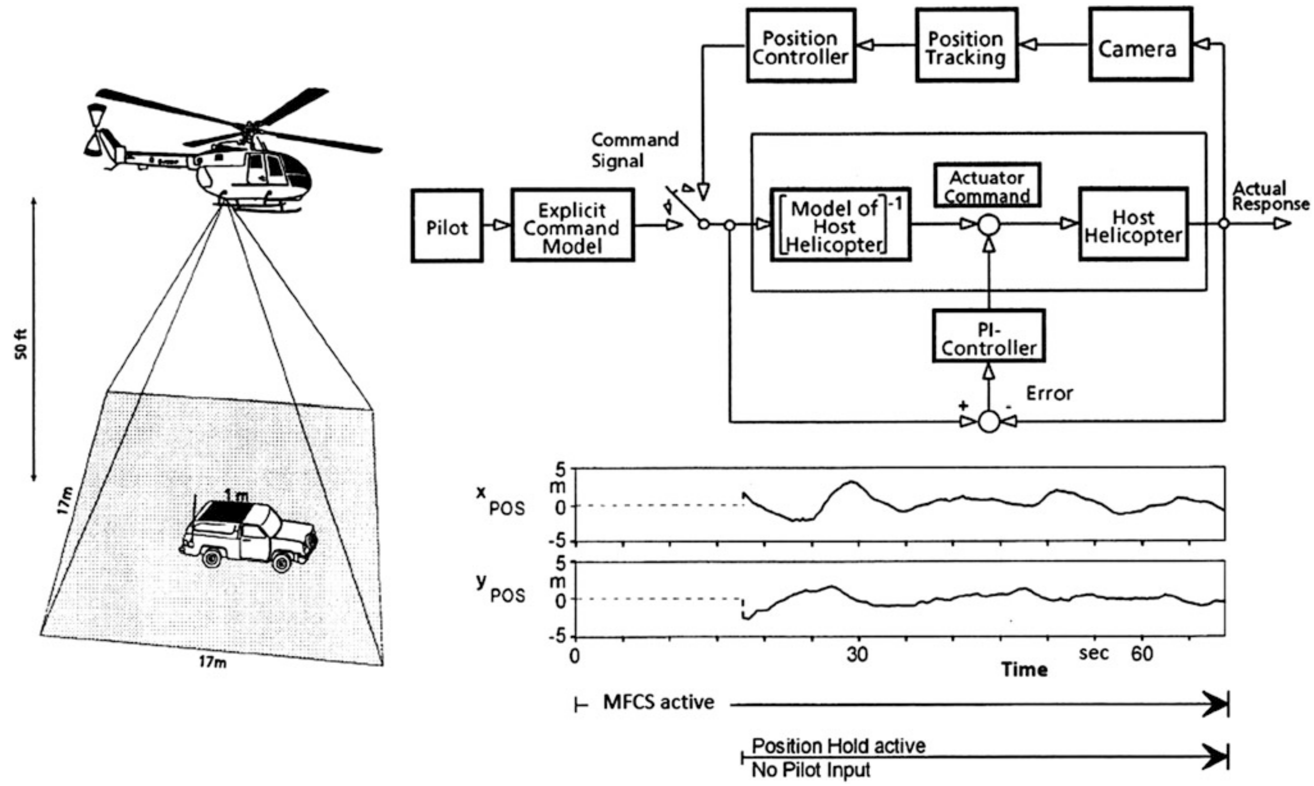

Fig. 8.31 Test flight for position hold (experimental arrangement)

8.4.5 Test Pilot Training

In cooperation with the English Empire Test Pilots' School (ETPS), ATTHeS was deployed for test pilot training since 1990, and also together with the French Ecole du Personnel Navigant d'Essais et de Réception (EPNER) since 1992 (see Fig. 8.34).

