

EVALUATION OF A NEW FLIGHT PATH COMMAND CONTROL CONCEPT

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ABSTRACT

The introduction of digital electric flight control systems as well as new theoretical techniques in multivariable control synthesis open new ways in overall control system design. In particular, the development of advanced command control systems offers great promise.

A digital command control system, which follows independent commands in change of glide slope angle and speed in the sense of 4-D-guidance, has been designed and evaluated in simulator tests. The commands are fed in by the pilot by means of control column or side grip controller deflection. The influence of certain control loop modifications has been investigated. Test results show the tracking performance, achieved by use of an optimized control law and suitably modified pilot interfaces.

INTRODUCTION

Remarkable progress in automatic flight control design has been achieved in recent years through the merger of two developments, the theoretical achievements in optimal control and the technology of safe electronic and electrohydraulic data processing and signalling systems, i.e. fly-by-wire (1, 2). Both gained impetus through digital computing techniques and corresponding hardware developments.

The effects with respect to the feasibility of the digital fly-by-wire concept(3) permit optimism such that advanced multivariable control would be employed most effectively, making use of the high accuracy, programmability and flexibility of digital computation.

Modern techniques open new ways in overall design of integrated guidance and control systems for aircraft, including sensors, pilot controls, instrumentation and automatic flight controllers for the longitudinal and lateral motion. Such advanced guidance and control systems improve the accuracy of conventional flight procedures and offer the possibility of accurate flight along steep, curved flight paths, which could be introduced in connexion with future terminal area air traffic control or noise abatement requirements.

In addition to the fully automatic modes modern flight control systems include command control - with the pilot in the loop - as basic mode. With command control the pilot does not steer individual deflections of the control surfaces, but commands changes of the state variables by means of his controls (See Figure 1).

This paper presents flight test results with an integrated guidance and control system developed for the DFVLR test aircraft HFB 320 and an exploratory

flight simulator study on a flight path command control system for the longitudinal motion.

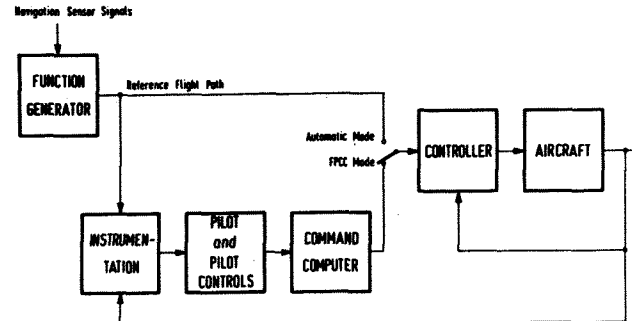


FIGURE 1. PRINCIPLE OF PILOT COMMANDED FLIGHT PATH CONTROL

PRINCIPLE OF FLIGHT PATH COMMAND CONTROL

Operating on a principle close to 'manoeuvre demand' or 'Control Wheel Steering'(4,5), 'Flight Path Command Control' is the basic mode of the integrated flight control system. The pilot directly steers the flight path angle as well as speed by feeding command inputs through deflection of his manipulator (control column or side grip controller) into the automatic controller. Thus the pilot takes charge whenever he wants a change in these flight path parameters. In this case he has two control options. One may be called a tracking mode with the pilot following a specific predetermined flight path reference profile e.g. stored in a flight director computer. The second mode allows the pilot full freedom in the application of flight path commands. In this case a new type of indicator is required, whereas for the tracking mode the Attitude Director Indicator may still serve as a primary flight path director indicator.

DESIGN PROCESS

The heart of the integrated flight control system is the automatic controller equivalent to CSAS. Figure 2 shows the control loop structure with additional feedforward loops for derivatives of commanded values which are necessary in order to keep the control error small for second order curved path command inputs. All controls are used, i.e. aileron, rudder, elevator, flaps and throttle. The commanded values are bank angle, side slip angle,

height, speed and angle of attack.

