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USE OF DFVLR IN-FLIGHT SIMULATOR HFB 320 HANSA FOR HANDLING QUALITIES INVESTIGATIONS

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Abstract

The Development of handling qualities criteria und airworthiness requirements for future aircraft using active control technology requires the use of highly sophisticated simulation tools and techniques such as in-flight simulation.

The DFVLR in-flight simulator used to cover the problem area mentioned above is based on a HFB 320 'HANSA' business jet aircraft. Simulation demands for handling qualities investigations and the resulting aircraft test equipment are given. The HFB 320 digital model following control system combined with 6 motivators gives five degrees of freedom simulation capability. The model following approach, realization and gust simulation under real turbulence will be discussed.

Flight test data are used to demonstrate the control system capability and simulation fidelity due to computer generated step inputs or manual flight maneuvers.

The applications of the HFB 320 in-flight simulator in several DFVLR handling qualities research programs are discussed and demonstrated by flight test results which show that the in-flight simulation technique is a suitable tool for solving the problems of handling qualities.

List of Symbols

a	acceleration
EPR	engine pressure ratio
h	altitude
K	gain factor
p	roll rate
q	pitch rate
r	yaw rate
S_e	side grip deflection pitch
u	speed deviation
u_a	actuator output
u_e	electrical actuator input
U_p	pilot inputs
VTAS	true airspeed
x	state vector
α	angle of attack
β	side slip angle
γ	flight path angle
δ	control surface deflection
ε	deviation
Θ	pitch angle
ϕ	roll attitude
φ	phase angle
ψ	course
ω	frequency
$(\dot{\ })$	differentiation with respect to time

Subscripts

a	aileron
e	elevator
F	flaps
G	gusts
H	'HANSA' test aircraft
M	model
P	pilot
th	thrust
x,y,z	body fixed directions

Abbreviations

BGT	Bodenseewerk Gerätetechnik
BMFT	Bundesminister für Forschung und Technologie
DLC	Direct Lift Control
FL	Flight Level
GLS	glide slope
GND	ground
ILS	Instrument Landing System
LOC	localizer
MBB-UH	Messerschmitt-Bölkow-Blohm Unternehmensbereich Hamburg
MSD	Mean Standard Deviation
NLR	National Aerospace Laboratory - The Netherland
PR	Pilot Rating
VFW	Vereinigte Flugtechnische Werke
RC/AH	Rate Command/Attitude Hold

1. Introduction

In the past handling qualities were related mostly to aircraft inherent parameters like frequency, damping and static stability. By the introduction of modern electric control systems the handling qualities became more and more functions of control system behaviour. Due to this the handling qualities characteristics of the whole complex of aircraft and control system had to be investigated to establish design criteria for good handling qualities.

For investigations covering this problem area simulation facilities are necessary which are able to simulate the system characteristics and the task environmental conditions with high fidelity.

As has been proved the in-flight simulation technique has turned out as a very suitable tool to solve these specific pilot-aircraft problems(1,2,3). This was the reason why the DFVLR started the development of an in-flight simulator based on the MBB-HFB 320 HANSA jet in 1969 (Figure 1).

The DFVLR-HFB 320 in-flight simulator will be described and some results of the use of this aircraft in handling qualities programs carried out since 1972 will be given.

2. In-Flight Simulator DFVLR-HFB-320 HANSA

2.1 Simulation Requirements

Requirements for flight simulators can be defined as to present realistic aircraft behaviour and environmental conditions. These demands are valid for ground based and in-flight simulators in general.

The fundamental parameters influencing pilots reactions and ratings are:

- outside view
- motion cues (six degree of freedom)
- aural cues
- aircraft dynamics
- control elements and dynamics
- instruments representation
- gust influence.

Using an aircraft as in-flight simulator especially all the requirements for outside view and motion cues are exactly fulfilled. The pilot, looking outside the windscreen and feeling the accelerations in the moving aircraft receives all the task dependent cues of real flight.

In in-flight simulation the presentation of motion is done by a control system forcing the simulator aircraft to follow precisely as commanded by the model aircraft. By this, the very important requirements of vision and motion cues are 'exactly' fulfilled. The degree of simulation fidelity is given by the 'model following' capability of the control system. The in-flight situation compared to ground based simulation is illustrated in Figure 2. In addition programmable cockpit instruments and an artificial feel system are mandatory.

Further for handling qualities investigations it is necessary to represent gust and non gust situations. In model non gust situations gust suppression of simulation aircraft is required. In model gust situations the in-flight simulator has to follow the model gust response. For the HFB 320 the gusts acting on the model can either be replayed from magnetic tape recorder or be measured from actual turbulence.