In both the cases, the prospective test pilots flew ATTHeS in various configurations without stabilization, for example, with different damping control sensitivity, and time delays. Furthermore, different controller functions and control couplings were tried out and finally also critical flight conditions with RPC effects (Rotorcraft Pilot Coupling) [32]. Following the description in Chap. 3, the aim of the training was to evaluate the configurations and to identify and avoid critical situations. Because of the ATTHeS flexibility, it was feasible for trainee pilots to test a wide range of possible flying qualities in a short time. Figure 8.35 shows a group of ETPS test pilots together with DLR staff members. These training courses were conducted in Braunschweig as well as in Boscombe Down, England, for ETPS, and in Braunschweig for EPNER.

8.4.6 Statistics of Utilization

The projects described in the foregoing demonstrate the flexibility and versatility of the in-flight simulator Bo 105-S3 ATTHeS. In addition, there are a variety of different projects that would not have been possible without ATTHeS [41].

As part of the European project ACT (*Active Control Technology*), flight tests with ATTHeS were performed in 1994 with an active sidestick, which was installed in place of the conventional controls. Various flight characteristics were investigated during pre-defined flight tasks.

In cooperation with the French research organization ONERA, flight tests with ATTHeS were carried out in 1995 to investigate the flying qualities in hover. The flight task consisted of tracking a moving vehicle as precisely as pos-

Fig. 8.32 Autonomous position hold in hover (*Credit* Braunschweiger Zeitung)

sible in a sideward flight. This task was to be accomplished by the test pilots with different preprogrammed helicopter flying qualities [42].

Altogether, ATTHeS was deployed at DLR from 1982 to 1995 for more than 1300 flight hours. Figure 8.36 shows the statistics of utilization and provides an overview of the numerous modifications and additions to the equipment, as well as of the various utilization and demonstration programs. The work carried out at DLR with ATTHeS and the unique flight test data are documented in numerous scientific publications of the DLR and of the partners, and were highly appreciated and utilized by the international research institutions and industry. Figure 8.37 shows a group of visitors at the DLR in June 1993 with senior representatives from ministries and industry, rightmost *Klaus Sanders*, a highly experienced safety pilot and engineer for many years at DLR, who provided significant contributions to the projects and flew as a reliable safety pilot in many flight tests with Bo 105 ATTHeS (see also Sect. 8.1).

Due to the age and other restrictions of the Bo 105-S3, and long before the ATTHeS crashed on May 14, 1995, DLR had initiated a new in-flight simulator [43, 44]. In the following years, this initiative evolved into the project ACT-FHS (*Active Control Technology Demonstrator – Flying Helicopter Simulator*) as a joint venture of the German Federal Ministry of Defense, the DLR and the industry (Eurocopter Germany, Liebherr Aerospace). This Flying Simulator was realized starting from 1996 based on a EC 135 helicopter and is since 2002 available at DLR for European research organizations and industry as a unique flying device for technology testing and demonstration (see Chap. 10).

