EXPERIENCES WITH HIGH AUTHORITY HELICOPTER FLIGHT CONTROL

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Abstract

The experiences with the helicopter In-Flight-Simulator ATTHeS (**A**dvanced **T**echnologies **T**esting **He**licopter **S**ystem) shall serve as an example for high authority helicopter flight control. ATTHeS is a modified BO 105 helicopter, equipped with a full authority nonredundant fly-by-wire system. Two on-board computers, one for data recording and one for the control task, provide ATTHeS variable stability capability. With the explicit Model Following Control System, in-flight simulation of other helicopters or command systems like rate command, rate command/attitude hold or other is possible.

The realization of a helicopter high authority control system requires theoretical and experimental research in the fields modeling/identification, control theory and simulation. The establishment of suitable simulation tools is essentially necessary to develop, to evaluate and to certify the integrated control system.

The effectiveness of good simulation tools is shown with the analysis of some strong impacts of actuator dynamics and nonlinearities to the flight dynamics, which were discovered during the flight tests in 1989. One pilot irritating effect was a pitch/roll oscillation of a few degrees, induced by the control system. Off-line simulations with flight test data were accomplished to confirm the explored effects and to point at possible solutions. In these simulations, the pitch/roll oscillations occured, when the actuator model included a time delay and a dynamic model. With these simulations, countermeasure could be found : the pitch/roll oscillation was suppressed by incorporating a time delay in the control system. New flight tests, accomplished in 1990, confirmed the simulation results.

With selected examples it is shown, that ATTHeS meets the defined requirements of

- low time delay
- decoupling
- off-nominal flight condition
- in-flight simulation.

Introduction

To reduce pilot workload and to improve system performance, classical flight control systems, such as stability augmentation systems (SAS) or Stability and Control Augmentation Systems (SCAS), are available for different helicopters [1]. These control systems with feed-forward and feedback loops use low authority fast travelling or high authority slow travelling actuators or a combination of both. They are designed to support the human pilot in low bandwith tasks with stbilization or autopilot functions.

Future helicopters for both civil and military applications request to extend the operational use. To fly in extreme environmental conditions with low pilot workload, high authority control systems are required with Advanced Control Technologies.

There exist only a few helicopters with high authority flight control systems. These helicopters are equipped with full authority fast traveling actuators. One group of these helicopters, such as the Bell 249 ARTI described in [2] and the Sikorsky UH-60 ADOCS discussed in [3] are used for technology demonstration and flight control research.

The tilt rotor V22 OSPREY is a typical example for an operational vehicle with a state-of-the-art flight control system. The development of the control laws for this prototype is discussed in [4].

When for research tasks variable stability is to be investigated, in-flight simulation capability of these vehicles is required. Up to now, only three of the helicopters with high authority actuating systems are used for in-flight simulation.

One of the first in-flight simulation results were achieved with the Bell 205 variable stability helicopter of the CAE and are discussed in [5]. Major contribution to the application of complex control systems to helicopters is discussed in [6]. These results were achieved with the US-Army/NASA CH-47 helicopter, which retired in 1989. The development of the in-flight simulator SHADOW, realized on a S-76 helicopter, is described in [7]. Some realization aspects of a highly maneuverable in-flight simulator on a BO 105 helicopter are summarized in [8]. The presented paper discusses some experiences with the flight control system of this helicopter.

The Advanced Technologies Helicopter Testing System (ATTHeS)

ATTHeS, shown in figure 1, is a modified BO 105 helicopter. It's crew consists of the simulation pilot in the middle front seat and the safety pilot, sitting on the left hand back seat. The fly-by-wire actuators for the main rotor and the fly-by-light actuator for the tail rotor are mechanically linked to the conventional controls of the safety pilot. The high travel rates of the actuators of 100 %/sec and the full travel range of 100 % document the actuational capabilities of this high authority flight control system.

The simulation pilot's controls are mechanically disconnected from the basic control system. Their position is measured electrically and fed into the on-board computer system shown in figure 2. It consists of two computers, one for data recording and one for the control task. The data recording computer stores the sensor data and the control computer data on a floppy disk and serves a telemetry for quick-look analysis in a ground station during the flight test.

The control computer runs a **M**odel **F**ollowing **C**ontrol **S**ystem (MFCS). The simulation pilot controls drive generic helicopter or decoupled dynamic models. The control system out of feed-forward and feedback loops minimizes the errors between the models and ATTHeS's states.

MFCS Layout Steps

The MFCS design and realization requires several steps and joins different research branches. They incorporate

- System Requirement Definition
- Modeling / Identification
- Control Theory
- System Simulation
- Hardware Realization and Flight Testing
- Flight Test Analysis

System Requirement Definition

The requirements of the overall system have to be defined carefully. They are very strong dependant on the basic helicopter characteristics, the actuating systems, the state measurement system and, finally, the on-board computer capability. The defined requirements have a strong impact on the modeling and identification, the control system layout and the realization.

For ATTHeS, the main requirements were defined as

1. The time delay, introduced by the MFCS, must be below 100 ms.
2. The MFCS must be able to decouple the BO 105.
3. The MFCS, designed for 60 kts, must be able to operate between 50 kts and 70 kts with satisfactory performance.
4. In-flight simulation of a linear helicopter model must be possible.

Emphasis in this paper is laid on the effectiveness of good simulation tools for MFCS analysis and layout.

Modeling and Identification

The modeling and identification is mainly dependant on the quality of the realized state measurement system and the installed actuation systems. The model degree of freedoms and the identification accuracy are the main keys for a successful control system layout and therefore influence strongly the achieved system performance. The interference between system identification and control system layout is described in [9].

Control Theory

In most in-flight simulators, explicit Model Following Control Systems are chosen, since the once defined controllers are not dependant on the commanded model. As shown in a block diagram of an MFCS in figure 3, this model is driven by the simulation pilot controls u_P and generates the desired states x_M.

Pilot Control Signal Acquisition

The pilot control signals have to be processed carefully since they activate directly the fly-by-wire system via the explicit model and the control system. Figure 4 shows different simulation pilot lateral control signals in the left time histories and the corresponding model roll acceleration in the right hand diagrams. In a first step, the unfiltered control has to be reduced by a trim value. This trim value is defined as the linear mean value of the last 100 samples before engaging the MFCS. Only the mean value is appropriate for the trim definition, since noise on the measured control would decentralize the trim value and result in an asymmetric system response. The model roll acceleration to this pilot control in the top right diagram is very noisy, when the control is in the trim position, which will result in high MFCS control activity. Therefore the pilot controls are discrete filtered with 4 Hz second order Butterworth Filters to reduce noise with a minimum of phase delay. The noise in the commanded roll acceleration in the middle right time history is significantly reduced. However, when the pilot control is in the trim position, the commanded roll acceleration is not zero as desired, which results in drifts in roll rate and roll attitude. To suppress this effect of undesired pilot control inputs, the trimmed and filtered pilot control passes a dead zone, where it is defined to be zero, when it is less than 1 % around trim. Now the commanded roll acceleration in the lower right diagram is exact zero, when the pilot stick is in the trim position. Only with this kind of control signal processing, realization of rate command / attitude hold is possible.

Feed-forward / Feedback

The generic model states are fed into a feed-forward controller. This controller represents mainly the inverse dynamics of the host helicopter and provides a quick system response to simulation pilot control changes. A detailed description of the feed-forward layout procedure is given in [10]. The controllers are derived from a linear model of the base helicopter around a nominal flight condition. The dependency on the modeling and identification accuracy is obvious.

Since modeling and identification inaccuracies, changes in nominal flight conditions and mainly gusts drive the base helicopter states x from the desired states x_M, feedback controllers are required to reduce these errors.