2.2 Test Equipment

To realize the simulation requirements for the longitudinal and lateral dynamic characteristics special components are installed in the HFB 320 test aircraft (Figure 3). Operating the aircraft as in-flight simulator the main features for the test equipment are:

- artificial feel system for primary controls
- electrically controlled flight instruments
- on board digital computer
- on board data acquisition system, data recording and telemetry system
- primary flight control system, fully fly-by-wire
- electrically controlled flaps and spoilers
- electrically controlled thrust
- safety equipment.

The evaluation pilots inputs are measured as analog electrical signals being converted before processed in the digital on board computer.

The evaluation pilots instruments are controlled by the computer (Figure 4), so that either data of the computed model or measured data can be displayed.

The controls on the right hand seat column, wheel and pedals are disconnected from the basic mechanical controls. The feel system is built up with mechanical springs of variable stiffness. Electrical trim devices are realized for all axis. The control surface/stick gearings are selectable by the evaluation pilot. As another option a side grip controller can be used instead of the normal wheel and column. The right hand controls and instruments are shown in Figure 4.

Together with the model aircraft dynamics the model following controller algorithm is built in the computer software. Interfacing the analog measurement equipment all data are available in the computer and can be recorded on a digital magnetic tape. A data set of 140 variables is recorded with 10 Hz rate as standard.

The telemetry system makes data available during flight tests on the ground. Figure 5 gives a view into the rear part of the cabin with the operator seat and installations.

All the control surfaces are operated via the on board computer. Therefore the primary flight control surfaces and spoilers use electro-hydraulic actuators with separate hydraulic power supply. For flaps electrical torque motors drive the basic hydraulic actuators while the thrust control system is fully electro mechanical.

For safety reasons the actuators of the primary controls are connected via clutches and shearpins with the mechanical system. The thrust actuator can be overridden by the safety pilot. An electronic box switches off the fly-by-wire system when detecting defined error states.

2.3 Model Following Control System

The control system for in-flight simulation is designed as an advanced model following control system with full state vector feedforward and feedback with compensation(4). A survey of the structure is given in Figure 6.

All function blocks are realized as software running in the on board digital computer. The model aircraft equations of motion and the model actuator dynamics are explicitly computed giving full feedforward information to improve the high frequency simulation capability. Due to feedforward the state feedback gains can be reduced.

The controller quality can easily be monitored because the full state vectors of model and test aircraft are available during flight tests. The controller has to minimize the difference of both model and test aircraft state vector. By using the explicit model computation the HFB 320 can be used as both, in-flight and fixed based simulator on the ground.

2.4 Gust Simulation

To obtain realistic flight test conditions the model has to be excited by actual atmospheric gusts. During test flights under natural atmospheric turbulence with a model receiving no gusts the motion cues percepted by the pilot are not coordinated with the information displayed on his instruments.

Simulating atmospheric turbulence in calm air a gust vector is fed into the model aircraft dynamics as demonstrated in Figure 7. In the verified structure a computer generated gust vector can be replayed from analog tape recorder. Simulating the correct model gust behaviour under external gust conditions a gust suppression device and a gust observer is required. The gust observer is realized by on line computation of a linear model of the HFB 320 aircraft using the measured control surface deflections as input. Comparing the state variables of the computed linear model of the test aircraft and the measured state variables a gust vector is generated.

Suitable filter constants for the compensator feedback gains of the observer where adapted in flight.

2.5 Realization of the Control System

The control system was built in as a part of the digital computer software, representing all in-flight simulator functions like controlling the flight instruments, data acquisition and recording. Actuator input signals attracted special attention, because rates and amplitudes had to be limited for safety reasons. Also nonlinearities generated by time delays of actuator systems and computing cycle times caused the optimized linear controller to be adapted to the real nonlinear system. As main tool for this task a hybrid simulation program running on an EAI P 600 hybrid computer system proved(5). Figure 8 gives a survey of the hybrid computer system used.

In this program all nonlinearities of the simulator aircraft and the actuators are simulated, also the influence of the limitations of the measurement equipment and data processing. The model following controller software is running in an identical form as in the on board computer. However, timing problems in program control occured computing the feedback loops. Due to severe influence of computer execution times on the dynamic and stability of the control system these times had to be represented exactly as they occured in the on board computer.

This ground based simulation system was used to adjust the feedback gain values of the linear controller design. Either step inputs generated in the on board computer program or pilot maneuver inputs can be used as test functions in ground based simulation or in flight tests.

