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FLIGHT CONTROL MODES FOR CONTROL OF AERODYNAMIC STATE PARAMETERS

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FLIGHT CONTROL MODES FOR CONTROL OF AERODYNAMIC STATE PARAMETERS

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1. Abstract

Design and evaluation of several automatic modes as part of a digital integrated AFCS for civil transport aircraft for speed control at different flight conditions are shown.

In cruise flight altitude and airspeed or Mach number respectively, are the controlled variables. During landing approach a chosen multiple of the stalling speed can be acquired and held, taking into account the varying configuration of the aircraft. Speed and angle of attack as possible measured and controlled variables are compared to each other. These modes utilize elevator and throttle as controls.

Performing a go-around maneuver the thrust is set at maximum power and the angle of attack is controlled by the elevator. Flaps and landing gear can be retracted automatically according to an optimized procedure.

Simulation and flight test results are presented, which indicate significant improvements in thrust control with respect to throttle activity by use of a control loop structure with dynamic precontrol of throttle and elevator.

2. Introduction

The increasing requirements placed on the flight control systems of civil transport aircraft with regard to the relief of pilots by appropriate autopilot modes, as well as for improving accuracy and safety of flight, led to systems of more complexity with a large number of components.

Therefore, future transport aircraft will be equipped with digital flight contol systems. Many functions will be incorporated by software, integrated only in a few computers. This results in substantially reduced weight and energy consumption and increased reliability compared with existing analog systems. Besides that easy implementation of very complex algorithms into the digital computer becomes an important advantage. These features promise further improvements in performance, in particular when new automatic modes and functions will be implemented for automation of longer flight phases, taking into account fuel consumption, flight time or other criteria. The development of such functions becomes more and more important as fuel prices escalate.

Future Flight Management Systems will compute flight routes for 4D-guidance and fuel saving vertical flight profiles. But flight route, altitude and airspeed can be varied only with respect to certain limits. Considerable restrictions exist by the regulations of Air Traffic Control. Prescribed flight procedures with restrictions in altitude and airspeed are current practice particularly in the Terminal Maneuvering Area. For every type of aircraft the airspeed for take-off, climb out or approach are given by the Airplane Flight Manual with respect to the actual weight and flap setting. Therefore, very precise control of altitude and air speed, or aerodynamic flow condition respectively, is necessary over the whole flight envelope and flight time.

For this purpose four autothrottle modes, as part of an integrated digital automatic flight control system for transport aircraft, were developed and flight-tested with the test aircraft HFB320. These will be presented in this paper*. The work is part of a research project sponsored by the Federal Ministry of Research and Technology and carried out by German industry BGT, MBB, VFW and the DFVLR.

3. Flight Control Modes and Sensor Concept

The automatic flight control system (AFCS) includes a control mode concept with a hierarchical structure according to the degree of automation.[1] Control Wheel Steering for lateral and longitudinal motion is the basic mode. In addition to well known autopilot modes, such as heading acquire (HDG ACQ), altitude acquire (ALT ACQ) and VOR navigation for example, automatic functions can be selected, which permit automatic execution of longer flight phases. These functions are making use of the ordinary autopilot and autothrottle modes. Four autothrottle modes are provided for control of aerodynamic variables during cruise flight, approach and the go-around maneuver.

The aerodynamic flow condition of a certain aircraft is defined by the lift coefficient c_L, which is not directly measurable. Thus the airspeed or Mach number respectively, derived from measured dynamic and static air pressure, is generally utilized. At low dynamic air pressure the angle of attack can be a suitable sensor signal, too. The comparison of specified accuracy limits for computed airspeed

(CAS) and corrected angle of attack, according to ARINC 706 Draft 3 for Digital Air Data Computer, show that at typical approach speeds of transport aircraft the aerodynamic flow condition can be described even more accurately by the angle of attack sensor signal. Figure 1 shows the corresponding speed error curve due to an angle of attack accuracy of ±0.25 degrees for the Airbus A310 at landing configuration and the error curve of the computed airspeed signal. At higher dynamic air pressure the accuracy of the computed airspeed signal is better than that of the angle of attack sensor signal.

