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**RECENT RESULTS OF IN-FLIGHT SIMULATION
FOR HELICOPTER ACT RESEARCH**

BY

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Abstract

The next generation helicopters, for both civil and military applications, will utilize integrated Active Control Technology (ACT). The implementation of ACT allows the departure from the classical design constraints and enables essential improvements for the conventional helicopter including an increased mission efficiency and a reduction of pilot workload. This can be achieved by tailoring the helicopter system dynamics to the demands of the flight task and to the capability of the human pilot.

The DLR has developed the helicopter in-flight simulator ATTHeS (Advanced Technology Testing Helicopter System) which is based on a BO 105 helicopter. In-flight simulators play an unique role in the ACT development with the phases design, integration, and evaluation. In addition, the realization of an in-flight simulator includes the realization of a full authority digital flight control system. Many aspects which have been considered in the in- flight simulator development can be transfered to the ACT development for operational use.

The explicit model following control system for ATTHeS is based on a feedforward and a feedback controller. The design of the feedforward controller has been emphazised especially to achieve a quick model following response with low gains in the feedback loops. In addition to the digital controller, the pilot controller dynamics, the actuator dynamics, and the signal conditioning are contributing to the MFCS performance. The effects of these ACT components are discussed. The overall system has been verified in flight tests. The achieved low time delay in the initial response, the grade of decoupling the host helicopter, and the acceptable long term model following demonstrate the simulation capability of the ATTHeS.

1. Introduction

The worth and benefits of the application of active control technology (ACT) have been well demonstrated for the fixed wing aircraft in a range of research and operational vehicles. The utilization of ACT inheres the potential in the design phase of an aircraft to increase its operational capabilities and to improve the piloting performance. The lessons learned from application in fixed wing vehicles are that the adaption of the ACT to the basic vehicle chararacteristics and the strong interrelations to other subsystems are of high influence on the integrated system performance.

The demand to improve the mission efficiency of helicopter systems and, at the same time, to reduce the workload of the pilots, is the driving influence in ACT development and implementation for the next generation of helicopters. The experiences with ACT in fixed wing aircraft have to be considered carefully to avoid unnecessary and misleading interferences but, however, these experiences cannot be crossfed directly to the helicopter. The basic helicopter has its specific and essential aspects. It is dynamically more complex due to a high level of interaxis coupling and the high order dynamics of the rotor systems. The flight envelope of helicopters includes an airspeed range between hover and forward flight with a drastic change in the stability and control characteristics. Modern missions require to fly the helicopter in agile maneuvers close to the ground and close to the obstacles of the terrain which involves a high demanding piloting task with an extremly high workload.

In general, ACT can be characterized as all the non-pilot induced automated open and closed loop control. The spectrum of ACT developments includes the two objectives:

(1) Reduction of undesirable motions and dynamical effects (local ACT).

(2) Adjustment of the helicopter flight dynamics (global ACT).

The use of ACT for the adjustment of the flight dynamics is treated in this paper. This technique yields the profit to tailor the integrated helicopter system dynamics to the specific mission demands and the ability of the human pilot. Keeping in mind the obvious aspect, that the pilot is the central element of the overall flying system who has to achieve with the helicopter system the desired mission performance, it has to be accepted that the pilot also plays the central role in the evaluation of the performance of the helicopter. He is the real scale to evaluate the ACT adaption to the helicopter in relation to the demanded mission performance. All elements which interfere with the piloting task are influencing the pilot's evaluation of the ACT acceptance. ACT performance evaluation is an evaluation of the integrated system. A test facility is required which allows a flight examination in an environment with an acceptable fidelity. The main elements of influence which have to be considered in the development of ACT for a helicopter are:

- the basic helicopter response characteristics,
- the ACT components,
- the pilot's controller characteristics, and .the format of information displayed for the pilot.

Figure 1 shows the interrelation of all these elements and their reference to the pilot. The ACT is composed of the components:

- the sensors and the data conditioning for the information,
- the effectors for the actuating, and
- the processors for the computation of the control laws.

2. Role of In-Flight Simulation

The detailed performance requirements for an ACT system and the many dependencies on the other system elements dictate an early-timed introducing of qualified test facilities. The pilot-in-the-loop testing will play an important role in all the development phases for design, integration, and evaluation. To examine the performance and to verify the system adaption, flight tests cannot be renounced. If the prototype helicopter is not available, a usual situation, it has to be replaced by a simulation facility with satisfactory fidelity. The great advantages of an in-flight simulator, compared to a technology demonstrator, are the capacity to vary the system characteristics, and compared to a ground based simulator, to fly the system in the real world with all the hardware elements installed [1].

Additional areas of the utilization of in-flight simulation are more general and basic research related:

- basic research for control law design,
- investigation of the response systems required by the missions,
- establishment of a data base for the definition of evaluation criteria,
- investigation of the interference effects between overall system response, the displayed information for the pilot, and the characteristics of the pilot's controller, and
- requirements for the response systems blending and for failure situations.

The second role of in-flight simulation for the ACT research and development follows from the experiences obtained during the development of an in-flight simulator. The realization of an in-flight simulator includes ACT research and development. The required capability of an in-flight simulator to be able to vary the response characteristics in a broad range and to be adaptable for installing hardware elements and software structures specifically formulates high demands on the control system design. Consequently, many of the lessons learned and the technical solutions can be tranferred directly to the development of ACT for operational helicopters.