3. Flight Test Results

3.1 Step Response

Using the same step inputs to the model aircraft as in ground based simulation flight tests were carried out in order to verify the controller quality as well as the simulation accuracy. It proved that the hybrid simulation program had to be modified to receive comparable results with flight tests. Mainly actuator dynamics had to be adjusted.

The used input signals were evaluated in flight tests for parameter identification of the simulator aircraft HFB 320(6). An on board computer program generated the signals suppressing all pilot inputs during runtime.

Using these inputs for validation of simulation accuracy speed, pitch attitude and pitch rate time histories of flight tests are plotted side by side for model and test aircraft (Figure 9). The fit of both curves is rather good regarding the deviations remaining within the margin of 0.4 m/s for speed, 0.2 deg for pitch attitude and 0.25 deg/s for pitch rate. These tests were flown in high altitude (FL 150) without atmospheric turbulence.

3.2 Flight Maneuvers

Besides step responses flight tests were performed with the pilot in the loop to check control input dynamics and gains in simulation mode. A time history plot is shown in Figure 10 for a descend, horizontal flight and a climb phase of all over 480 seconds maneuver time(7).

The good fit of the test aircraft to the model commands is obvious even in long terms effected by the compensator function of the model following control concept.

Drift effects occur for the computed altitude, because there is no feedback gain and no compensation for this variable. Indicated altitude was computed from measured static pressure. The simulation accuracy of the lateral directional motion was not so exact. A compromise had to be accepted because only aileron and rudder are available for controlling three degrees of freedom, no sideforce generators are installed.

For handling qualities investigations it seemed to be more useful to adjust roll rate and roll attitude rather than side slip angle.

3.3 In-Flight Simulation under Gusts

Flight tests have been carried out to verify gust simulation in flight. Two modes were tested, artificial gusts and measured atmospheric turbulence were fed into the model aircraft dynamic.

Evaluating model aircraft gust behaviour gusts from a tape recorder were fed into the dynamic computation. The gust model used was generated on the hybrid computer system according to the Dryden gust model. In this test phase the gust vector represented only angle of attack disturbances.

Plotted time histories in Figure 11 give an impression of the response of model and simulator aircraft in this configuration. Step inputs set in the computer program instead of pilots commands show the response of model aircraft simulation under artificial turbulence. It proved to be necessary to give also feedforward information to the controller simulating flight under atmospheric turbulence to obtain as good accuracy as under command inputs. In further flight test investigations there will be also gains for $\dot{x}_M$ variables to test aircraft actuator inputs.

To verify the accuracy of the gust observer again step inputs to the model actuators were used. In calm air (FL 160) no gusts should be measured, so the observer has to follow exactly the motions of the simulator aircraft. This can be seen in time histories in Figure 12.

In order to suppress low frequency 'gusts' it is necessary to compensate differences between test aircraft and gust observer states, being computed as a linear model of the simulator aircraft. Deviations at high frequencies are however interpreted as 'gusts'. This effect is obvious for the angle of attack disturbances as shown in Figure 13 (α_G = observed gusts).

In these time histories of maneuver flights under natural atmospheric turbulence in 2.500 ft altitude are shown. Obvious are the high frequency angle of attack variations measured in the gust observer. The response of the model aircraft shows that gusts of these frequencies have only little effect on the model motion, whereas lower frequencies give the major effect.

4. HFB-320 In-Flight Simulator Applications

The DFVLR basic handling qualities research programs are related to transport aircraft. The general goal is to establish new handling qualities criteria which are applicable for future advanced control systems. Further, methods to describe and to evaluate the pilot/aircraft system will be developed.

4.1 Direct Lift Control (DLC) Handling Qualities Research

Since 1972 the HFB 320 in-flight simulator was used in several handling qualities programs to investigate the potential of DLC in landing approach(8,9,10,11).

Several DLC concepts were evaluated in actual landing approaches down to 500 ft (GND)(8). The pilots describing functions were measured in flight-path tracking experiments(9) and DLC was evaluated in special altitude tracking experiments with different combinations of aircraft pitch and heave dynamics(10).

Figure 14 shows the time histories of altitude tracking where the pilot had to minimize the error between a commanded altitude and the actual altitude by his stick action. By plotting the model and the actual aircraft response the model following fidelity is shown (Figure 14). The system evaluation was carried out by performance measures (msd of altitude error) and pilot effort ratings (Figure 15). For comparison the investigations are made in flight and on the ground using the HFB 320 as fixed based simulator.

Effects of lack of motion cues are given by the differences in performance and pilot ratings as shown in Figure 15. The general results of this experiment are shown in Figure 16 comparing the aircraft/system parameters (pitch/heave motion) with pilot effort boundaries.