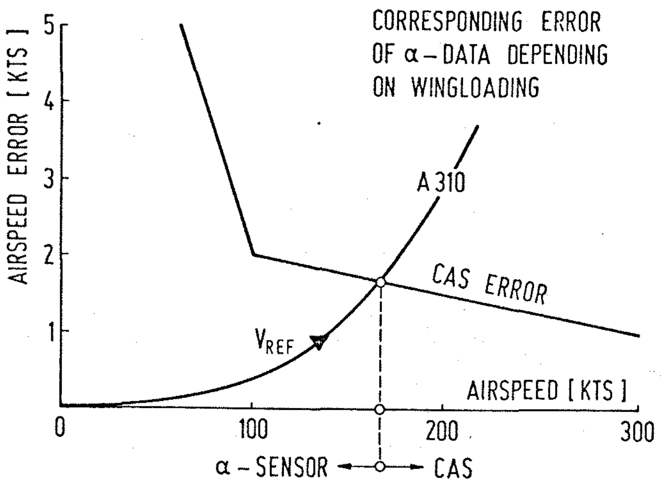


Figure 1. Accuracy Requirements on Computed Airspeed and Corrected Angle of Attack According to ARINC 706 Draft 3

For cruise flight two modes VC and MA, controlling a selected computed airspeed or the Mach number respectively, are provided which cover the whole flight envelope.

To achieve a short landing distance the landing approach is carried out with an airspeed as slow as possible. On the other hand, a certain safety margin is to be kept for preventing the stall during flight maneuvers with increased normal load factor or due to wind shear and gusts. Utilizing the AFCS mode VS it is possible to select an appropriate multiple of the stalling speed on the glareshield controller of the AFCS. Automatically the actual aircraft configuration with respect to flap setting, spoiler position, landing gear, etc. is taken into account by the control law computation. With this control mode the pilot is relieved from consulting the Airplane Flight Manual to read the appropriate approach speed according to the actual weight and flap setting.

Two alternative control concepts utilizing the angle of attack or the airspeed respectively as measured and controlled variables were investigated.

Besides that the altitude or the vertical speed is the second controlled variable in the AFCS mode VS and the two cruise modes VC and MA. Elevator and throttle are utilized as controls.

In the case of a missed approach the aircraft can be transferred automatically from descent to the climb with the go-around (GA) mode. After starting this mode the thrust is immediately increased to the maximum allowable value and the angle of attack for the steepest possible climb is commanded and then controlled by the elevator. Landing gear and flaps can be retracted according to an optimized procedure, which depends on the properties of the aircraft and the engines.

4.0 Dimensioning of the Flight Control System

In accordance with the hierarchical structure of the flight control system, dimensioning of the controller consists of step-by-step development of a coupled multivariable feedback system. All essential sensor and command inputs act on the controls available to the flight control system. For control of longitudinal motion these are elevator and throttle. If the selected controller structure (Figure 2) is applied strictly, the design of the system eigenmodes can be separated from the gain determination of the command feedforward loops and the disturbance compensating loops.

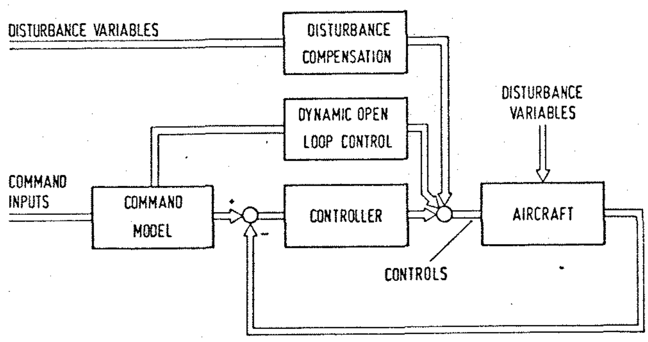


Figure 2. Principle of Control Loop Structure

Well-damped eigenvalues must be achieved for all flight conditions and for every conceivable combination of AFCS modes. This also provides an improved response to gusts in case of no direct feedforward gust allevation system. Disturbances resulting from configuration changes of the aircraft, for example extension and retraction of flaps or landing gear, can be modelled with a good degree of accuracy and can therefore also be compensated by open loop control.

Various methods are used to determine the gains of the flight control system and to schedule them to flight condition parameters. It should be emphasized that the classical methods such as the time vector method and the root locus method have proved to be as useful as modern numerical design methods such as solving the Riccati equation or automatic parameter optimization by minimizing a cost function.[2][3][4]

The methods were used with equal priority and their results have supplemented and supported each other. As the control system gains and the system dynamic after minimization of a cost function do not necessarily comply with the engineer's ideas, gain modification "by hand" together with a nonlinear simulation still plays an important part in the development of a multivariable feedback system. The design engineer has a fairly wide decision range in which there is more than one satisfying combination of possible structures and corresponding gains for achieving good closed loop response.

In the first design step, feedback of the complete state vector was considered. The physical effects of the various control loops were then examined both by analytical methods and by simulation.