3. DLR Helicopter In-Flight Simulator ATTHeS

Recognizing the requests for a flying testbed for an application in the ACT research and development, a helicopter in-flight simulator is under development at the DLR Institute for Flightmechanics. The ATTHeS (Advanced Technology Testing Helicopter System) is based on a BO 105 helicopter (Figure 2).

The next generation of helicopter systems will be flown in missions including agile maneuvers and high gain piloting tasks which have to be performed in an airborne simulation, too. The possibility to cover the required range of dynamic response behavior is limited by the characteristics of the helicopter being the host for the in-flight simulation. The high control power and the quick initial reaction on pilot inputs of helicopters with a hingeless rotor system are an excellent precondition. Correspondingly, the BO 105 helicopter is well suited to be a host for an in-flight simulator. As an example, Figure 3 illustrates the control power and the bandwidth of the BO 105 in the roll axis. The level of interaxis coupling, the high order response, and the level of gust sensitivity induced by the rotor system complicate the design of a full authority digital flight control system.

The test helicopter is equipped with a nonredundant fly-by-wire (FBW) control system which was developed by MBB in the seventies to investigate helicopter control and guidance technology. In the last year the FBW control link for the tail rotor was replaced by fly-by-light (FBL). The testbed requires a two-men crew consisting of the simulation pilot and the safety pilot. The safety pilot is provided with the standard mechanical link to the rotor controls, whereas the simulation pilot controllers are linked electrically/optically to the rotor controls. The FBW/FBL actuator inputs commanded by the simulation pilot and/or by an implemented flight control system are mechanically fed back to the safety pilot's controllers. With this function, the safety pilot is enabled to monitor the rotor control inputs which is an important safety aspect. The safety pilot can disengage the FBW control system by switching off the FBW system or by overriding the control actuators. In addition, an automatic safety system is installed monitoring the limitations of the hub and lag bending moments.

The testbed can be flown in three modes:

- the FBW disengaged mode, where the safety pilot has the exclusive control,
- the 1:1 FBW mode, where the simulation pilot has the full authority over the controls, and
- the simulation mode, where the simulation pilot is flying with full authority a simulated system.

In the 1:1 and simulation mode the flight envelope is restricted to 50 ft over ground in hover and 100 ft over ground in forward flight.

Since 1982 the testbed is operated by the DLR. Up to now, the ATTHeS was used in different test programs by the Institute for Flightmechanics representing approximately 400 flight hours. The flight tests include the two main objectives to study the handling qualities for the definition of evaluation criteria for high level augmented helicopters and to realize model following control systems (MFCS) for in-flight simulation purposes.

The designed MFCS was first implemented in 1985 for an evaluation of the overall system performance and to address the issue of realization the in-flight simulator ATTHeS. To demonstrate the performance and simulation accuracy, different existing helicopters were simulated and rate and attitude command response systems were evaluated in flight [4]. The results show satisfactory simulation fidelity for moderate maneuvering (see Figure 4). The realized MFCS design was based on a feedback network. The achieved bandwidth of the overall system has been estimated with about 3.3 rad/sec in the roll axis as an example. The decrease in the bandwidth of more than 1 rad/sec, compared with the basic helicopter, resulted from additional effective time delays (about 250 msec for the overall simulator system) which are introduced by the MFCS elements. Especially, the frame time, the computational time for the generation of the command model inputs and the refreshing of the actuator inputs, the conditioning of the signals used in the feedback loops, and the shaping of the pilot control inputs produce the total MFCS effective time delays. The desire to use the airborne simulator also for high gain piloting flight tasks forced the redesign of the flight control system. The primary aim of the redesign was to improve the initial response which results in an increased system bandwidth. Therefore the implementation of a feedforward has been emphazised. The adaption of the feedforward to the host helicopter dynamics and the balance between feedforward, feedback loops, and the other ACT elements have been the subjects of the evaluation approach.

4. MFCS Design

The most promising and also challenging method of active control system design to optimize flying qualities of a helicopter is to force the basic vehicle to respond on the pilot's inputs as a commanded model. Model following control is useful when one or more various sets of flight vehicle equations of motions can be specified as the desired commanded models. In principle, two model following control concepts can be distinguished as illustrated in Figure 5. In an implicit model following, the control inputs to the host vehicle are formed from the vehicle response (x), the pilot input (u_p), and the controller. The controller can be composed of a feedback and a feedforward. The commanded model states (x_m) appear only in the performance criterion for the lay-out of the overall system. The command model is implied in the controller which is designed to force the host vehicle to behave like the commanded model ($x = x_m$). Consequently, a variation in the commanded model needs a new adaption and a new design of the controller. For the explicit model following, the commanded model response (x_m) is calculated explicitly from the pilot inputs (u_p) and is fed into the controller. The feedforward controller is calculated from a model of the host vehicle (state matrix A and control matrix B). The controller is not depending on the state and control matrix of the command model. A flight vehicle state feedback (x) is implied to minimize the influence of noise and feedforward inaccuracies and to reduce the tendency of long term drifts in the response.

As a consequence an explicit model following control system is being developed for the ATTHeS in-flight simulator [5]. The advantage for in-flight simulation use is the undependency of the feedforward on the coefficients in the control and state matrices of the commanded model. This yields the flexibility for the variation of the commanded model response behavior. A slightly more detailed MFCS system structure is presented in Figure 6. It represents a simplified model of the host helicopter, the model following controllers, and the other components which essentially contribute to the MFCS performance. For an integrated design the influence of these elements have to be considered, too.