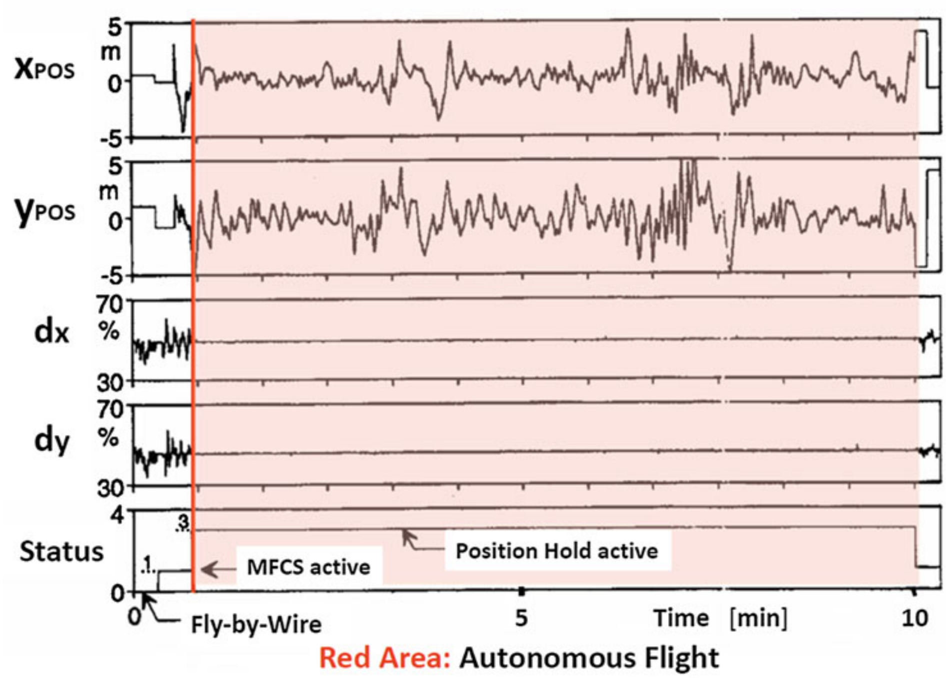

Fig. 8.33 Test flight for position hold (measurement protocol)