4.2 In-Flight Simulation of the A 310 Airbus with DLC in Landing Approach

These experiments carried out in cooperation with MBB-UH, VFW and BGT are funded by BMFT(11). Main emphasis in this investigation is laid on the evaluation of different spoiler DLC concepts for longitudinal control. The influence of these concepts on handling qualities and pilot vehicle performance under real ILS approach environmental conditions are determined. 63 ILS approaches were flown by two pilots evaluating four aircraft DLC configurations. Both, the longitudinal and the lateral directional dynamics of the A 310 aircraft were simulated by the HFB 320. The results of these investigations showed that the flight path control could not be improved by DLC. The reason is that in case of series closure for manual flight path control (see Figure 17) by pitch attitude with DLC the outer loop bandwidth is increased to values of the inner pitch stabilization loop bandwidth. The high frequency pitch/flight path coupling leads to higher pilot workload especially for sluggish pitch aircraft dynamics. The pilot wants to have a clear frequency separation of the inner and outer loop.

A simple handling quality parameter could be found which is a measure for the loop bandwidth separation. This is the flight path to pitch attitude phase difference for inner loop frequency characterizing the coupling between the two loops. So a new general applicable flight path criterion could be established as shown in Figure 17(11).

4.3 Handling Qualities Investigations of Rate Command/Attitude Hold System (RC/AH) for Future Transport Aircraft

Future transport aircraft will fly with fully 'fly-by-wire' control systems. One solution to improve aircraft behaviour and to reduce pilot workload is a rate command/attitude hold system (RC/AH)(12). But to design such a system in an optimal way a large amount of handling qualities research is necessary.

The HFB 320 In-Flight Simulator was used in a cooperative program with the NLR to investigate the handling qualities of such a system in landing approach. This program is a typical example for the in-flight simulator flexibility in adapting advanced concepts in a quick way by reprogramming the on board computer model.

The RC/AH system function is shown in Figure 18 using a sidegrip (developed by DFVLR Institut für Flugführung, see Figure 4) as control element for pitch and roll. By this system the pilot only commands pitch or roll rates, in loosing his grip the last attitude will be hold automatically by the system. The flight tests showed that the pilot control behaviour changed dramatically compared with conventional aircraft. This is caused by the fact that the pilot is released in stabilizing the aircraft and in counteracting the external disturbances, which are alleviated automatically by the system.

A typical approach flown with the RC/AH feature in the HFB 320 by modelling the command dynamics in the on board computer is shown in Figure 19. This approach though flown under moderate gusts, shows the extremely low pilot activity in both, pitch and roll axis.

Further, these results show a change in pilot aircraft loop situation leading to pulse type control inputs by the pilot. The closed loop high frequency pilot aircraft control loop never exists for that task.

This new pilot control situation and the changed pilot control technique require modified or new handling qualities criteria which are able to describe that behaviour.

5. Conclusions

In this paper a short description of the DFVLR-HFB 320 in-flight simulator was given. Regarding general simulation requirements it was illustrated which way had been chosen for realization. The technical installations were introduced giving an impression of the completion of the test aircraft as in-flight simulator. Due to on board digital computation it was possible to adapt the model following control system to various model aircraft concepts without great efforts and test aircraft modifications.

The flight tests being carried out since 1972 proved that this in-flight simulator was a good tool to get valid results for handling qualities investigations for transport aircraft. Flying under realistic outside world conditions the obtained results were more relevant for the pilot/aircraft performance and pilot ratings.

6. References

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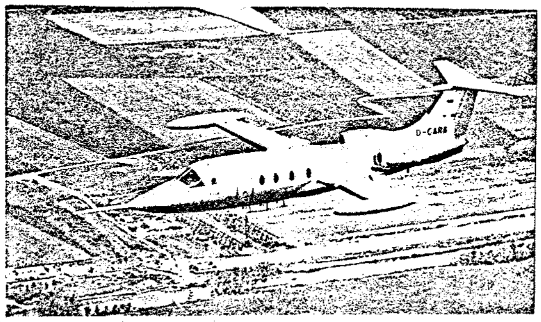