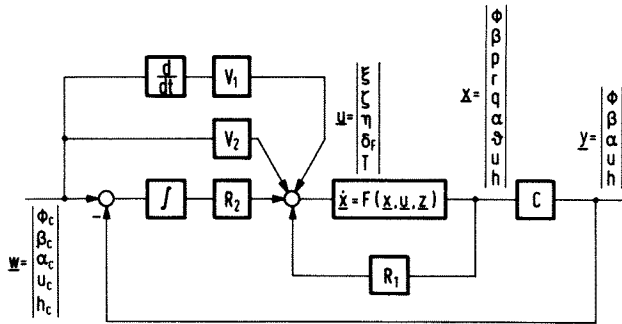


FIGURE 2. AUTOMATIC FLIGHT CONTROL SYSTEM

The control coefficients are obtained as a result of a simulator aided synthesis process. A numerical optimisation algorithm is used for the fixation of all parameters subject to a cost function weighting (See Figure 3).

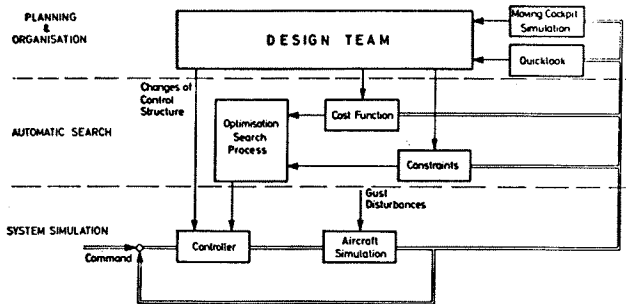


FIGURE 3. COMPUTER AIDED CONTROL SYNTHESIS

The following cost function quantities are considered:

- Deviation from the commanded values,
 - i.e. height (Δh)
 - speed (Δu)
 - angle of attack $(\Delta \alpha)$
 - side slip angle $(\Delta \beta)$
 - bank angle $(\Delta \phi)$
- control rates,
 - i.e. aileron $\dot{\xi}$
 - rudder $\dot{\zeta}$
 - elevator $\dot{\eta}$
 - flaps $\dot{\delta}_F$
 - throttle \dot{T}
- rate of pitch q , bank p and yaw r .

All known non-linearities are introduced in the evaluation of the cost function. The results are observed by the design team. This provides the necessary feedback information in order to establish whether the weighting of the individual cost con-

tribution has attained proper correspondence with the engineering objective.

In order to include the pilot's rating in the design process at an early stage, especially in the case of FPCC, a pilot in a moving simulator-cockpit can observe automatic flight in rough air and also operate FPCC. The simulator is linked to the simulation computer. In particular in the case of the design of a command control system the pilot's comment is of great importance. If the pilot does not completely accept the automatic control loop behaviour, there is a great probability that by his commands he will interfere with the automatic controller because of lacking confidence in its performance. The pilot's and the designer's judgement may cause modifications of the cost weightings in further optimisation runs.

This kind of design procedure is a trade off between pure computer optimisation and the optimisation based on a full scale simulation, i.e. - in the case of FPCC - the pilot is kept in the loop during the whole optimisation process. The latter would lead to excessive pilot engagement.

FLIGHT TESTS WITH THE HFB 320

The flight tests with the business jet type aircraft HFB 320 essentially concerned to fully automatic approaches on steep, curved glide path profiles. The accurate flight along curved paths requires high accuracy of the navigation and control system. A hybrid navigation system on board of the HFB 320 is used for measuring the position in earth-fixed coordinates, which possibly will be utilized in future airline aircraft. In the sense of complementary filtering the data of an Inertial Navigation System (INS) are blended with the barometric height and the data of a VOR/DME-System or a microwave landing system such that the platform position is precisely updated and the navigation receiver signal noise is smoothed. For the flight tests the DLS (i.e. DME based landing system, the german proposal for a future MLS), which is located on the airfield of Braunschweig, was used for updating the platform position. The output signals of the hybrid navigation system are fed into the integrated flight control system by cross coupling nearly all state components with all controls. Dependent on the distance from the airfield the height of the reference flight path is computed in a function generator on board.