An important design objective was to reduce the number of feedback loops to the really necessary ones without loss in performance. A further design objective was to maintain the existing structure and gain factors of the basic inner control loops when further loops were added by activation of other AFCS modes.

4.1 Feedforward Open Loop Control

In contrast to the feedback loop design, the feedforward open loop control is determined explicitly. High control accuracy is strongly dependent on the precision of the control surface positioning with respect to the dynamic feedforward open loop control signal. On the one hand, the command model must not exceed the flight-mechanical capabilities of the aircraft, on the other hand, all knowledge of the aircraft dynamic behaviour during stationary and instationary flight phases must be taken into account for the open loop control. If the error because of undesired stimulation of the eigenmodes is reduced, then unnecessary deflections of the controls would also be reduced. This is, for example, the case when elevator deflection and thrust increase are needed during a steady turn or at extension of flaps.

An important criterion for the quality of speed control is low throttle activity. Therefore, an open loop control law is termined on the basis of the force equations. The force equations in x- and z-direction provide the following expression for the thrust setting:

$$\frac{T}{W} = \frac{\dot{H}}{v_K} + \frac{\dot{v}_K}{g} + \left(\frac{c_D}{c_L} + \frac{w_W}{v_{TAS}}\right) n \quad (1)$$

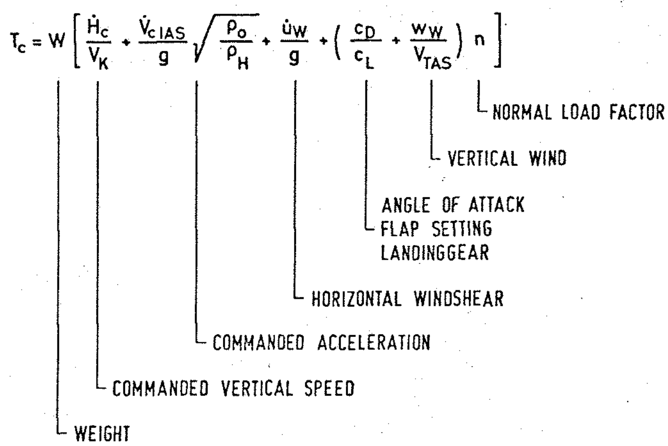
Since the indicated airspeed v_{IAS} is the controlled variable for speed, v_K must be substituted by:

$$v_K = v_{TAS} + u_W \quad (2)$$

with

$$v_{TAS} = v_{IAS} \sqrt{\frac{\rho_o}{\rho_H}} \quad (3)$$

The resulting thrust command is shown in Figure 3.



$$T_c = W\left[\frac{\dot{H}_c}{v_K} + \frac{\dot{v}_{cIAS}}{g}\sqrt{\frac{\rho_o}{\rho_H}} + \frac{\dot{u}_W}{g} + \left(\frac{c_D}{c_L} + \frac{w_W}{v_{TAS}}\right) n\right]$$

Figure 3. Computation of Thrust Setting

The weight W of the aircraft is a multiplicative factor for all of the various input variables and is therefore of great importance for open loop control of the thrust. Determination of the weight from the take-off weight minus the weight of fuel used during the flight is necessary, but sufficient with respect to the measurement accuracy.

During climb and descent, the thrust requirement depends on the flight path angle $\gamma = \dot{H}/v_K$. In all autothrottle modes a continuous command function for altitude rate $\dot{H}_C$ is generated, resulting in corresponding changes of the thrust setting.

The thrust law shows that further variables determine the thrust required for changes in speed. The thrust is immediately be adjusted in proportion to the acceleration command. Also the drag-lift ratio c_D/c_L has to be taken into account. During cruise flight condition the drag-lift ratio is relatively constant. Therefore, changes can be ignored in this case. But during landing approach with changing flap position or landing gear extension the effect of changes in the drag-lift ratio on the speed error becomes significant, due to the decrease in aerodynamic efficiency. An approximate thrust correction as a function of the flap position at an average angle of attack is therefore provided.

Changes of the normal load factor n during a turn maneuver are also to be considered. It becomes obvious that the open loop thrust control can easily be performed, because the variables needed for a suitable thrust setting can be derived within the computer. In principle, this is also true when, in addition, the remaining terms of the required thrust setting with respect to wind disturbances (w_W, u_W) are considered. For the control system presented in this paper, these terms are neglected for open loop thrust setting.