The influence of feedback loops to the system dynamics can be analysed with classical control theory methods. Figure 5 shows the roll root locus of an 8 degree of freedom (DOF) linear 60 knots level flight model of the BO 105 dependant on linear and integral roll rate feedback K_p and K_I. In the first layout step, K_p is increased, which increases the roll frequency, while the roll damping decreases. With a defined proportional roll rate feedback, the integral roll rate feedback is increased. The roll damping now decreases rapidly with nearly constant roll frequency. Corresponding time histories of the design point (1) ($K_p = 20\,/rad/s, K_I = 0.02\,/rad$) and point (2) ($K_p = 40\,/rad/s, K_I = 0.02\,/rad$) are shown in figure 6. The actuator and roll rate responses to pilot step inputs accord well between linear simulation and flight test in the design point 1, while in the design point 2 the real helicopter response is more damped than the simulation result.

Influence of Measurement Accuracy

The angular rate controllers ensure a quick and exact roll rate response. However, attitude control is required to suppress drifts in the attitude. In addition, low consistency of the measured data results in disharmonized control commands. The controller consists of linear roll attitude feedback and nonlinear pitch attitude feedback, integral feedback is not yet analysed. Therefore angular rate measurement errors impact attitude errors to the overall system. Figure 7 shows the dependency of the roll attitude error e_Φ on the attitude controller K_Φ. No attitude control yields a steady drift in roll attitude, increasing gain suppresses the attitude error, which is linear dependant on the offset error in the roll rate measurement.

System Simulation

The need for good simulation tools in the control system design process is dictated by the high level of performance required from the overall system. To meet these high demands, the control system consistency with the basic helicopter and with the subsystems has to be evaluated in simulation with increasing integration level depending on the progress of system design. One great advantage of envolving simulation procedures is to get a detailed understanding of the physical effects of a broad spectrum of influencing factors. The steps with increasing simulation complexity are

- realistic fixed body linear model simulation,
- nonlinear simulation including rotor dynamics and subsystem models, and
- real time simulation of the overall system.

These various levels of simulation are incorporated in the design approach and in preparing the verification flight test. All simulation programs can be driven with generic inputs as well as with flight test data.

Extended Linear Model

In a first step the linear model of the host helicopter can be derived by the linearization of a nonlinear model. This ensures a good compatibility with the nonlinear simulation. The demanded high model fidelity requires to generate and verify the linear model from flight test data. The technique to identify the elements of the state and control matrices using flight test data can be characterized as an inverse problem of model following design. The used system identification technique is discussed in detail in [11].

The identified model is an extended 8 DOF linear fixed body model

$$\dot{x} = A \cdot x + B \cdot u$$

with the state vector

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

and with the control vector

$$u^T = (\delta_x, \delta_y, \delta_c, \delta_{tr}).$$

The roll response serves here as an example to describe the extension of the helicopter model. For a 6 DOF model the differential equation for the roll response is

$$\dot{p} = L_p \cdot p + L_{\delta_y} \cdot \delta_y$$

An extended model structure including first order tip path plane dynamics for the longitudinal and lateral flapping have been set up in the following form (here roll and lateral flapping only).

$$\dot{p} = L_{b_{1s}} \cdot b_{1s}$$

$$\dot{b}_{1s} = -\frac{1}{\tau_B} \cdot b_{1s} - p - \frac{K}{\tau_B} \cdot \delta_y$$

$\tau_B = 16/\gamma\Omega$ is a time constant derived from the linearized flapping dynamics. By differentiating the first equation and inserting into the second the final structure of this model can be written in fixed body variables as

$$\ddot{p} = \tilde{L}_{\dot{p}} \cdot \dot{p} + \tilde{L}_p \cdot p + \tilde{L}_{\delta_y} \cdot \delta_y.$$

A more detailed description is given in [9]

Nonlinear Simulation

The nonlinear non-realtime simulation yields a higher level of accuracy describing the dynamics of the host helicopter including rotor dynamics and the influences of simulated disturbances. At DLR a standardized nonlinear **sim**ulation for **h**elicopters (SIMH) was developed and is in use for various non-realtime simulation applications [12]. The high fidelity of the simulation has been validated by crosschecking simulation data with flight test data. The comprehensive simulation includes the modeling of:

1. Main rotor with blade element modeling (10 blade elements and 5 msec frame time) including
   - rigid blades,
   - coincident spring restrained flapping and lagging hinges,
   - quasi-static aerodynamics loads,
   - trapezoidal downwash,
   - nonlinear aerodynamics, and
   - aerodynamic coefficients depending on local blade angle of attack and Mach number.
2. Tail rotor with tip path plane modeling.
3. Empennage and fin modeling with
   - 2D strip theory and
   - simplified downwash interference.
4. Fuselage modeling with
   - forces and moments depending on angle of attack and sideslip and
   - simplified downwash interference.
5. Engine and RPM governor modeling with
   - first order linear relationship between power and torque and
   - PID controller.

The basic SIMH has been extended for the use in the control system design approach. The following modules have been added:

1. Digital control system module.
2. Fly-by-wire control module.
3. Data acquisition and conditioning module.

Realtime System Simulation

After the phase of designing the MFCS in non-realtime simulation the software of control system and data handling is implemented in the onboard control computer. Connecting the computer for simulating the basic helicopter, the MFCS software can be checked in realtime on the ground. In this ground-based simulation the engineers are provided with the recorded data for off-line analysis and several quicklooks for evaluation of the realtime performance of the control system software. The quicklook informations can be displayed in the formats of selectable time histories or crossplots and of a multi-function-display.

Up to now the model used for this realtime simulation is the extended model described above. A realtime version of the nonlinear simulation is under development on an AD100 computer [13].

To underline the effectiveness of good simulation tools, the analysis steps of the following phenomenon is discussed.

During flight tests in 1989, a pitch/roll oscillation of a few degrees attitude was observed by the pilots. The time histories of the longitudinal axes are shown in figure 8. When the pitching maneuvre is finished at about 10 sec, the oscillation starts in longitudinal and collective control.

Since these oscillations were not observed in the simulations, the extended linear simulation was applied to get insight in possible reasons for these oscillations. A very good coincidence of flight test and simulation is presented in figure 9. This result was achieved, when the actuator simulation was extended with a dynamic model and a time delay. With this simulation tool, the MFCS was adapted to the actuating system by incorporating a time delay in the feedback loops. This delay represents the calculation time for the feed-forward and the delays of the actuation system and the base helicopter. It is therefore different for the pitch and roll axes and minimizes the interference between feed-forward and feedback. Especially during rapid simulation pilot control inputs, the artificial delay increases the damping of the overall system significantly. From figure 10 it can be seen, that the oscillations are suppressed.

The found modifications were implemented in the real-time program and flight tested in 1990. Although the flight test data in figure 11 do not show the simulated maneuvre, it can be observed clearly, that the oscillations are suppressed.

Causes for flight test phenomena and effective countermeasures can be found with a good simulation tool before the flight test. This procedure saves flight test time drastically.

Hardware Realization and Flight Testing

When the various simulations are successful accomplished, it seems to be easy to implement the MFCS in the real world helicopter. Besides installing the computer systems, sensors and data acquisition system, one major task is to process the sensor data for the feedback control system. High frequency filters supply small delays but do not suppress measurement noise and therefore introduce high control activity. Low frequency filters mostly suppress measurement noise but do not have neglectable phase delays, which reduce the control system stability margins. For control system applications, a compromise has to be found.