4.1 Feedforward Design

Without taken into consideration the effects of internal and external noise an accurate model following shall be achieved only with the feedforward controller, in a first step. Let the host vehicle be described by the differential equation

$$\dot{x} = A \cdot x + B \cdot u_c \qquad (1)$$

with the state vector x(m), the dynamic matrix A(m,m), the control vector u(n) and the control matric B(m,n). The explicit model follows the equation

$$\dot{x}_m = A_m \cdot x_m + B_m \cdot u_p. \qquad (2)$$

It is assumed, that the model's state vector x_m and and control vector u_m are of the same dimension as the host vehicle vectors.

Starting at an initial condition, where

$$x = x_m = x_{Trim} \qquad (3)$$

the host vehicle and the model are in the same trim condition, a feedforward control has to be calculated, which forces with

$$\dot{x} = \dot{x}_m, \, x = x_m \qquad (4)$$

the host vehicle to behave like the model. Inserting (4) in (2) and solving for u_c yields

$$u_c = B^+ \cdot (\dot{x}_m - A \cdot x_m) \qquad (5)$$

The feedforward control is a function of $u_c = f(B^+, A, \dot{x}_m, x_m)$ where B^+ is a pseudoinverse of the control matrix B. Two general aspects can be stated from this principal functional relationship:

- The feedforward performance is directly depending on the fidelity of the model describing the host helicopter dynamics.
- At least six state variables have to be controlled with only four controls. The host helicopter control matrix cannot be inverted in an exact mathematical way.

The models used for the ATTHeS feedforward calculations are obtained from system identification procedures. The method of system identification is described in detail in [6]. The calculated responses of the defined helicopter model on pilot inputs is compared with the measured responses of the real helicopter. The model coefficients are adjusted by minimizing the differences between model and measured responses using an identification criterion. If the adjusted model can be explained as a "learning" model which has to follow the real helicopter dynamics, system identification can be described as the inverse problem of the model following control design approach. In addition, the accuracy of the measurement is influencing the fidelity of the identified model in a similar way as for the model following performance.

For the MFCS redesign an extended 8 DOF model of the BO 105 in forward flight has been extracted [7] . The increased number of DOF is required to get a satisfactory modelling of the initial responses in the pitch and roll behavior.

$$\dot{x} = (u, v, w, \dot{p}, p, \dot{q}, q, r, \Phi, \Theta)^T$$

The achieved improvement of the model is illustrated in Figure 7. Using only a 6 DOF model for the feedforward calculation includes the tendency of overcontrolling the system after a pilot input because final values for the rotational acceleration responses after a step input are modelled. Alternatively, two concepts are pursued in the feedforward design approach. Both consider the unbalanced number of states to be controlled and the available number of controls in a helicopter. One is using the full model of the host BO 105 helicopter for a pseudoinversion of the control matrix. The influences of zeros in the right half plane are canceled to achieve a minimum phase system. In the other design a state feedback is implemented to achieve a controllable system. The feedforward is based on a reduced model with

$$x = (\dot{p}, \dot{q}, r, w)^T$$

The influence of the states p, q,Φ, Θ, u, v are compensated by the state feedback.

4.2 Feedback Design

The implementation of a well defined feedforward controller reduces the efforts in the design of the feedback loops. In both approaches a classical network of proportianal and integral controller loops is applied. Low feedback gains could be realized which are of essential importance for helicopters and for helicopters with a hingeless rotor, especially. High feedback gains create the tendency to shift the closed loop poles resulting from the rotor eigenvalues to low stability or even instability.

The feedback gains are optimized to minimize the sensitivity of the closed loop system corresponding to variations in the plant dynamics parameters, measurement noise, and external noise. The gain values are obtained by using computer aided design techniques [8]. Pre flight verification is performed in an extended nonlinear simulation of the overall system.

5. Aspects of System Realization

Requirements have been specified for the onboard systems depending on the experiences learned from the first design and on the limited space available in the test helicopter:

- A realization with a minimum of computers is demanded to avoid software interface problems.
- The elements of the onboard systems have to be related clearly to the tasks.
- Software modifications must be accomplished in a host computer in a ground station.
- The onboard hardware and software have to be evaluated in a realtime ground simulation.
- The flight tests have to be observed and managed from a ground station.

5.1 Onboard System

Figure 8 shows a block diagram of the MFCS onboard system. Two PDP11/73 computers, ruggedized for operation in the airborne environment, are installed. The tasks of the computers are definitely separated in the data recording task and the model following control task. This technique allows a largely autonomous treatment of the data streams for model following and for data recording.

The data recording computer is equipped with a 64 channel A/D converter. All sensor signals are sampled with a frequency of 100 Hz. The 10 msec sampling cycle is generated by an automomous real-time clock. A sampling time, significantly higher than the model following frame time, has been specified to achieve an improved accuracy for the model following evaluation. Both computers are linked by a dual port memory. The measured signals which are used in the control computer and the signals which are calculated for the model following are transmitted via the dual port memory for recording. The data are recorded on a floppy disk. In addition, the data are transmitted to the telemetry via a serial line. The telemetry data are only used for quick look purposes.

The MFCS computer consists of a 16 bit LSI - 11/73 control processing unit. Attached to it is a battery packed back-up CMOS memory. The measured signals of the simulation pilot's inputs and of the state variables, which are used in the feedback loops, are obtained directly from the preconditioned sensor signals with an installed 16 channel A/D converter. The calculated command signals for the four control actuators are D/A converted. A digital input line is used for initializing the MFCS status. Modifications of the software code are first performed in the host computer on the ground and then transfered to the onboard computer via a minituare digital tape device.