Figure 1. DFVLR-HFB 320 In-Flight Simulator

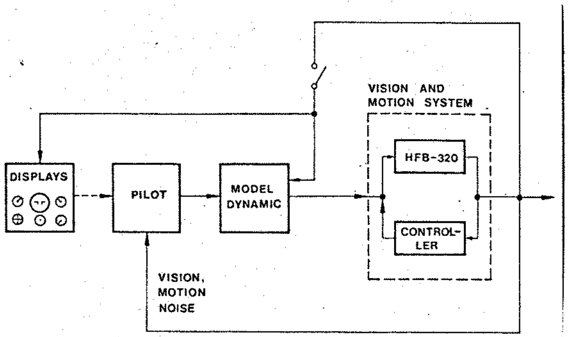

Figure 2. General Situation of In-Flight Simulation

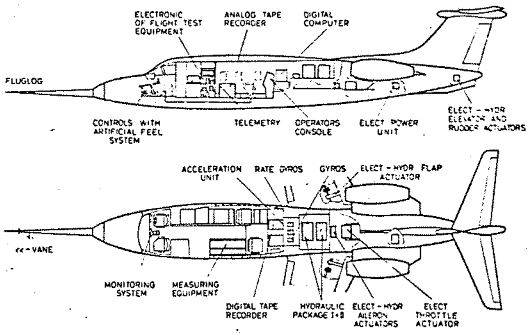

Figure 3. Flight Test Equipment Installation

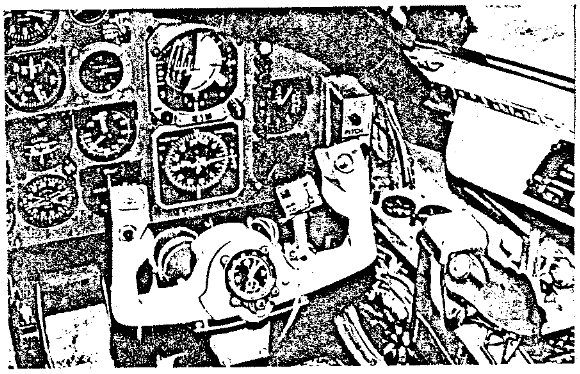

Figure 4. Evaluation Pilot's Controls and Instruments

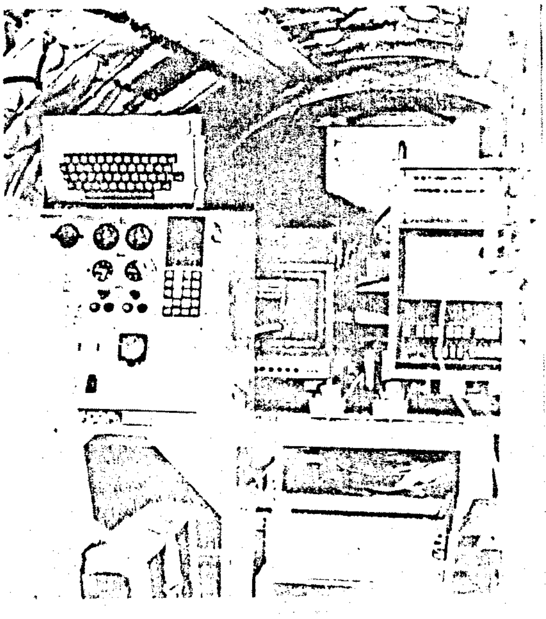

Figure 5. Cabin Installations

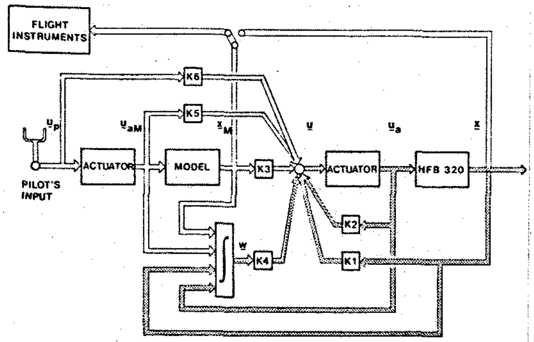

Figure 6. Model Following Control System

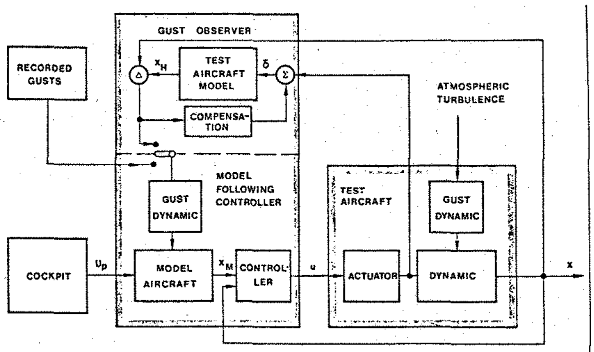

Figure 7. Gust Simulation Scheme

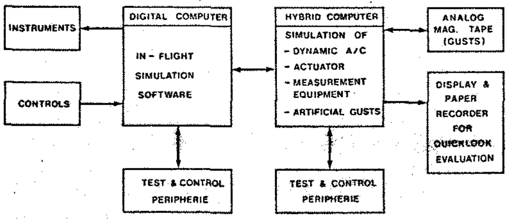

Figure 8. Ground Simulation Facilities

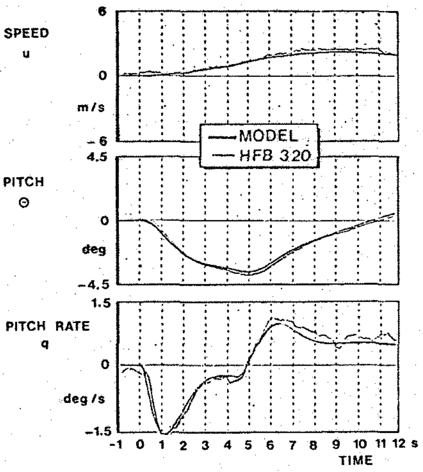

Figure 9. Step Response of Model and HFB 320 (Elevator Input)