A general investigation and analysis on helicopter state measurement data is given in [14]. Figure 12 shows examples for raw data, sampled with 100 Hz, and filtered data. From the upper diagram it can be seen, that the noise level on the pitch rate Q is in the maneuvering range. Therefore it is analog filtered with 7 Hz to suppress the noise of the first rotor harmonics. The signal in the second diagram is sampled by the control computer with 20 Hz. For the MFCS, helicopter fixed velocities have to be calculated. For the longitudinal axes, the differential pressure VEEBAR and the angle of attack ALPHA are measured. The calculated longitudinal U and vertical velocities W are discrete filtered with 1 Hz (U) and 4 Hz for W. The filter frequencies are compromises between low noise level and small time delays.

In cases, where controlled states are not measurable, observation technique may be applied as shown in [15].

Flight Test Analysis

During the flight tests, selected MFCS and helicopter states are transmitted to a ground station and displayed on PC-screens. The flight test engineer supervises the experiments. The flight test data, stored on floppy disks, is transferred to a magnetic tape. With these data, compatibility checks are performed periodically to ensure a high data quality. After transferring the data to the DLR-mainframe computer, the flight tests are analysed extensively with a special program package. To document the capabilities of ATTHeS, mainly time histories are used.

In [8] it is shown, that requirement (1) of the system requirement definitions is already met by the feed-forward path of the MFCS.

The decoupling performance was investigated with a pitching maneuvre, where the base helicopter has a strong roll coupling. A computer generated doublet signal (+/- 5 % for 2 sec each) in the longitudinal control was fed to a decoupled explicit model which responds with a nose up/down maneuvre with constant altitude, roll attitude and sideslip angle. The MFCS responds in all actuators as can be seen from figure 13 (left). The lateral control ETAYS is required to suppress the pitch-to-roll coupling of the BO 105, collective ETA0S and pedal controls ETAPS are used to minimize the rate of climb and to hold the sideslip angle. The pitch rate Q and the pitch attitude THETA in figure 13 (right) have a good model following. The roll rate and attitude error during this maneuvre is less than 0.05 rad, which underlines the good decoupling performance of the MFCS.

To investigate the airspeed range of the MFCS, original designed for 60 kts, decelerating and accelerating maneuvres, as shown in figure 14, were flown. By simply changing the pitch attitude THETA with the decoupled rate command/attitude hold model the forward velocity U changes between 50 kts and 80 kts. The roll attitude error and the sideslip error is less than 0.05 rad. Therefore the required speed range can be flown with ATTHeS.

In-flight simulation was investigated with extended linear helicopter models of BO 105, BK 117 and AH 64. The controls in figure 15 and the states in figure 16 describe the in-flight simulation of an AH 64 linear 60 kts model. The simulation pilot had to fly roll maneuvres while maintaining airspeed. Collective pitch and pedals had to be left at their trim position. From figure 15 it can be seen, that the MFCS controls in the solid lines have a high activity in all axes to simulate the AH 64 with a BO 105. The roll attitude PHI in figure 16 is in the range of +/- 0.5 rad and shows an excellent model following, although the MFCS design point is 60 kts level flight. Also yaw rate R and vertical velocity W have a good model following. The pitch attitude THETA shows some errors, which indicates a low pitch damping in the simulated helicopter dutch roll frequency. Since this low pitch damping tends to PIO's, the pitch rate and attitude control has to be improved.

Conclusions

The realization of a high authority helicopter flight control system requires the close teamwork of modeling, identification, control theory, system simulation, data acquisition and conditioning, software development and system integration. The modeling and identification branch supplies linear models and data for the control system layout, which can be performed with classical methods and optimization.

Simulation tools are a fundamental requirement for control system development and layout.

Pilot control and state measurement signal conditioning has to be considered carefully for system integration and successful control system realization.

The Advanced Technologies Testing Helicopter System, realized on a BO 105 with a high authority Model Following Control System, meets the requirements of

- low time delay,
- decoupling performance,
- off-nominal flight condition and
- in-flight simulation capability.

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Figure 1. ATTHeS In-Flight Simulator