5.2 Real Time Realization

After the initialization of the control system, the commanded model and the control system are held in the trim position. The model following starts when the simulation pilot switches on the MFCS. The MFCS computer generates a 10 msec cycle which is the basic subcycle for the generation of the frame time and the refreshing time of the model following. In the ATTHeS a frame cycle of 50 msec has been realized. The pilot inputs and the state variables used in the feedback are sampled with 50 msec. The frame time has been established concerning the initial response characteristics of the host helicopter and of the possibly commanded models. A high ratio of frame rate compared to the closed loop system bandwidth is required to minimize distortions and abruptness in the continuous system output responses. The influences of the dynamics of the measured pilot control inputs and the dynamics of the actuators have been considered. A limitation of a desired time decrease is defined by the computer capacity, of course.

As an example Figure 9 illustrates the roll step responses of a high bandwidth first order control model and the second order response which represents the BO 105 with appropriate approximation. The first order model formulates high requirements on the actuator dynamics in the initial response, especially. Due to the commanded final value in the roll acceleration which is unrealistic for a helicopter, the feedforward calculates high commanded signals for the actuator. In consequence, the feedforward tends to overcontrol the helicopter in the short term. In addition, the initial command produces errors between the command and the measured response signals which are fed into the feedback controllers. This effect can be reduced by an extension of the command models with an increased degrees of freedom. An introducing of a shaping of the contol pilot signals yields a similar improvement.

In the BO 105 the 1/rev (7 Hz) and 4/rev vibrations of the main rotor affect the measured pilot's control input signals and must be attenuated before the signals are fed into the feedforward. Efficient analogue filters are producing phase delays which are dereasing significantly the bandwidth of the MFCS. As a result of the sampling with a 20 Hz frequency the 4/rev noise content is folded to the 8 Hz frequency. Specific digital filters with a second order "Butterworth" characteristic and with a cut-off frequency of 4 Hz are implemented. The filters reduce the amplitude at the 7 Hz frequency to a 40% level. The approximated effective time delay is about 12 msec.

In the first flights the pilots have commented the abrupt response of the simulator following very small control inputs. A simple control shaping has been inserted to smooth the control signals. A dead zone with 1% of the full control travel around the trim values was very well accepted by the pilots for the stick, pedals, and the collective. In Figure 10 the conditioning of the control signals is depicted in the time domain. Corresponding to the use of side stick controllers which mostly are using a mixture of motion and force control inputs, a more sophisticated shaping technique has to be designed.

The continuous actuator signals are achieved from a D/A conversion of the digital 20 Hz outputs of the MFCS computer. The zero-order-hold converter is the simpliest and commonly used conversion technique. The analogue actuator command signals contain spectral content with frequencies up to the frame rate frequency (ω_f) and the side band components with the multiples of ω_f , as illustrated in Figure 11. The main rotor actuating system has a bandwidth of about 5 Hz which acceptably covers the primary frequency band. In connection with the replacement of the FBW link by the FBL link for the tail rotor, the bandwidth of the tail rotor actuator has been increased to 50 Hz. To avoid actuator abruptness relating to the 20 Hz side band components, an intersampling with a cycle of 10 msec produces a satisfactory smoothing of the commanded actuator signal.

5.3 Feedback Data Acquisition

For the feedback control loops an online data acquisition is necessary to calculate the model following errors. The used sensor signals are:

- aerodynamic states V, α, β for the calculation of the airspeed components u, v, w,
- angular rates p,q,r, and
- attitudes Φ, Θ

The measured sensor signals are disturbed by the frequencies of the main rotor and tail rotor. Phase delays, induced by anti-aliasing filters, are not so critical for the signals used in the feedback loops. On the other hand, the effects of phase delays have to be reduced for a well balanced feedforward-feedback control system design. Filters with a second order characteristic and a cut-off frequency of 7 Hz have been selected in a simulation and flight test evaluation approach. The phase lag of the filters result in an effective time delay which is lower than the frame time of the control system.

Another aspect of feedback design for a high level control system is to investigate the observer/estimator technique for an improvement of the quality of measured signals and for using variables in the feedback controllers which cannot be measured directly. An approach to overcome the arising effects with the filters for the angular rate signals and with increasing gains in the angular rate feedback loops is the implementation of an estimator for the angular accelerations. A "Luenberger" observer for the roll and pitch accelerations has been evaluated in flight tests. This technique involves a mathematical model of the host helicopter to furnish an estimation of the angular accelerations and rates. The errors between the estimated and measured rate signals are fed back to compensate model inaccuracies and gust influences. The achievable accuracy and stability of the estimator is highly depending in the fidelity of the host helicopter model. Figure 12 demonstrates the performance of the designed estimator.

5.4 Performance in Flight Tests

The initial response and the bandwidth capability of the ATTHeS simulator is essentially depending on the feedforward controllers. The use of the angular accelerations for pitch and roll in the feedforward improves the initial response characteristics of the overall system. Figure 13 summarizes the effective time delays for the overall in-flight simulation system in the roll and pitch axis. In addition, the effective time delays of helicopter testbeds, equipped with a digital control system, are compared. The main elements contributing to the time delays between the commanded responses and the measured responses are specified. The overall effective time delays of the ATTHeS simulator are about 110 msec for the roll axis and about 160 msec for the pitch axis. The higher value for the pitch behavior results from the slower response of the basic helicopter in this axis due to the higher moment of inertia. The computational time (frame rate and refreshing rate) contributes 42 msec. Only a small improvement can be achieved by reducing the computational time which is envisaged by a planned replacement of the MFCS computer.