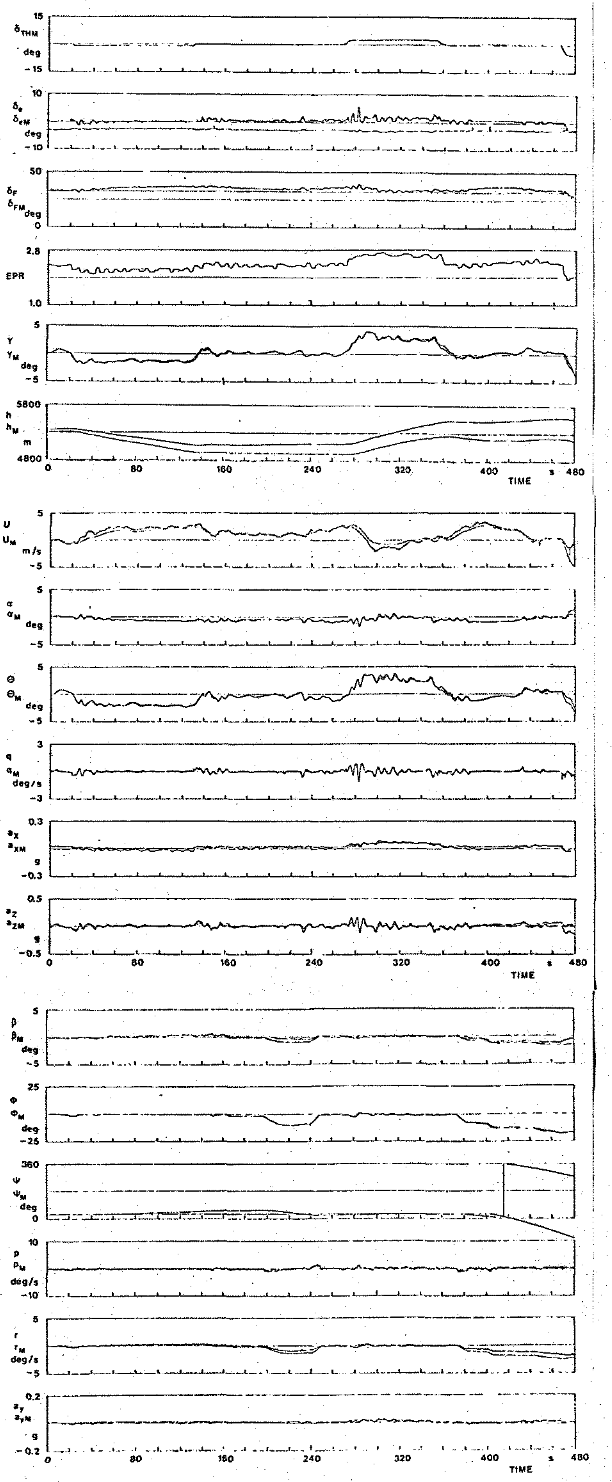

Figure 10. Time Histories of Maneuver Flight

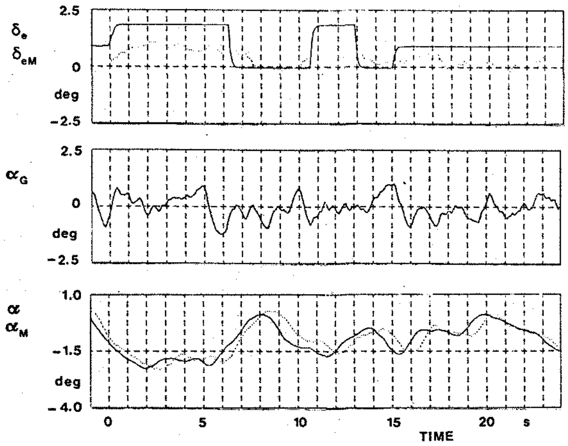

Figure 11. Step Response with Artificial Gust Inputs

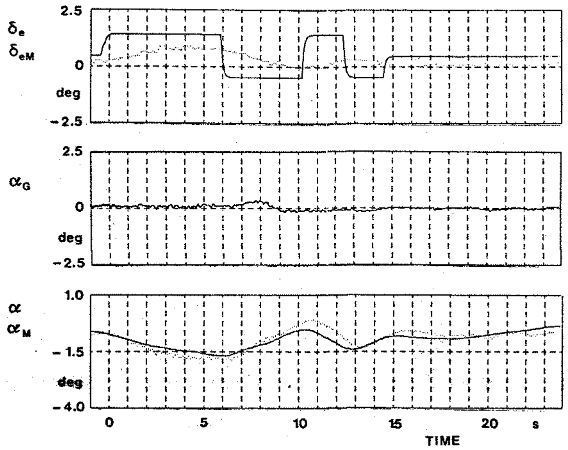

Figure 12. Step Response with Gust Observer