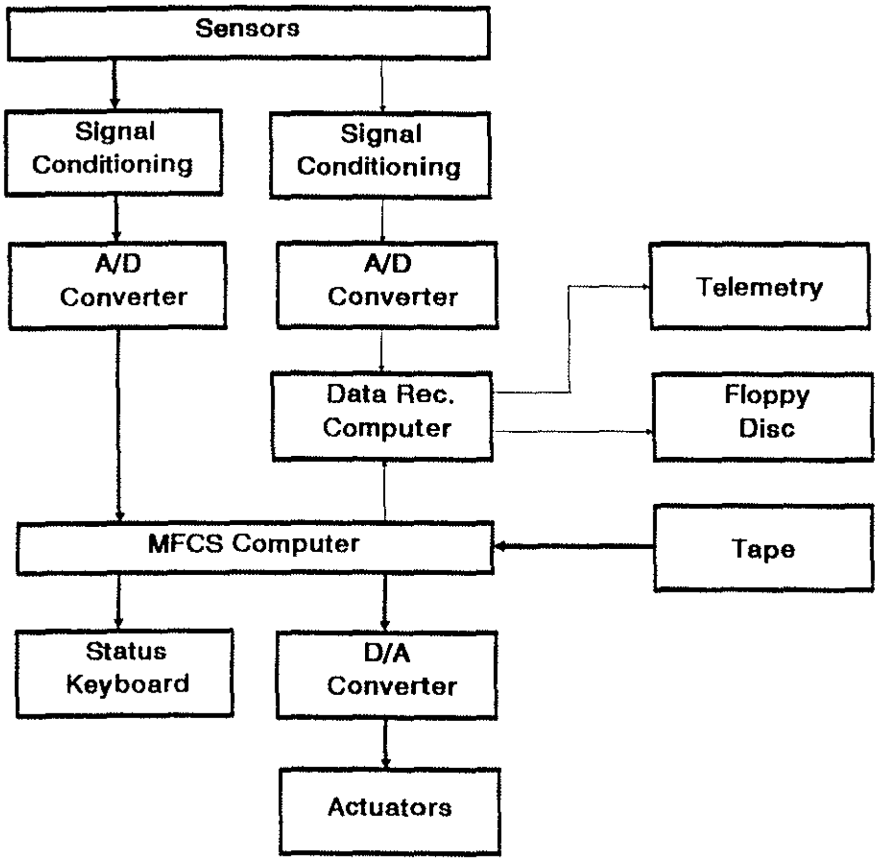

Figure 2. On-Board Computer System

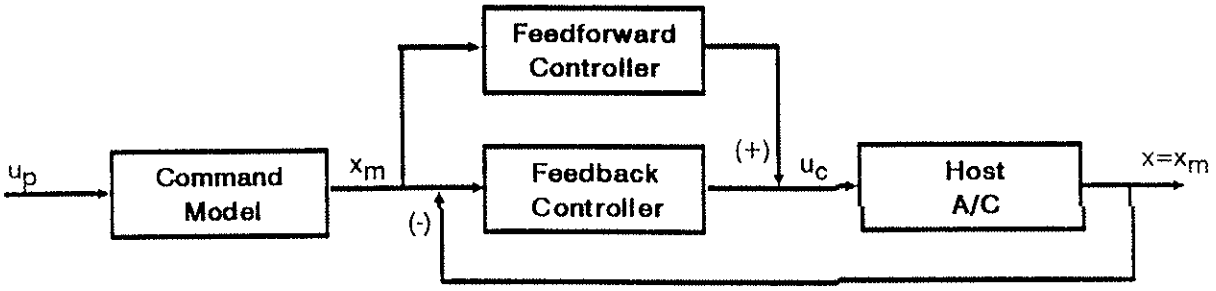

Figure 3. Explicit Model Following Control System

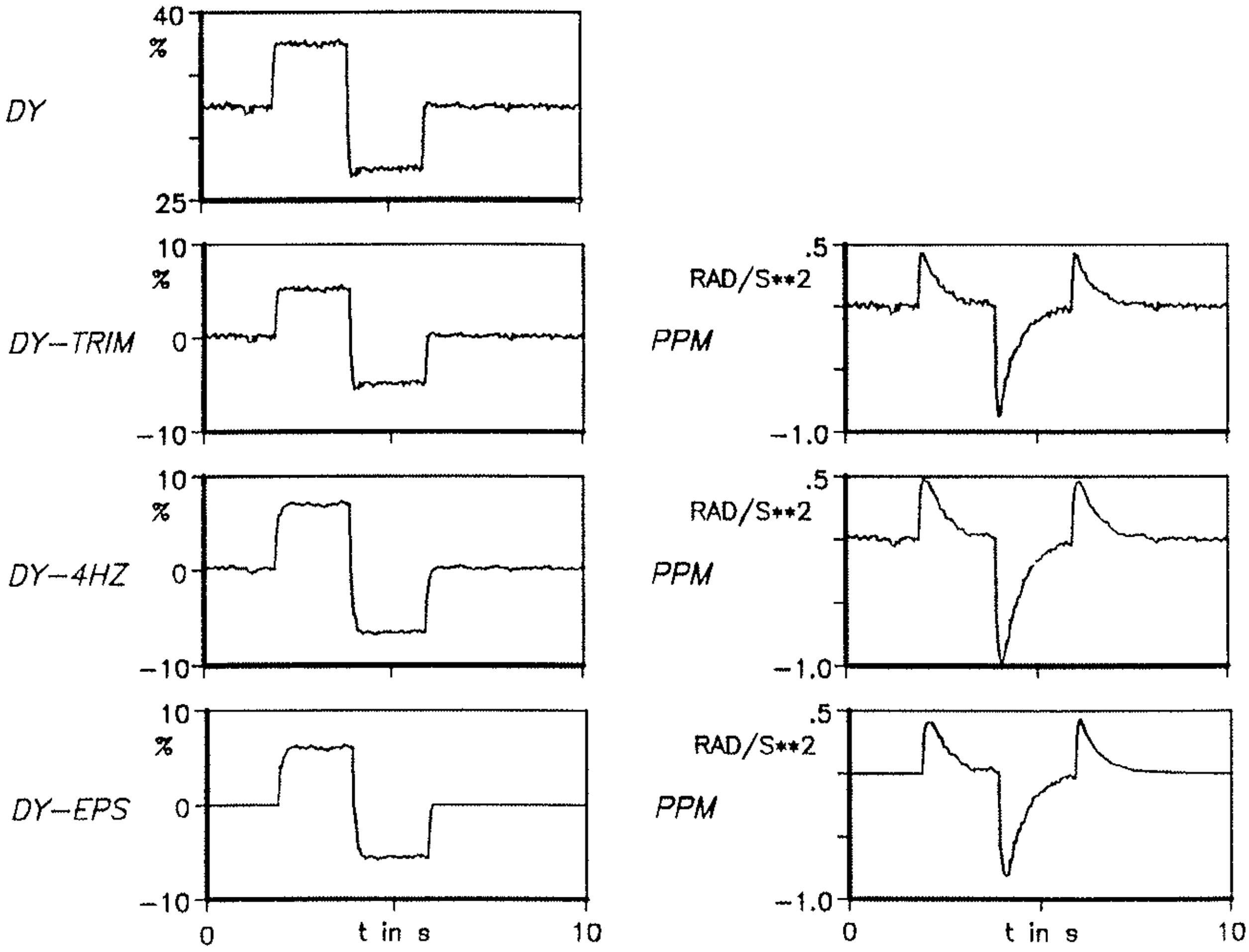

Figure 4. Pilot Control Signal Acquisition

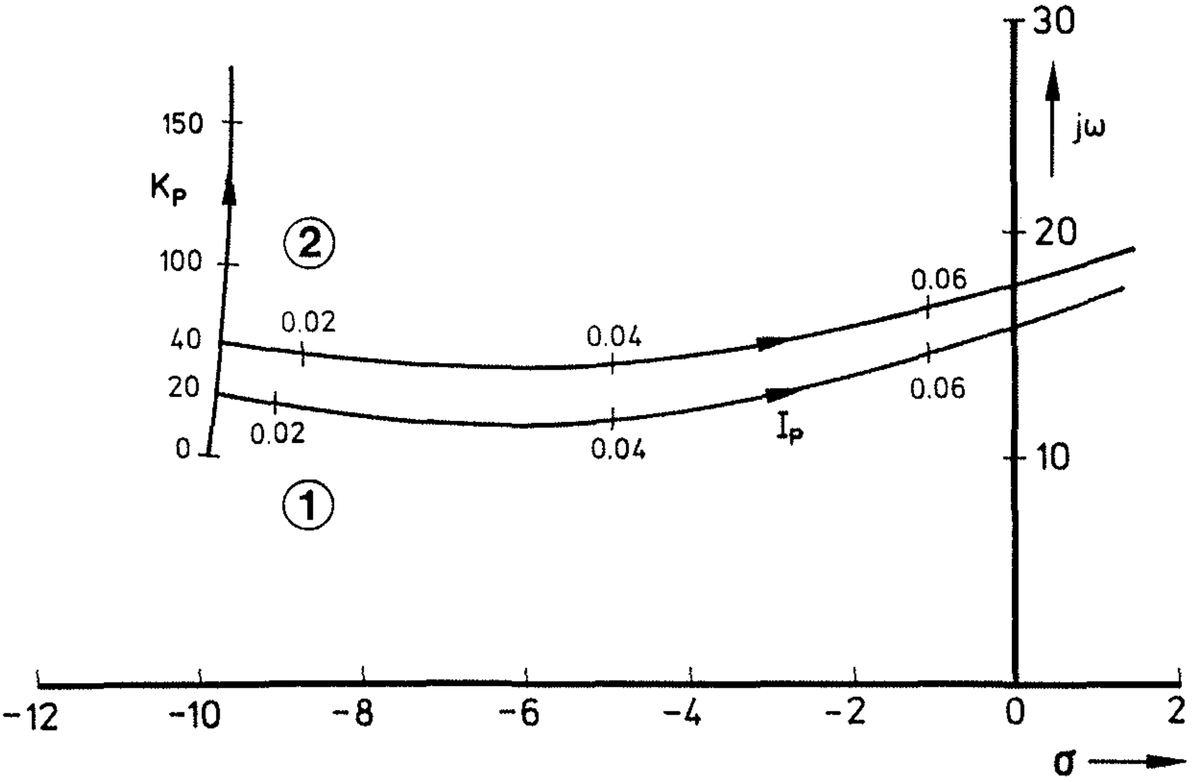

Figure 5. Root Loci of Closed Loop System

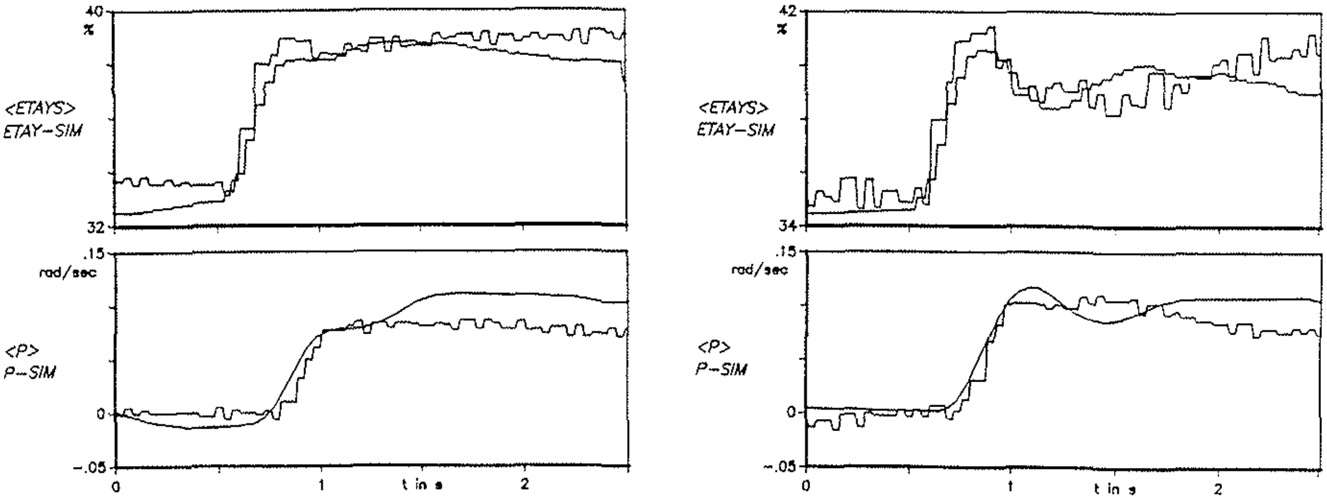

Figure 6. Step Responses at Design Points (1) and (2)