For an evaluation of the simulator bandwidth capability, the phase delay and bandwidth criteria, defined in the updated military handling qualities specification, can be quoted. Figure 14 demonstrates the simulation potential of ATTHeS. The overall system bandwidth is achieved with a rate response model which is close to the response characteristics of the basic BO 105. An increased bandwidth can be realized by feeding the differentiated pilot control inputs into the feedforward controller but the pilots have commented the high activity in the rotor controls as unacceptable. Compared with the basic BO 105 helicopter a low reduction in the bandwidth has been accepted. Nevertheless, the obtained bandwidth values guarantee the capability to cover the expected range of flight dynamics of future helicopter systems. Correspondingly, a flight test program is planned with ATTHeS to verify the level boundaries for high bandwidth high time delay configurations.

An additional scale for an evaluation of the performance of a flight control system is the grade of decoupling which can be obtained by the control system. Figure 15 shows the decoupling performance of the ATTHeS model following control system. For a commanded rate response system, fully decoupled in pitch and roll, a well decoupled response is obtained in flight tests only using the feedforward controllers. A slightly rising initial off-axis response is suppressed by the actuator inputs from the feedforward controller. An improvement in the mid and long term decoupling is achieved by the feedback controller.

Different models to be followed have been investigated. Besides the implemented response system models, 6 DOF models of existing helicopters were used to define the commanded flight dynamics. Figure 16 gives a representative result from the flight tests showing the difference between only an engaged feedforward and a feedforward-feedback system. Almost identical overall system response is obtained in the short term response. With increasing time the model following is improved when the feedback is engaged.

6. Conclusions

The role of the in-flight simulation for the development of ACT systems has been discussed. The explicit model following control system implemented in the DLR fly-by-wire helicopter represents an excellent example for the ACT utilization. Aspects of realization which can be transfered to the ACT development for operational use are:

- The design of the feedforward controller has to be based on a host helicopter model with adequate fidelity.
- Two feedforward concepts are pursued. Both consider the unbalanced number of states to be controlled and the number of controls in the helicopter.
- In an ACT design approach the influences of the ACT components (control system computation, actuators, pilot controllers, and data conditioning) have to be evaluated to achieve the desired performance of the integrated system.

The DLR in-flight simulator ATTHeS is meeting the requests on a facility for the ACT development. The overall simulation performance with

- high bandwidth and low effective time delays,
- well reduced interaxis coupling, and
- satisfactory long term model following

underlines the good potential of the ATTHeS to cover a broad range of helicopter systems to be simulated in flight.

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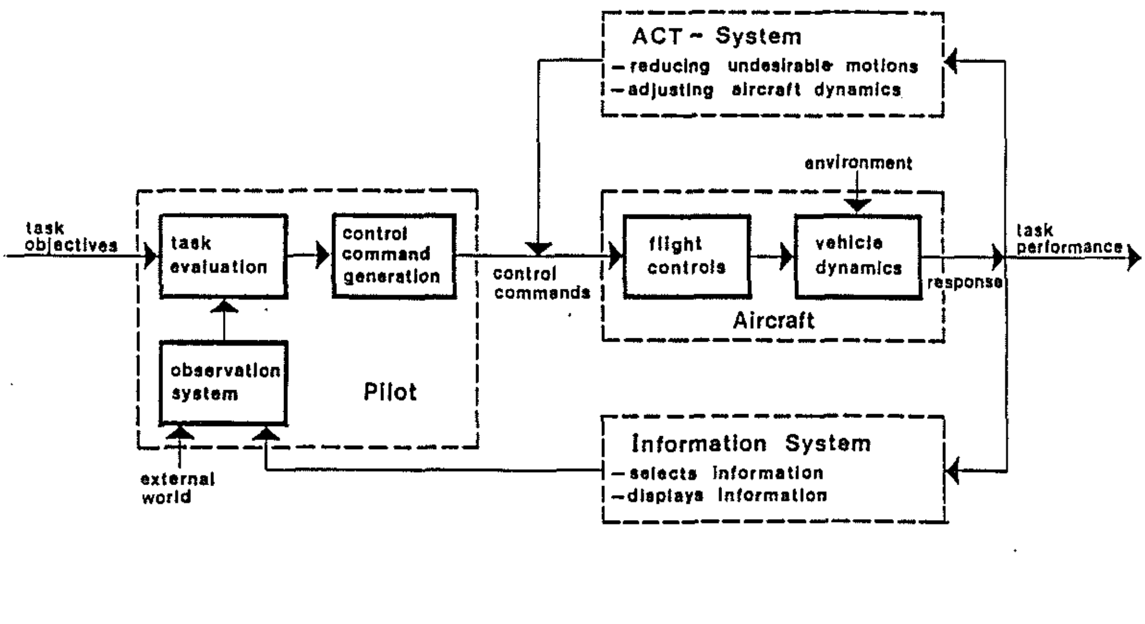