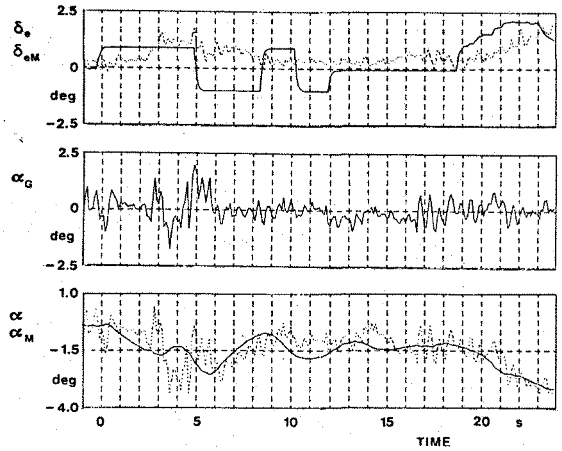

Figure 13. Time Histories of Flight in Turbulence

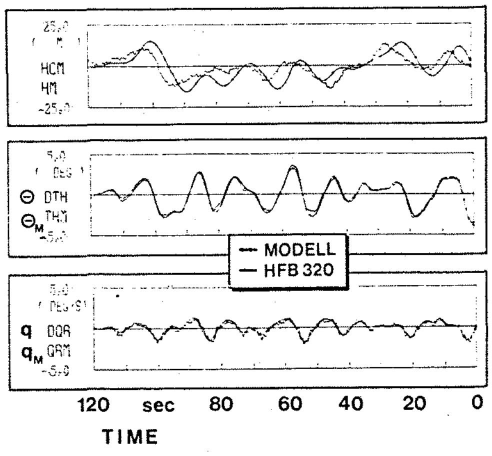

Figure 14. Time Histories of Altitude Tracking

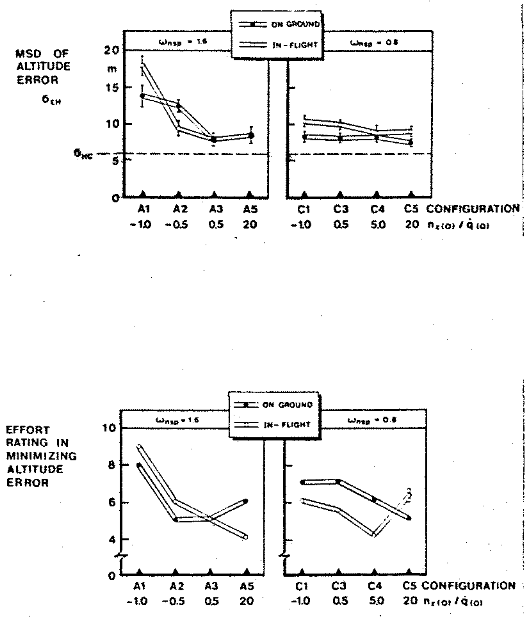

Figure 15. Mean Standard Deviation of Altitude Error and Pilot Effort Rating Summary