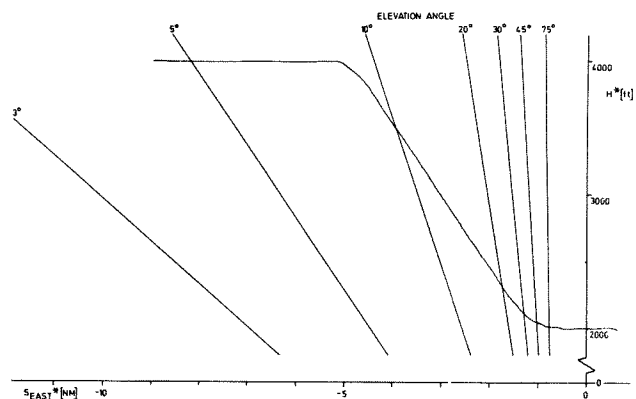


FIGURE 4. AUTOMATIC APPROACH WITH HFB 320 (5° GLIDE PATH ANGLE)

Figures 4 and 5 show the actual path of an approach with 5° glide path angle in the vertical and horizontal plane, where the updated platform position SEAST^W, SNORTH^W and H^W is plotted.

For safety reasons, i.e. because of insufficient system redundancy, flight testing of automatic flight path control was carried out at altitudes above 2000 ft GND. Therefore the reference flight profile, consisting of parabolic and rectilinear segments, shows a transition into horizontal flight, which ends 2000 ft laterally above the DLS elevation station. The flight task for the lateral motion was the interception and straight on approach on a DLS-Radial to the runway. Besides the automatic flight path control the integrated flight control system was keeping the approach speed on 140 Kts and the angle of attack on the commanded value which was constant in the case of this flight test. In order to avoid the cone effect problems instead of angular "beam quantities" the lateral and vertical deviations in (ft) were nulled out by the automatic controller.

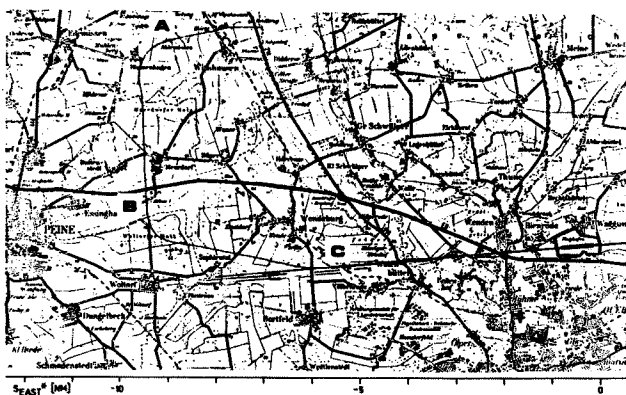


FIGURE 5. AUTOMATIC APPROACH WITH HFB 320 (5° GLIDE PATH ANGLE)

The lateral control was carried out either by Control Wheel Steering (i.e. ϕ -command and bank angle hold), heading hold or fully automatic control. The fully automatic approach was started at point A in a distance of 9 NM northwest of the DLS-azimuth station on Braunschweig airfield. The intercept procedure began in cross direction to the DLS-Radial at point B. In a distance of 1.6 NM apart from the Radial an intercept heading of 20° apart from the approach course was taken.

The aircraft was established on the Radial at point C and began the smooth transition into the descent with 5° glide path angle. The maximum deviations in height have been less than 10 ft during the whole approach. During the descent phase at a height of 2500 - 3000 ft GND a wind shear caused a lateral deviation of about 150 ft, which was nulled out until the transition into horizontal flight.

The figure 4 shows also the aircraft angular position relative to the DLS-Elevation station.