Figure 1. Pilot - vehicle system

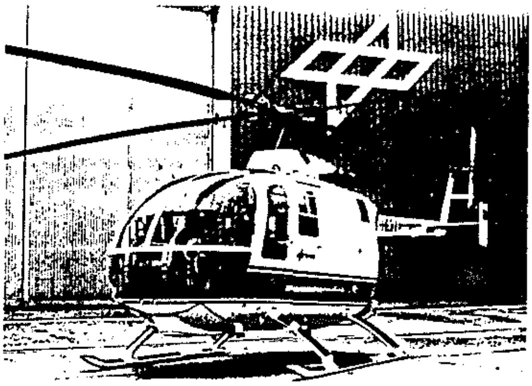


Figure 2. ATTHeS in-flight simulator

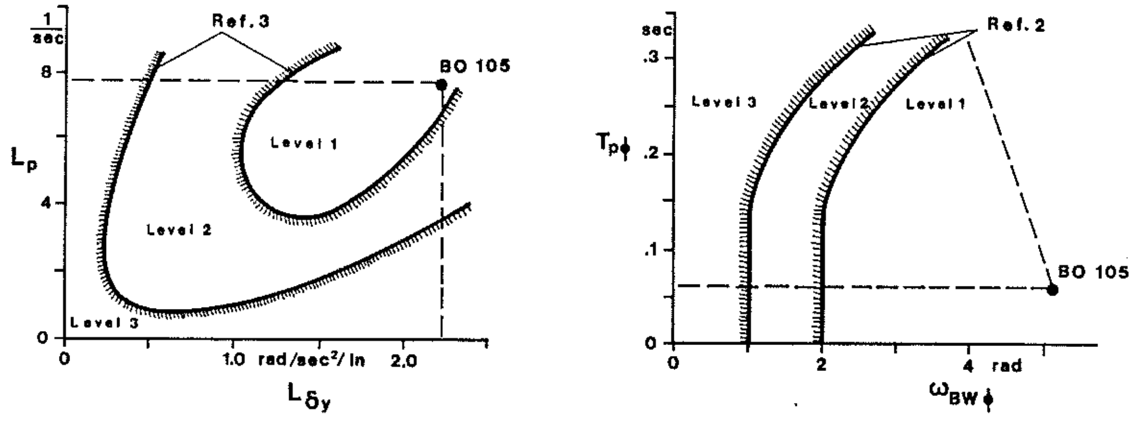


Figure 3. Control power and bandwidth in roll axis for the basic BO 105 helicopter