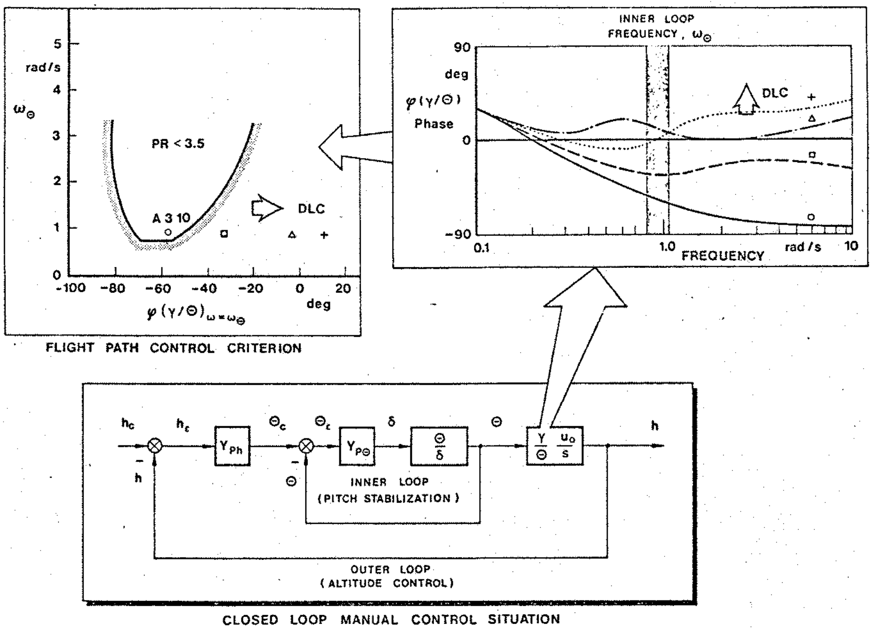

Figure 17. General Flight Path Control Criterion for Transport Aircraft

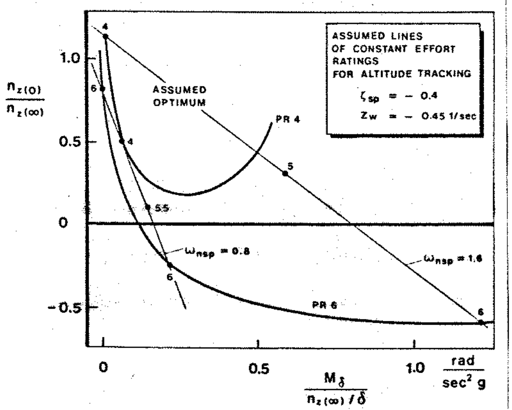

Figure 16. Effort Ratings vs Pitch/Heave Motion Parameters

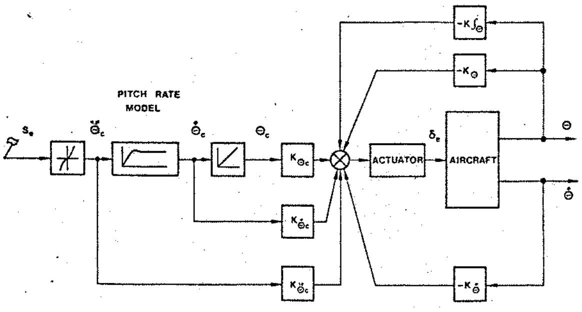

Figure 18. Rate Command / Attitude Hold Schematic (Pitch Axis)

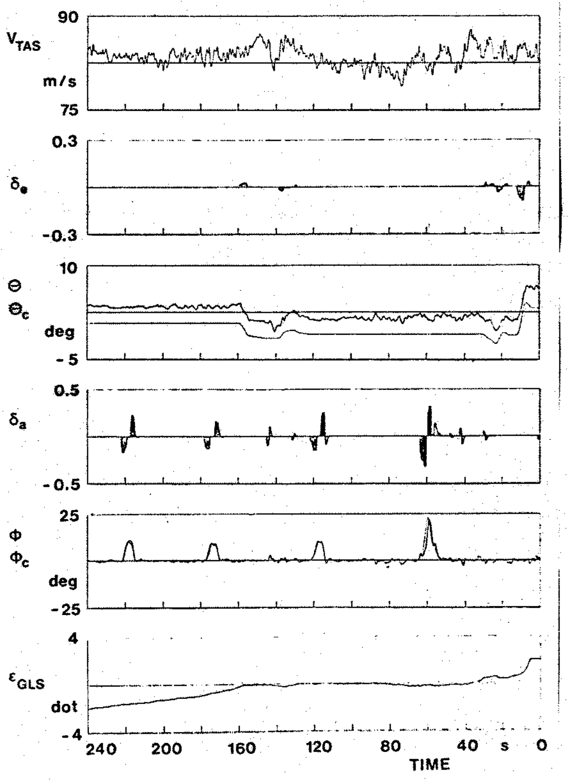

Figure 19. Landing Approach under Gust Conditions with RC/AH-System