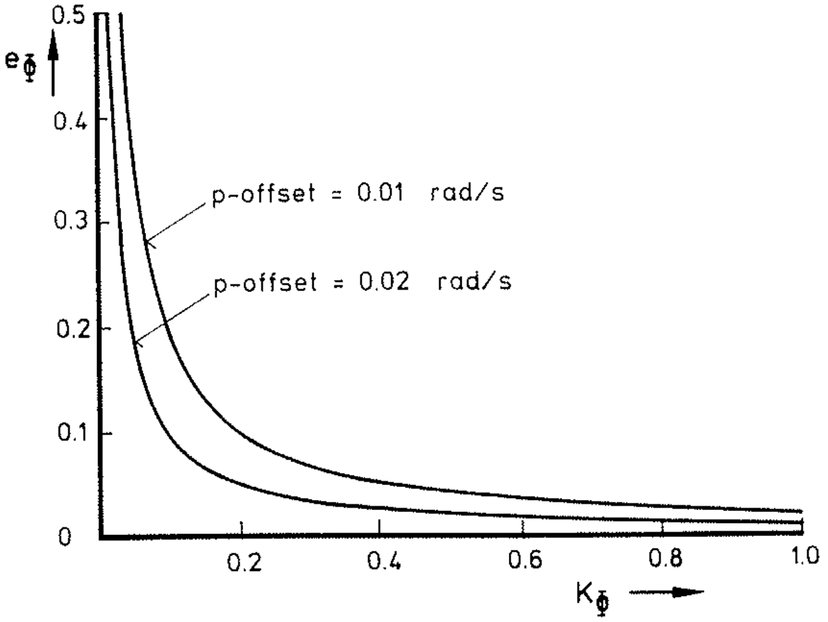

Figure 7. Attitude Error as Function of Attitude Controller

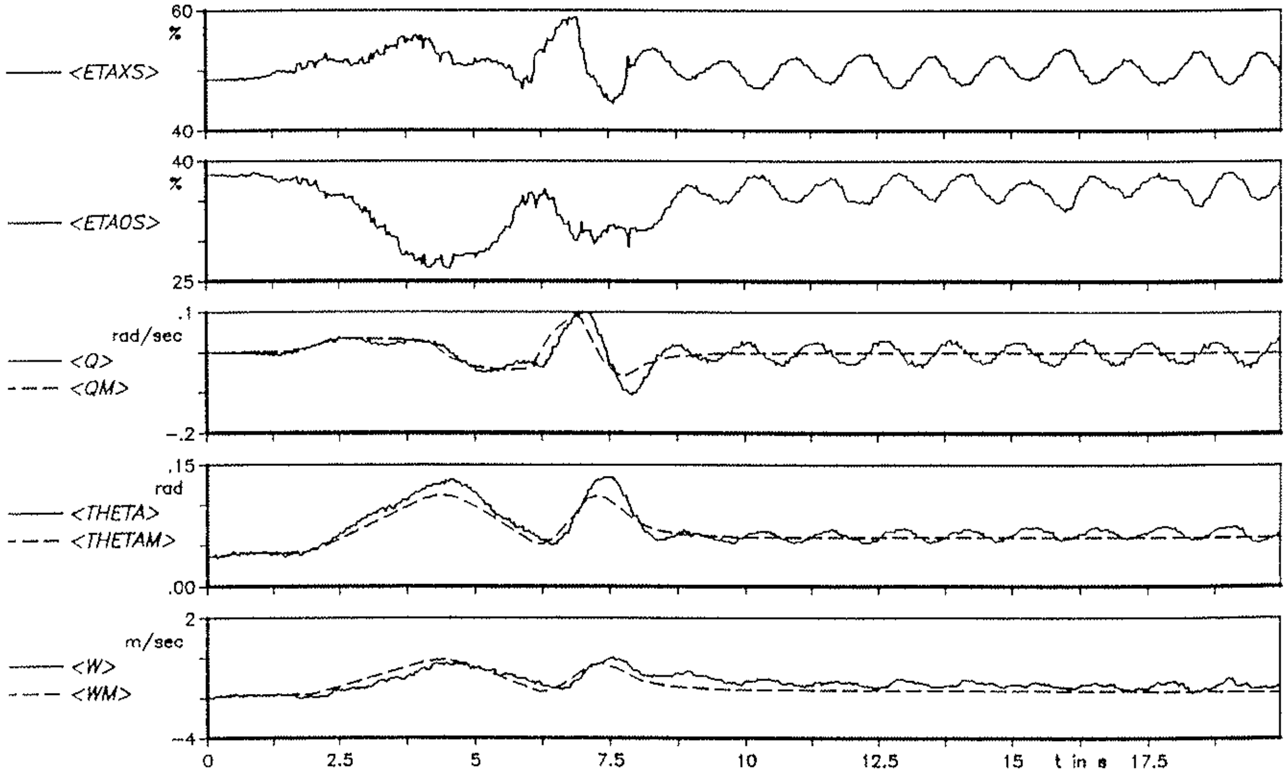

Figure 8. Pitch/Roll Oscillation in Flight '89

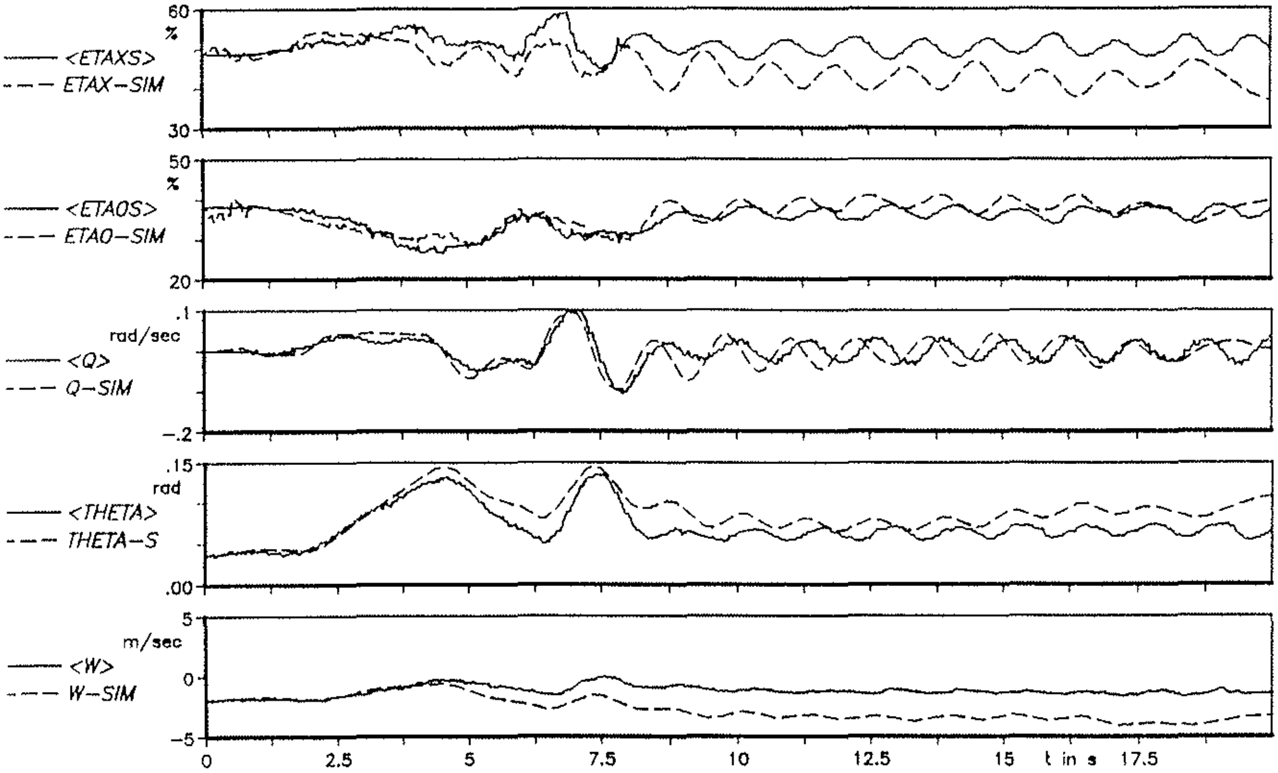