The flight tests have shown that integrated flight control systems ensure a very accurate guidance along curved paths in the automatic mode. But the question arises if it is possible to reach an adequate accuracy with pilot commanded flight path control and acceptable pilot workload. For answering this question an exploratory

flight simulator study on a flight path command control system for the longitudinal motion was carried out.

FLIGHT SIMULATOR TESTING

Flight path reference function

A curved steep approach profile has been chosen as the flight path reference function. The command parameters for the automatic controller are height, speed and angle of attack as functions of the distance to go. The speed and the angle of attack are to be kept constant, whereas the height changes from 4000 ft to 2000 ft, as shown in Figure 6. These commands describe the simulator flight task for the longitudinal motion only, using different control system features.

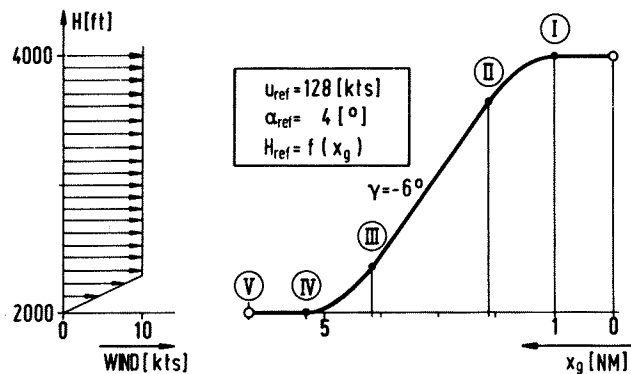


FIGURE 6. REFERENCE FLIGHT PATH AND WIND SHEAR PROFILE

The lateral task consists of keeping the aircraft on the centerline of the Localizer without automatic control aid. Atmospheric turbulence is simulated including horizontal and vertical gusts as well as wind shear during the final flight path sections.

As a favorable side effect of atmospheric turbulence simulation little irregularities of the moving system, caused by short travel in each axis within which wash out capability has to be achieved, are no longer objected by the pilot.

Thus flight path deviation under these reproducible conditions could be evaluated as an objective performance measure.

Flight simulator test system

The simulator consists of a medium size digital computer, a moving cockpit system with 4 degrees of freedom (pitch, heave, roll, sideways motion), the cockpit being quickly interchangeable. The software reproduces a 6 degree-off-freedom, nonlinear model of the DFVLR-test-aircraft HFB 320. Nonlinearities in the control elements in particular in the flap and engine controls, e.g. speed limitations, sensitivity thresholds and backlash, are also taken into account.

The test cockpit is shown in Figure 7. The Attitude Director Indicator is used as the main instrument for all pilot controlled configurations investigated. Provision is made for different flight director laws. Because of the flight task of controlling a curved steep flight path the conventional flight director law had to be modified.

The modifications are developed again by use of the simulator with the pilot in the loop. This was extremely necessary because, as is obvious the pilot reacts very sensitively on changes of the instrumentation. Instead of height (or glide path) deviation and the pitch angle θ , the height deviation h and the vertical speed \dot{h} , relative to the reference flight path were used for the flight director pitch signal.



FIGURE 7. SIMULATOR TEST COCKPIT

For certain test configurations an additional display was available next to the Attitude Director Indicator. This display provided useful monitoring information on the momentary position of the airplane relative to the reference flight path.

Two types of pilot control handles were used alternately, the control column and a palm grip manipulator, developed by the DFVLR.