Fig. 8.34 Training of future EPNER pilots

Fig. 8.35 Training course with ATTHeS for ETPS pilots

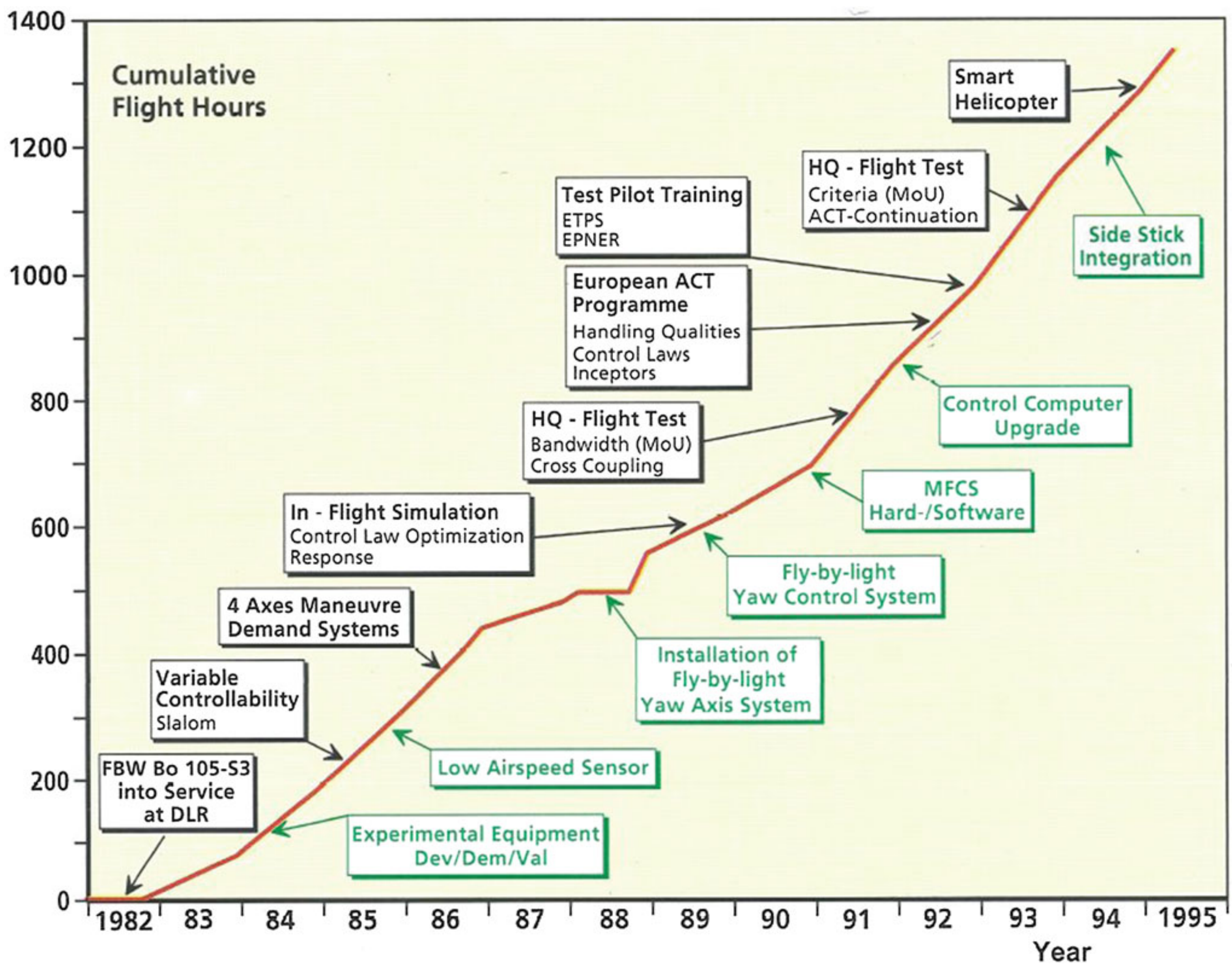

Fig. 8.36 Statistics of ATTHeS utilization

Fig. 8.37 Group of visitors at DLR (from *left*: *E. Eckert*, *B. Gmelin*, *H. Huber*, *F. Thomas*, *K. Schymanietz*, *Ives Richard*, *P. Hamel*, *H.-J. Pausder*, *L. Müller*, *Ph. Roesch*, *M. Rössing*, *J. Kaletka*, *K. Sanders*)

References

1. von Gersdorff, K., Knobling, K., (Ed.): Hubschrauber und Tragschrauber. Bernard & Graefe Verlag München (1982)
2. DFVLR e.V., Dornier GmbH, MBB GmbH: Versuchsträger Variabler Stabilität—Mittelfristiges Programm—Memorandum für das Bundesministerium der Verteidigung, Dec 1969
3. Marchand, M., Wilhelm, K.: Flugmechanische Untersuchungen über die Einsetzbarkeit eines Hubschraubers zur Simulation von V/STOL-Flugzeugen, DLR-FB, pp. 75–59, Braunschweig (1975)
4. Janik, K., Schmitt, H.: Hubschrauber BO 105 als Versuchsträger variabler Stabilität—Aufgabenstellung und Realisierungsmöglichkeiten, Symposium über Versuchsträger variabler Stabilität, Manching 12. Juni 1970, MBB-Bericht MBB-DU 52-70-Ö (1970)
5. Derschmidt, H.: Steuerung und Cockpit für BO 105 als Flugversuchsträger, MBB Technische Niederschrift TN D125-2/71 (1971)
6. Attlfellner, S., Rade, M.: Bo 105 in-flight simulator for flight control and guidance systems. In: First European Rotorcraft and Powered Lift Aircraft Forum, Southampton England (1975)
7. Formica, B., König, H., Bender, K., Mansfeld, G.: OPST1—an digital optical tail rotor control system. In: 14th European Rotorcraft Forum, Milano Italy, Sept 1988