Figure 9. Simulated Pitch/Roll Oscillation

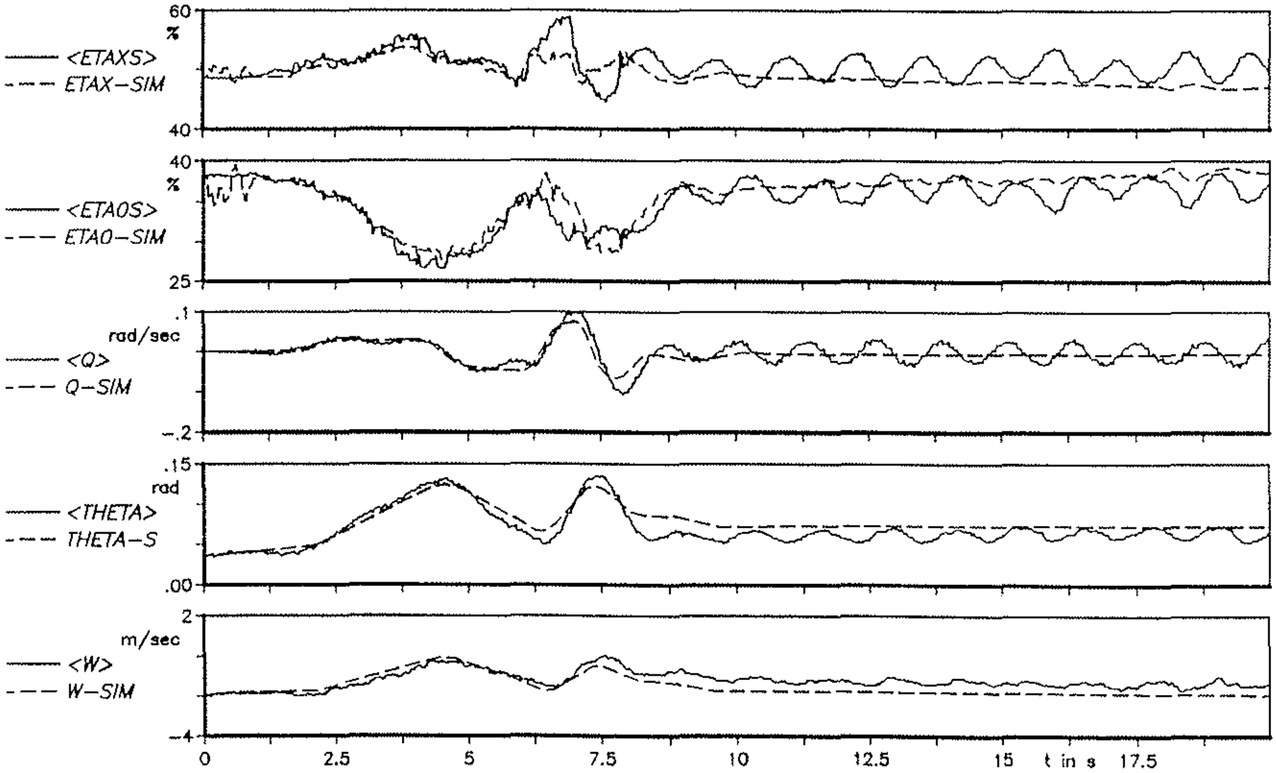

Figure 10. Pitch/Roll Oscillation suppressed in Simulation

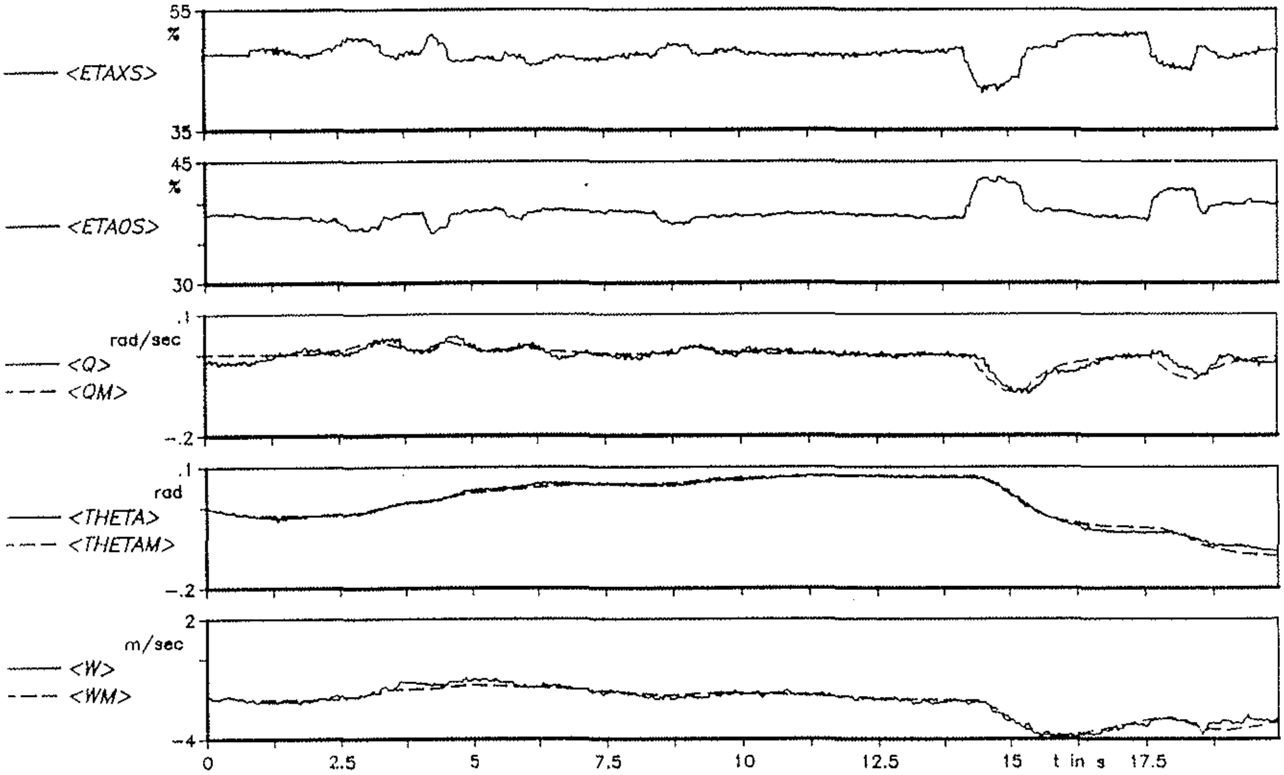

Figure 11. Pitch/Roll Oscillation suppressed in Flight '90