Test configurations

As mentioned earlier different control system features were tested in the flight simulator study, some of which are illustrated in Figure 8. All were used with the same control task as explained in the previous section. Two basic configurations are used as references, the manual control and fully automatic control. The remaining three are FPCC-configurations. The first one with command of $\dot{\theta}$ comes close to that known as Control Wheel Steering and the last two are both pure FPCC-configurations with direct command either of the flight path angle (' γ -command') or its derivative (' $\dot{\gamma}$ -command'). At this point, two significant differences should be mentioned between the $\dot{\theta}$ -command on the one hand and the pure FPCC system on the other hand. The first distinction is that of using an auxiliary flight path variable θ instead of genuine flight path parameters. The second one becomes evident in the control loop structure. In the case of ' γ - and $\dot{\gamma}$ -command' the automatic flight path control loop - which is part of all FPCC-configurations - is separated from the control loop of the pilot. Thus, opposite to the ' $\dot{\theta}$ -command', flight path disturbances due to atmospheric turbulence do not affect the pilot control loop, i.e. the pilot control loop is unburdened of the need to deal with external disturbances.

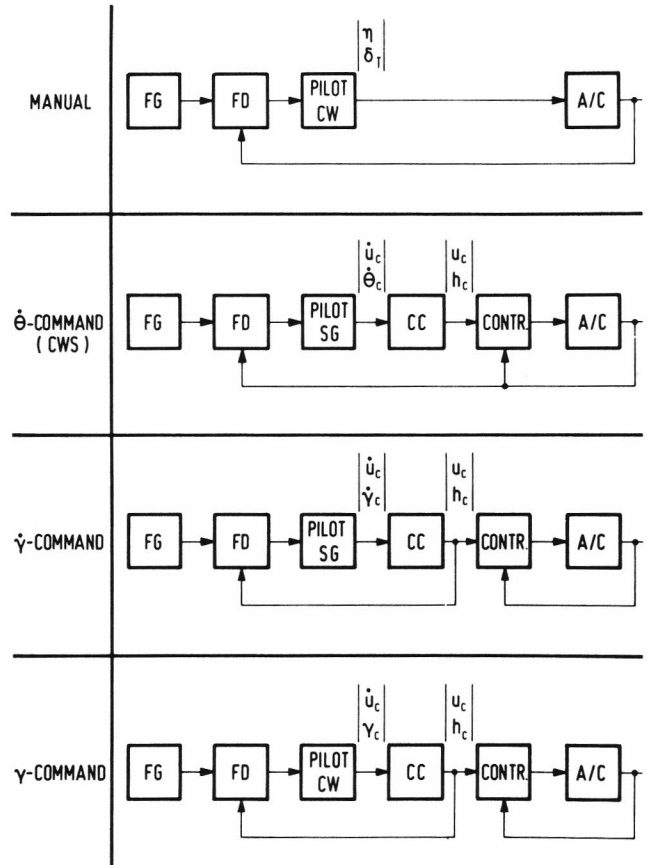


FIGURE 8. TEST CONFIGURATIONS

EXPERIMENTAL RESULTS

After an extensive phase of training runs a number of simulator flights were conducted for a statistical evaluation of flight path tracking accuracy, infact ten flights for each configuration. Because of the exploratory nature of this test program only one pilot was engaged in this phase of evaluation flights.

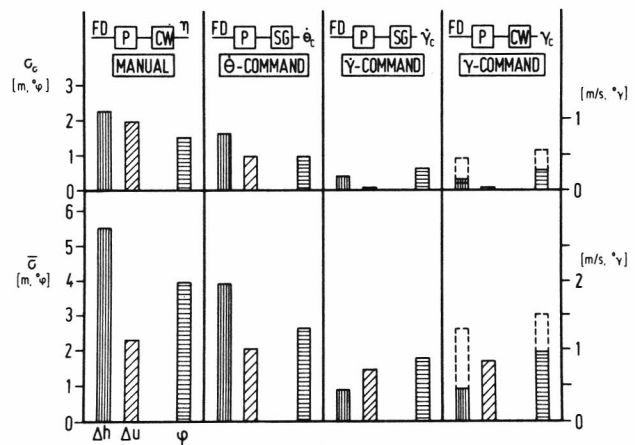


FIGURE 9. STANDARD DEVIATIONS OF ALTITUDE, SPEED AND BANK ANGLE (WHOLE TEST FLIGHT DISTANCE)