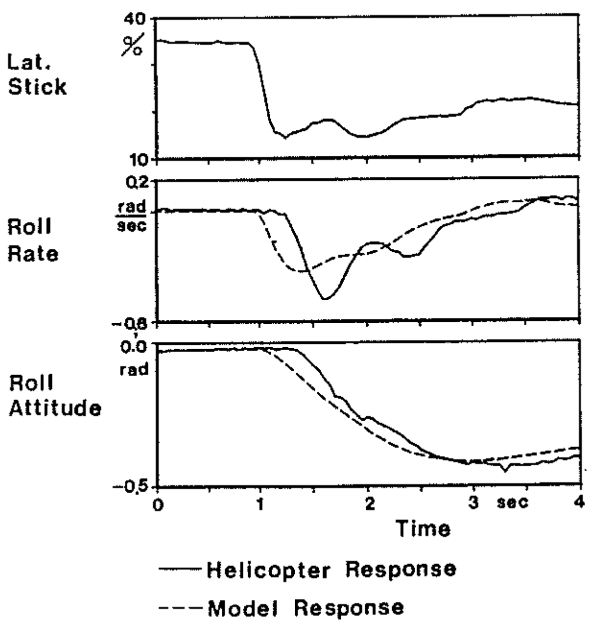


Figure 4. Model following performance of first MFCS design

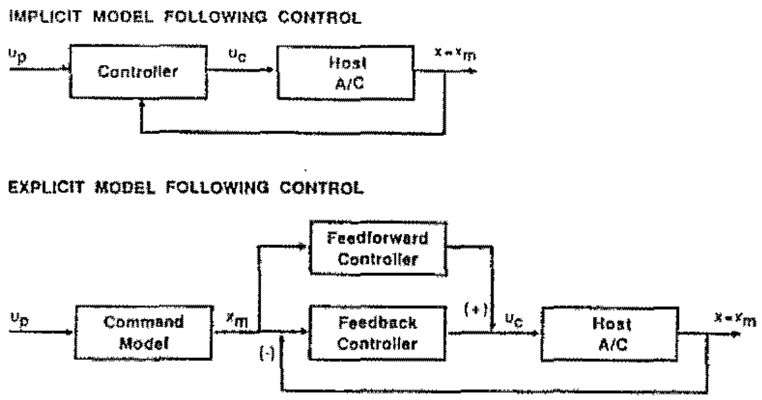


Figure 5. Concepts of model following

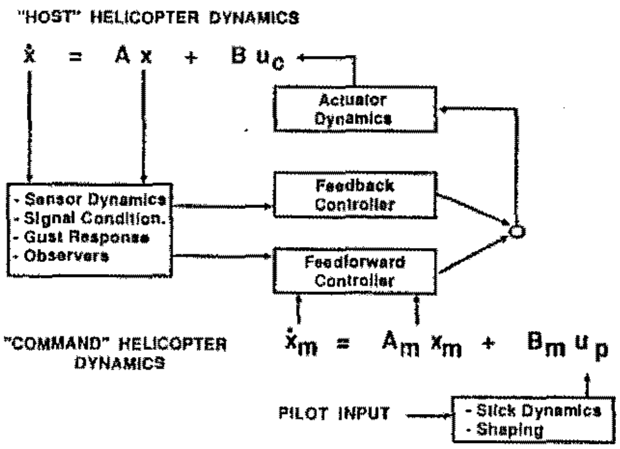
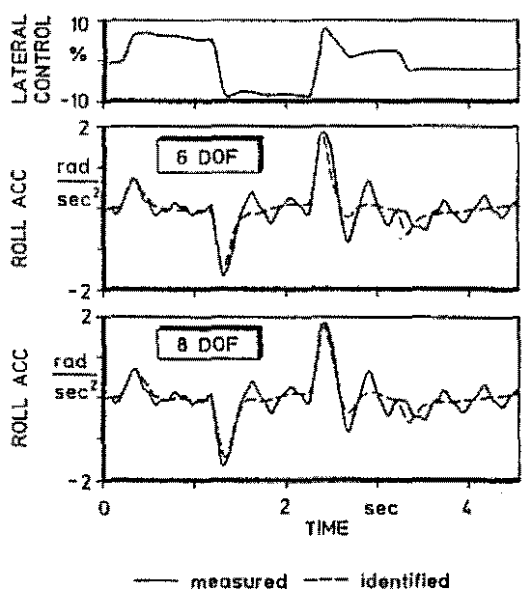


Figure 6. Structure of explicit model following

Figure 7. Comparison between responses of 6 and 8 DOF models



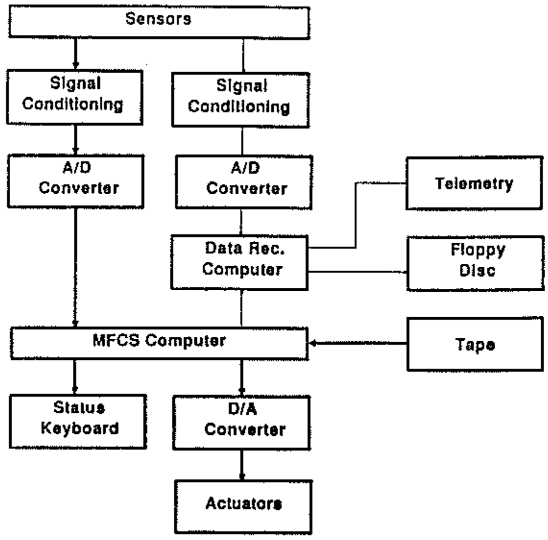


Figure 8. On - board system

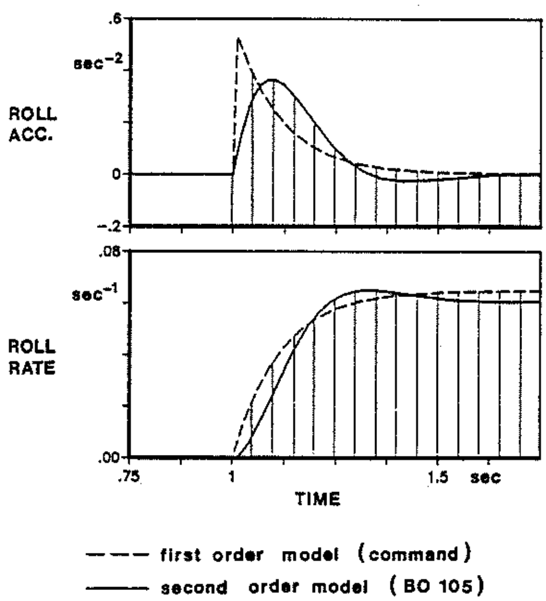


Figure 9. 50 msec sampling of helicopter response data

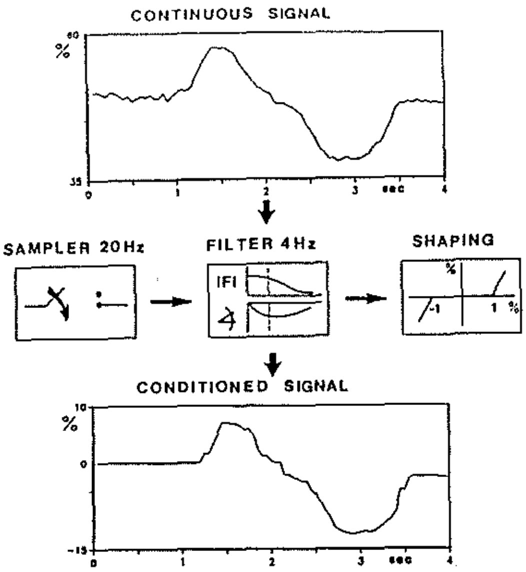


Figure 10. Conditioning of pilot control inputs

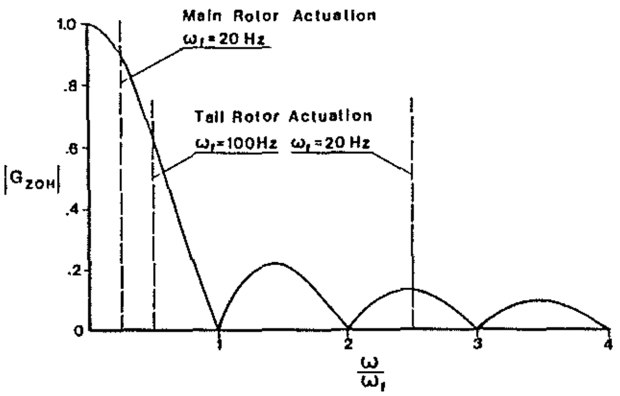
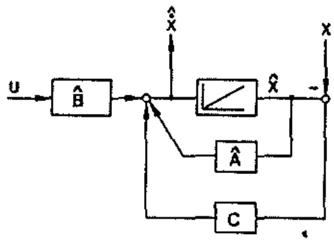