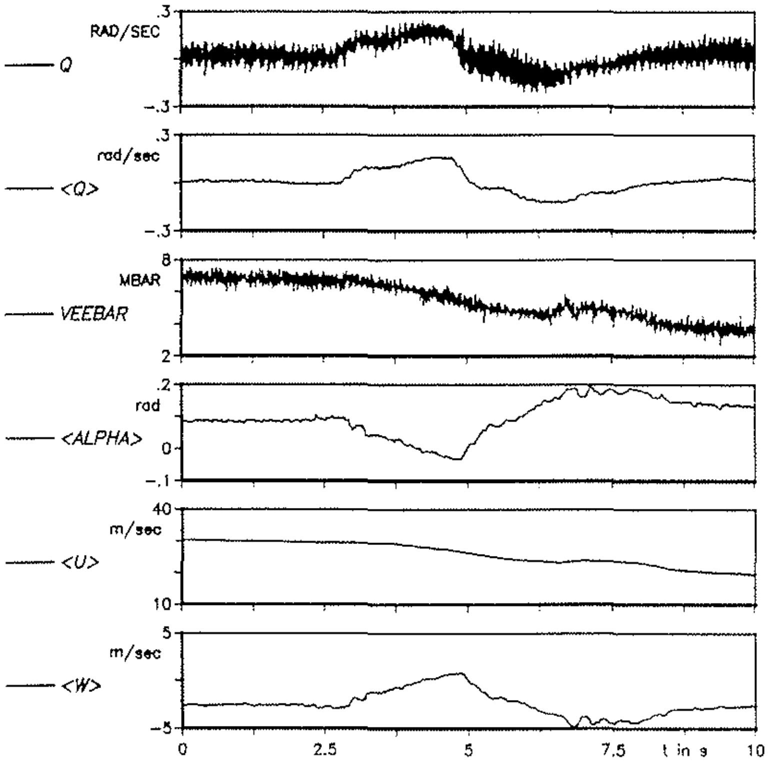

Figure 12. Sampled and Filtered Helicopter States

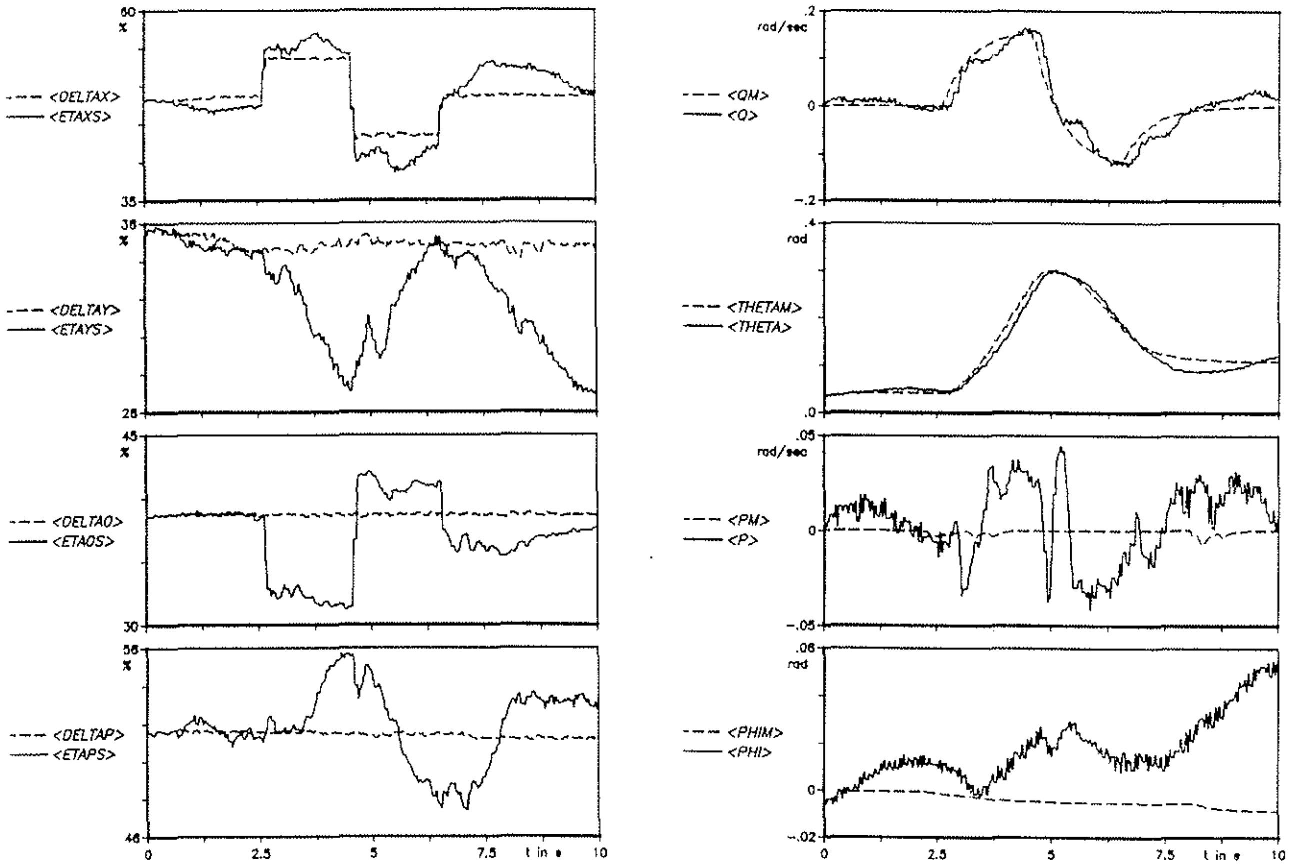

Figure 13. Controls and states for pitch/roll Decoupling

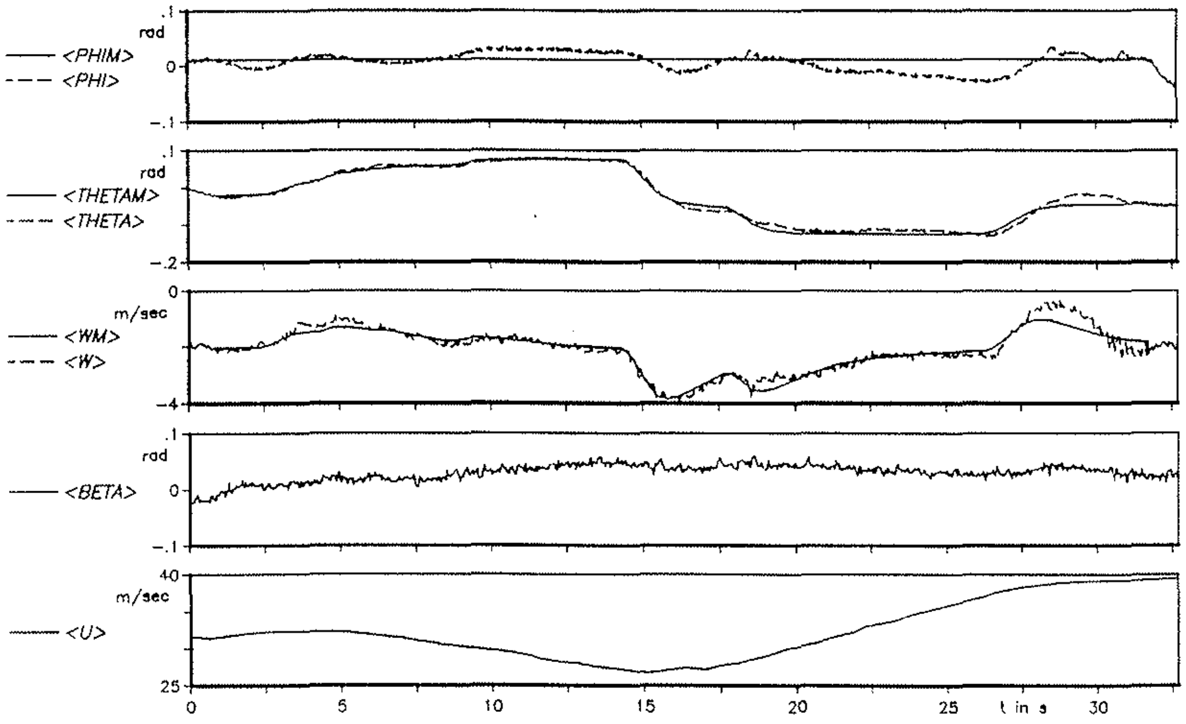