8. Mansfeld, G., Bender, K., Holle, K.: DISCUS—Ein fehlertolerantes Fbw/Fbl-Experimentalsystem. DLR-Nachrichten **61**, 6–11 (1990)
9. Hofer, H.: OPST1/ DISCUS, Informationen zu Projektanteilen der Firma Liebherr Aerospace Lindenberg GmbH (2013)
10. König, H., Stock, M., Zeller, S.: OPST1—an optical yaw control system for high performance helicopters. In: 45th Annual Forum and Technology Display of the American Helicopter Society, Boston USA, May 1989
11. Tischler, M.B., (Ed.): Advances in Aircraft Flight Control. Taylor & Francis (1996)
12. Key, D.L., Gmelin, B.: A Decade of Cooperation. American Helicopter Society, September/October, Vertiflite (1989)
13. Bouwer, G., Hilbert, K.B.: A Piloted Investigation of Decoupling Helicopters by Using a Model Following Control System, 40th Annual Forum of the American Helicopter Society, Paper No. A-84-40-07-4000, Arlington Virginia USA, May 1984
14. Hilbert, K.B., Lebacqz, J.V., Hindson, W.S.: Flight Investigation of a Model-Following Control System for Rotorcraft, AIAA 3rd Flight Testing Conference, Las Vegas Nevada, Apr 1986
15. Kaletka, J., von Grünhagen, W.: Identification of mathematical derivative models for the design of a model following control system. In: 45th Annual Forum & Technology Display of the American Helicopter Society, Boston USA, May 1989
16. von Grünhagen, W., Kaletka, J.: Application of system identification for rotorcraft control system design, 4. In: Braunschweiger Aerospace Symposium "Sicherheit im Luftverkehr", Technische Universität Braunschweig, Sept 1994