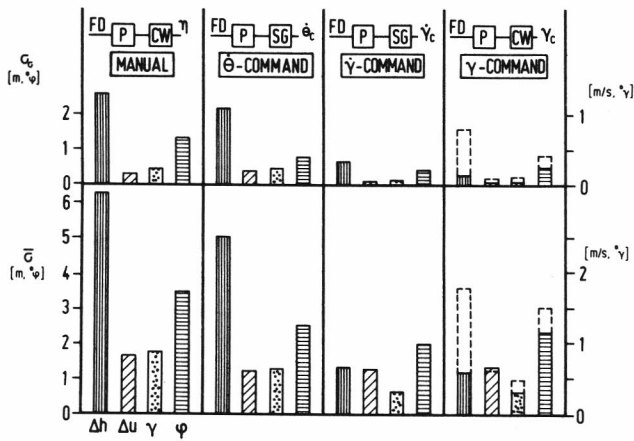


FIGURE 10. STANDARD DEVIATIONS OF ALTITUDE, SPEED FLIGHT PATH ANGLE AND BANK ANGLE (6° DESCENT SECTION)

The statistical data were evaluated in terms of the means of standard deviations of relevant flight path parameters for each of the five flight path sections shown in Figure 6, as well as for the whole flight path distance. Figures 9 and 10 show some results for the whole flight path distance and the 6° descent section respectively.

The mean value of the standard deviations and the scatter around this value, again expressed as standard deviation, are plotted for the deviation in height, speed and bank angle with respect to four test configurations.

The mean values show a significant increase in tracking accuracy for the 'γ- and γ̇-command' in comparison with the 'Manual' and the 'θ̇-command' configurations. This tendency becomes more significant for the scatter around these mean values. These quantities turn out to be highly correlated to the pilot's rating, i.e. positive rating for low deviation values. Also the number of training runs necessary for the accomplishment of reproducible results is correlated to these values. Two kinds of columns are shown in the case of 'γ-command'. Those drawn with dotted lines illustrate the results for a pure γ-command configuration, which look significantly poorer than those of the γ̇-command configuration. The reason is, that for good performance of the pilot control loop the pilot has to generate considerable lag. Therefore, from the statistical results the pilot's rating turned out much worse than for the 'γ̇-command'. This could be mended by artificially lagging the pilot's signal with a time constant of 5 seconds. The corresponding results are shown in the solid line columns in Figure 9 and 10. It should be noted, that because of the introduction of the artificial lag, within the important frequency range the pilot no longer controls pure γ but a γ-command signal blended with γ̇.

The time histories in Figure 11 and 12, showing one representative flight for each of the configu-