Figure 11. Frequency response of a zero-order-hold



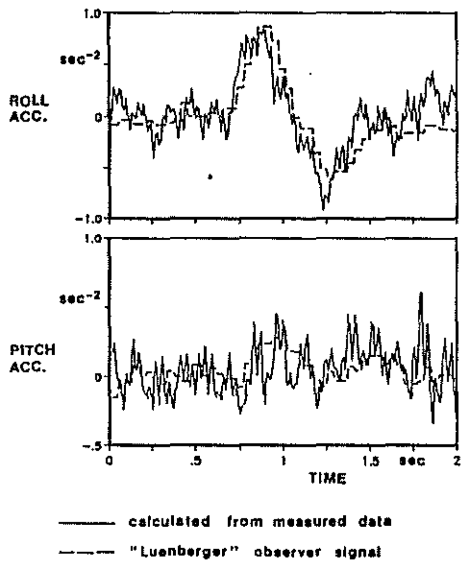


Figure 12. Flight test data of angular acceleration estimator

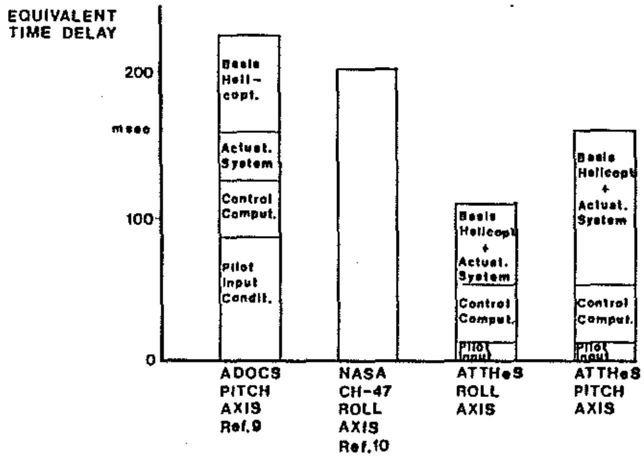


Figure 13. Effective time delays

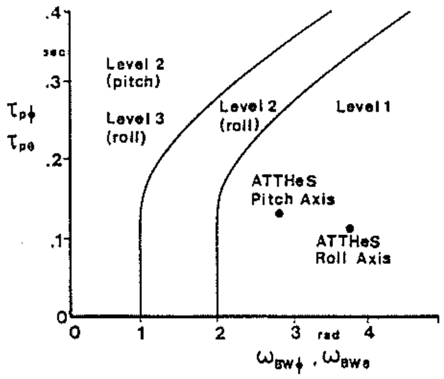


Figure 14. Bandwidth performance of ATTHeS

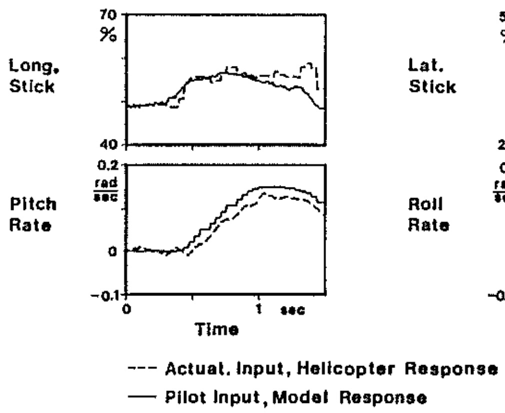


Figure 15. Reduction of interaxis coupling (only feedforward)

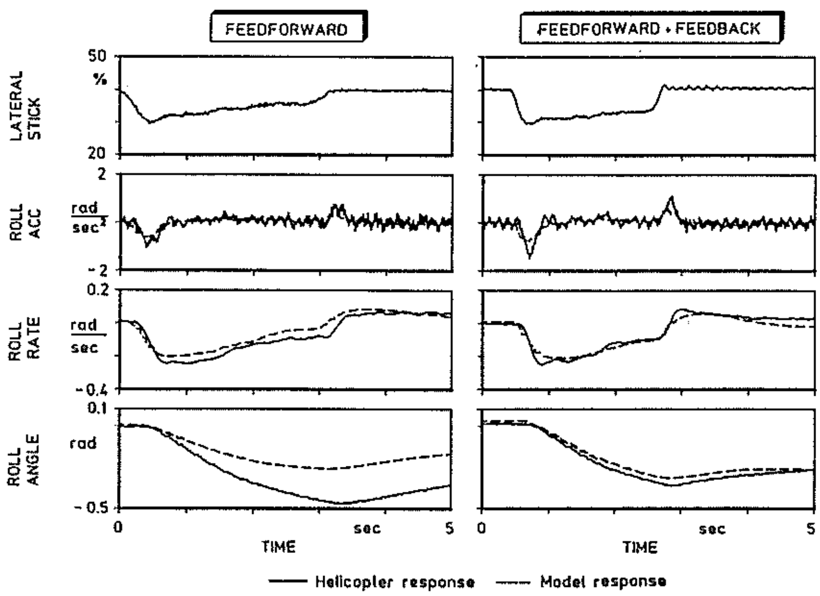


Figure 16. Flight test data of BK 117 simulation