17. Pausder, H.-J., Bouwer, G., von Grünhagen, W.: A highly maneuverable helicopter in-flight simulator—aspects of realization. In: 14th European Rotorcraft Forum, Milano Italy, Sept 1988
18. Pausder, H.-J., Bouwer, G., von Grünhagen, W.: ATTHeS in-flight simulator for flying qualities research. In: In-Flight Simulation for the 90's, International Symposium, DLR Braunschweig, DGLR Conference Proceedings, Paper 15, Braunschweig (1991)
19. Bouwer, G., Pausder, H.-J., von Grünhagen, W.: ATTHeS, a helicopter in-flight simulator with high bandwidth capability. In: 48th Annual Forum and Technology Display of the American Helicopter Society, Washington DC USA, June 1992
20. Huber, H., Hamel, P.: Helicopter flight control—state of the art and future directions. In: 19th European Rotorcraft Forum, Cernobbio Italy, Sept 1993
21. von Grünhagen, W., Bouwer, G., Pausder, H.-J., Henschel, F., Kaletka, J.: A high bandwidth control system for a helicopter in-flight simulator. Int. J. Control **59**(1) (1994)
22. Hamel, P.: Advances in aerodynamic modeling for flight simulation and control design. GAMM-Mitteilungen **2000**(1–2), 7–50 (2000)
23. Gmelin, B., Bouwer, G., Hummes, D.: DFVLR Helicopter In-Flight Simulator for Flying Quality Research, Vertica, Pergamon Press, Vol. 10, No. 1 (1986)
24. Gmelin, B., Bouwer, G.: Development and Application of Helicopter In-Flight Simulation at DLR, La Recherche Aérospatiale No. 1, pp. 59–72 (1995)
25. Pausder, H.-J., Bouwer, G., von Grünhagen, W., Holland, R.: Helicopter In-Flight Simulator ATTHeS—A Multipurpose Testbed and its Utilization, AIAA/AHS Flight Simulation Technologies Conference, Hilton Head Island SC USA, Aug 1992
26. Hamel, P., (Ed.): In-Flight Simulation for the 90's, International Symposium, DLR Braunschweig, DGLR Conference Proceedings, pp. 91–05 (1991)
27. Pausder, H.-J.: A study of roll response required in a low altitude slalom task. In: 11th European Rotorcraft Forum, London UK, September 1985
28. Anon.: ADS-33E-PRF, Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft. United States Army Aviation and Missile Command, Aviation Engineering Directorate, Redstone Arsenal, Alabama, 21 Mar 2000
29. Gmelin, B., Pausder, H.-J., Hamel, P.: Mission-Oriented Flying Qualities Criteria for Helicopter Design via In-Flight Simulation, AGARD-CP-423, Paper 4 (1987)
30. Pausder, H.-J., Bouwer, G.: Recent results of in-flight simulation for helicopter ACT research. In: 15th European Rotorcraft Forum, Amsterdam The Netherlands, Sept 1989
31. Ockier, C.J., Pausder, H.-J.: Experiences with ADS-33 Helicopter Specification Testing and Contributions to Refinement Research, AGARD-CP-560, Paper 4 (1995)
32. Hamel, P.: Rotorcraft—Pilot Coupling, A Critical Issue for Highly Augmented Helicopters?, AGARD-CP-592, Paper 21 (1997)
33. Pausder, H.-J., Blanken, C.L.: Investigation of the effects of bandwidth and time delay on helicopter roll-axis handling qualities. In: 18th European Rotorcraft Forum, Avignon France, Sept 1992
34. Padfield, G.D.: Rotorcraft handling qualities engineering—managing the tension between safety and performance, AHS Alexander Nikolsky lecture. In: 68th Annual Forum and Technology Display of the American Helicopter Society, Fort Worth Texas USA, May 2012
35. Bouwer, G., von Grünhagen, W., Pausder, H.-J.: Model Following Control for Tailoring Handling Qualities—ACT Experience with ATTHeS, AGARD-CP-560, Paper 11 (1995)
36. Bouwer, G., von Grünhagen, W.: LYNX Helicopter In-Flight Simulation with ATTHeS, DLR-IB 111–92/47, Braunschweig (1992)
37. Bender, K., Leyendecker, H.: Untersuchungen zu einem Fehlertoleranten Hubschrauber-Flugregelungssystem mit Abgestufter Redundanz, DLR-Mitteilung, pp. 97–01. Braunschweig (1997)
38. Mansfeld, G., Bender, K., Tersteegen, J.: Entwicklung und Flugerprobung eines fehlertoleranten Fly-by-Light Gierregelungs-systems. DGLR-Fachausschuß-Sitzung Flugeigenschaften. Flugregelung, Braunschweig (1991)
39. Hamers, M.: Vollautomatische Navigation mit ATTHeS, DLR-IB 111-94/16 (1994)
40. Bouwer, G., Oertel, C.-H., von Grünhagen, W.: Autonomous helicopter hover positioning by optical tracking. Aeronaut J, **99** (984) (1995)
41. Bouwer, G., Pausder, H.-J.: Fliegende Simulation mit Hubschraubern. In: Luftfahrtforschung in Deutschland. Bernard & Graefe Verlag Bonn (2001)
42. Bouwer, G., Taghizad, A., Mödden, H.: ONERA and DLR Cooperation on the Smart Helicopter Concept—Handling Qualities Data Base for Hover and Low Speed Flight, AGARD-CP-592, Paper 11 (1997)
43. Anon.: HESTOR—Entwicklung eines Fliegenden Simulators für Hubschrauber, Rahmenvorschlag, MBB/DFVLR, June 1984
44. Gmelin, B., Kissel, G., Mansfeld, G.: Key Technologies for a New Flying Helicopter Simulator. In: In-Flight Simulation for the 90's, International Symposium, DLR Braunschweig, DGLR Conference Proceedings, Paper 7 (1991)

Author Biography

Bernd Gmelin was a research scientist and head of the Rotorcraft Department at the Institute of Flight Mechanics of DLR at Braunschweig (1973–1999). From 1999 to 2006 he headed the DLR Helicopter Program under the German/French DLR/ONERA Common Rotorcraft Research Program. Prior to joining DLR, he was a researcher at the Institute for Rotorcraft in Stuttgart (1968–1973). He received his Dipl.-Ing. degree in Aerospace Engineering from the University of Stuttgart (1968). His primary interests are mathematical modeling, helicopter simulation in the wind tunnel, control systems, flying qualities, helicopter in-flight simulation. He is a member of the German Society for Aeronautics and Astronautics (DGLR) and of the American Helicopter Society (AHS). He is the recipient of the AHS Agusta International Fellowship Award (1996), DLR/ONERA Team Award (2006), and AHS Fellow Award (2008).