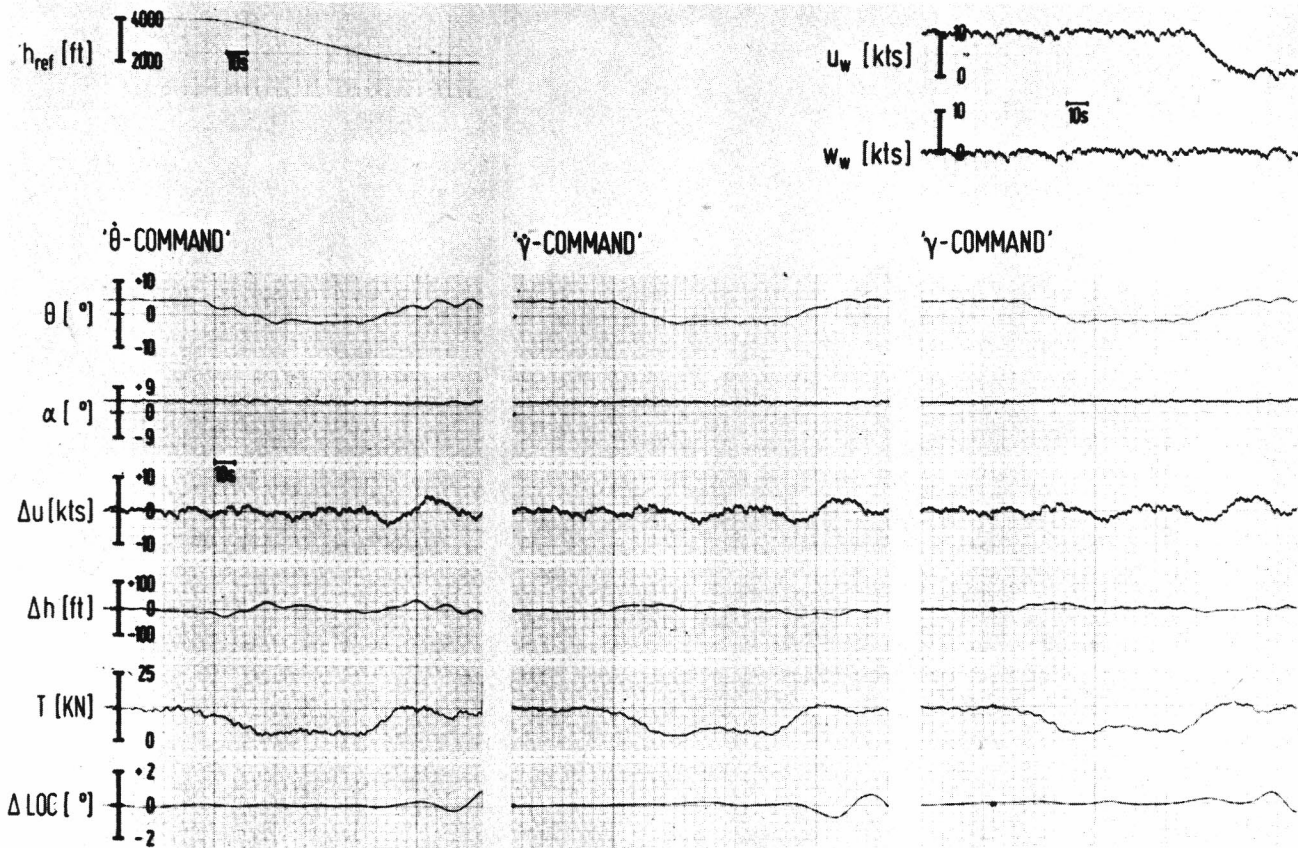


FIGURE 11. TIME HISTORIES OF PILOT COMMANDED FLIGHT PATH CONTROL WITH θ̇-, γ̇-, γ-COMMAND (SIMULATOR TEST FLIGHTS)