Figure 14. Acceleration Maneuvre

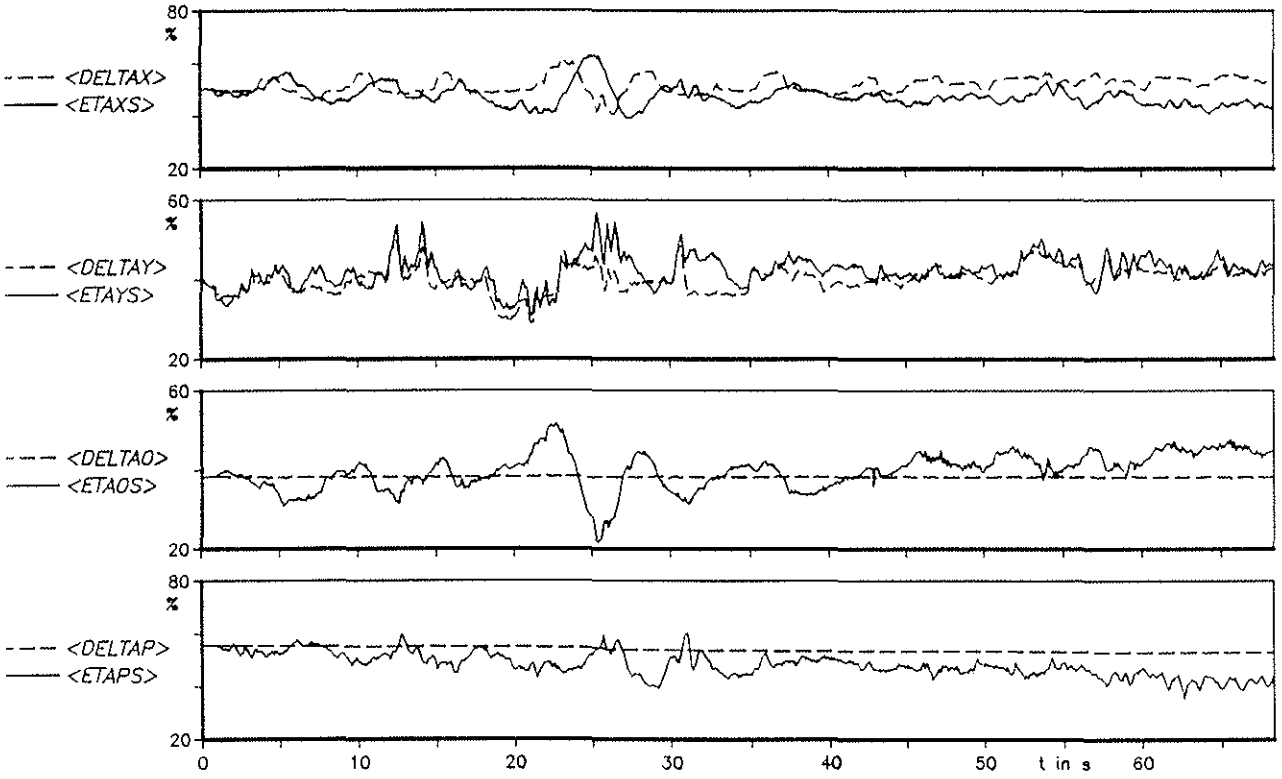

Figure 15. Controls during In-Flight Simulation of AH-64

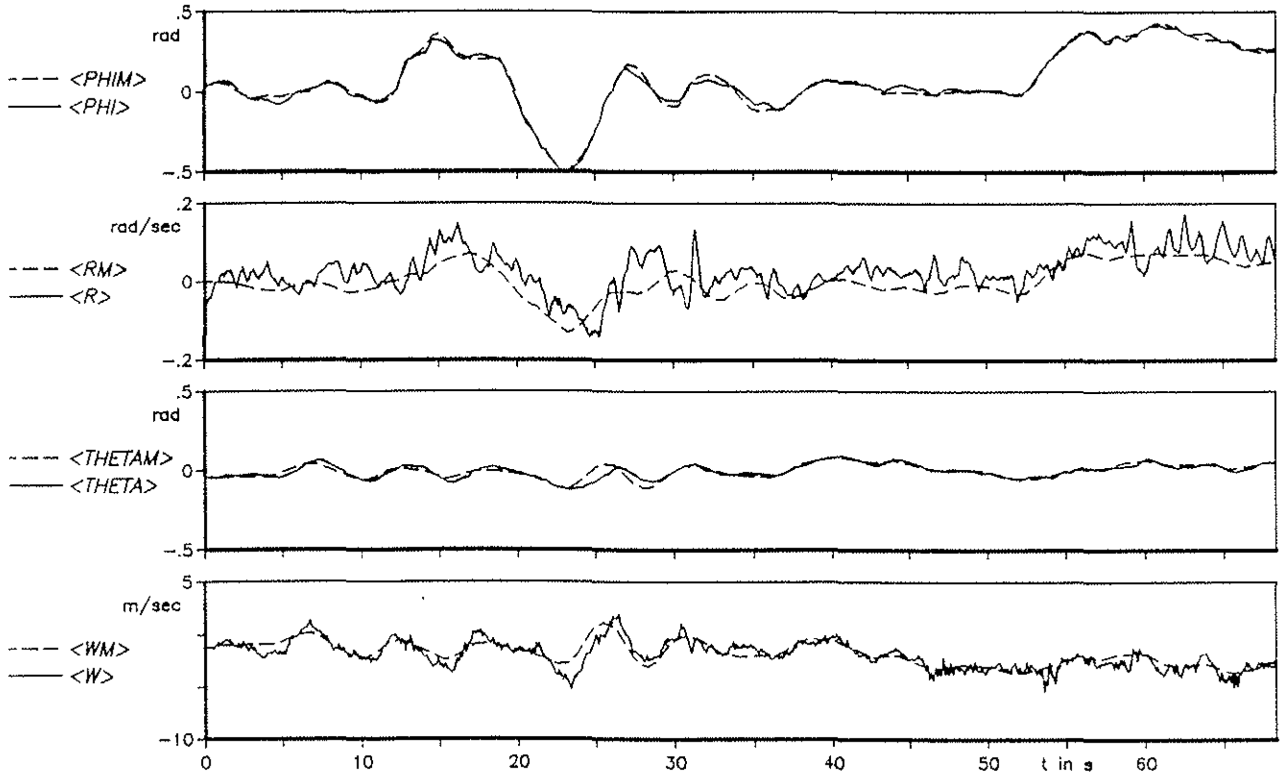

Figure 16. States during In-Flight Simulation of AH-64