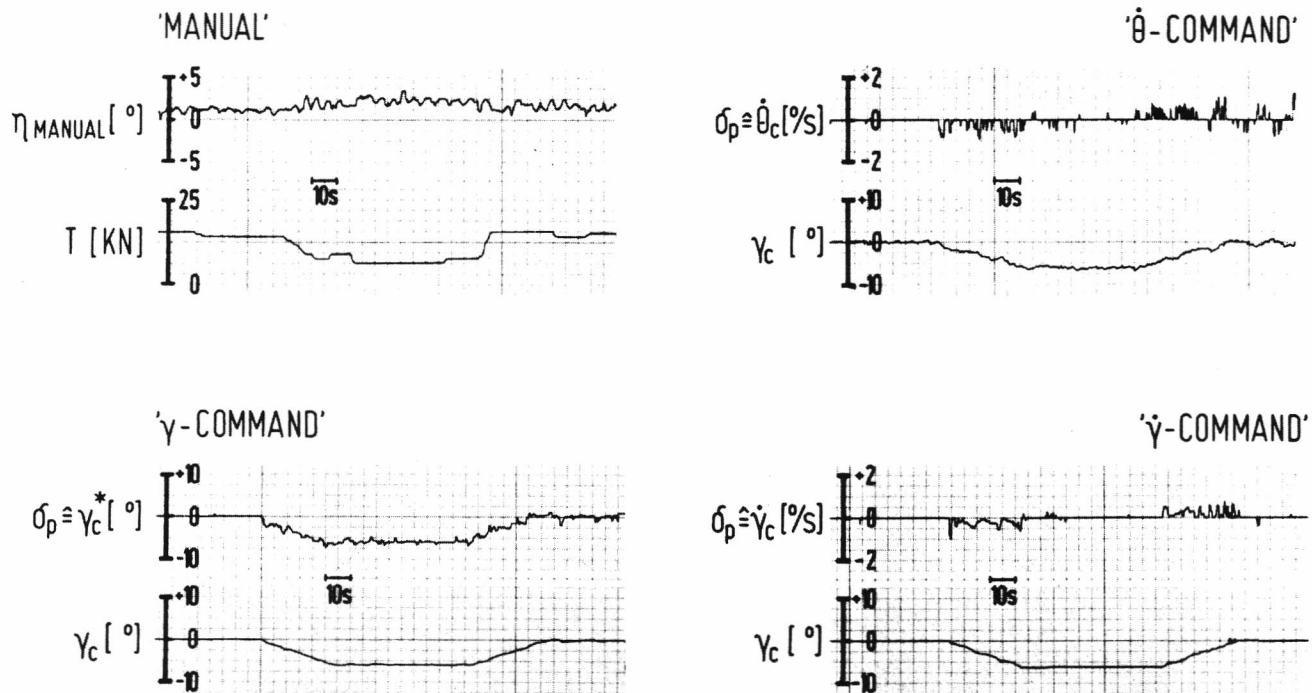


FIGURE 12. COMMAND TIME HISTORIES OF $\dot{\theta}$ -, γ -, $\dot{\gamma}$ -COMMAND VERSIONS (SIMULATOR TEST FLIGHTS)

rations ' $\dot{\theta}$ -command', ' $\dot{\gamma}$ -command' and the modified ' γ -command', give additional indication that the tracking performance of the modified ' γ -command' version is almost identical to that of the ' $\dot{\gamma}$ -command'. Furthermore the same identity can be recognized, if these time histories are compared with those of the fully automatic version. That means, the performance of flight path control achievable with the γ - and $\dot{\gamma}$ -command configuration is almost completely defined by the performance of the automatic flight path control system working on the pilot commands. On the other hand the performance of the ' $\dot{\theta}$ -command' configuration is more or less dependent on the degree of external disturbances, which both the automatic controller and the pilot try to eliminate, in general not to their mutual benefit. In addition to the loss in flight path guidance accuracy, much higher throttle activity can be observed. This is a result of more pilot activity particularly in comparison with the ' $\dot{\gamma}$ -command' (See Figure 12). Looking at the time histories of the command of flight path angle γ_c the shortcomings of the ' $\dot{\theta}$ -command' configuration, compared to ' γ - and ' $\dot{\gamma}$ -command' again become evident. The reference profile in altitude, the time histories of the horizontal and vertical gust disturbances including wind shear, and the elevator and throttle control time histories for a representative test flight in 'Manual' are included for reference.

CONCLUDING REMARKS

A digital integrated guidance and control system is designed by use of the computational capabilities and the moving cockpit system of a flight simulator. Being able to do the design work of the command control system with direct link to the simulator and to include the pilot's comment as early as possible, was very useful.

The performance of the integrated guidance and control system was tested in flight with the DFVLR test aircraft HFB 320. Automatic approaches have shown a very accurate guidance along steep curved paths, as well as a precisely controlled aircraft motion.

Comparative investigations of different Flight Path Command Control configurations for the longitudinal motion were carried out subject to the flight task of tracking a curved steep approach flight path. Both statistical test data and the pilot's comment demonstrate good results for the pilot command parameters $\dot{\gamma}$ or blended γ - $\dot{\gamma}$ with the pilot flight director loop decoupled from that of the automatic flight path control.

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