4.2 Energy Control

As mentioned previously, low throttle activity is a particularly important criterion in flight control system design. On the other hand, increasing the thrust is the only possibility of supplying additional energy to the aircraft, i.e. it is not possible to fly without any activity of the throttle. Minimization of the throttle activity is achieved if the thrust is used only for modification of the total energy and if the exchange of potential and kinetic energy is controlled by the elevator. A controller which controls altitude H and indicated airspeed v_{IAS} can, therefore, be named an energy controller.

If small deviations from a reference steady flight condition are considered, the linearized form of the change in total energy can be expressed by

$$\Delta E = mg\Delta H + mv_K \Delta v_K \tag{4}$$

whereby the mass is regarded as constant for short times.

Since the controller is intended to control the indicated airspeed v_{IAS}, the appropriate substitution of v_K must be carried out with the equations (2) and (3).

This then results in

$$\Delta E = mg\Delta H + mv_K \left(\Delta v_{IAS} \sqrt{\frac{\rho_0}{\rho_H}} + \Delta u_W \right) \tag{5}$$

If the energy is to remain constant, then any change in the wind u_W will cause a deviation in speed and altitude. In addition, any change of altitude at a constant wind speed will result in speed error. In case of flight at higher altitude (corresponding to the change in air density) or with higher velocity v_K, deviation from the airspeed v_{IAS} causes increasing altitude errors. Conversely, it can be said that speed control will be satisfactory if it is possible to achieve good altitude maintenance with the elevator at high altitudes and high speeds. A controller which is intended to control the total energy by means of the thrust must be designed in accordance with the structure in Figure 2. In addition to open loop control of the thrust defined in chapter 4.1, proportional and integrated speed feedback must be provided. If the potential and kinetic energies are regarded as command inputs, then the two paths must be connected together with appropriate weight:

$$\Delta T \sim \frac{\Delta E}{v_K} = W \left(\frac{\Delta H}{v_K} + \frac{\Delta v_{IAS}}{g} \sqrt{\frac{\rho_0}{\rho_H}} + \frac{\Delta u_W}{g} \right) \tag{6}$$

The speed feedback loop is therefore dependent on the aircraft weight and the air density. Parameter investigations have shown that a constant gain K_{TV} is sufficiently satisfying throughout the operational envelope considered. The altitude feedback loop is dependent on the velocity v_K; the thrust control becomes weaker as the velocity increases. This explains why the gain K_{TH} has a noticeable effect only in the case of the aircraft flying at low speeds. However, simulations of flight with the AFCS modes VC and ALT HOLD engaged and with simultaneous flap setting show that inclusion of K_{TH} provides an additional reduction in the throttle activity. The controller structure implemented in the flight control system, divided into pitch damper, altitude controller, and speed controller, is shown in Figure 4. Dimensioning of the other control gains is shown in more detail in reference (5).

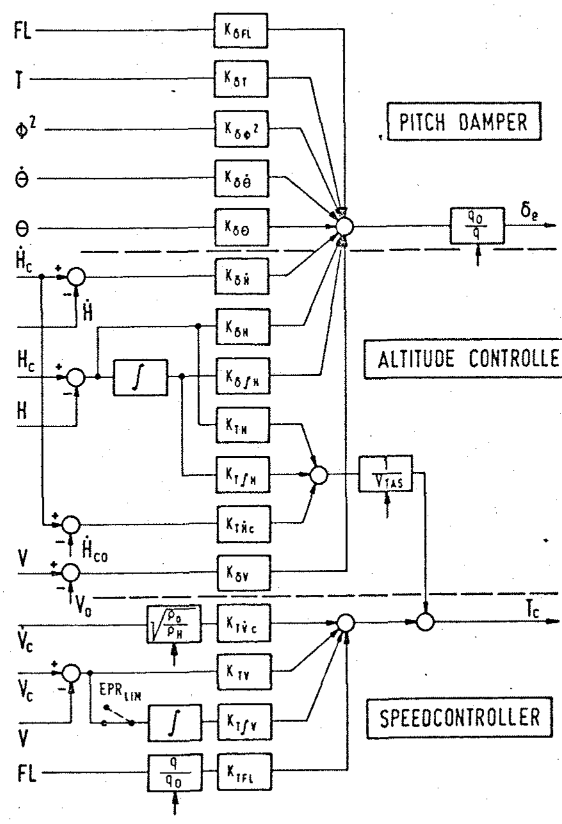


Figure 4. Control Loop Structure for Coupled Air Speed and Altitude Control

4.3 EPR Control

Realisation of thrust presetting requires a very precise control of thrust value changes. For that purpose good knowledge about the relationship between stationary thrust and power lever angle, Mach number, altitude, temperature as well as further specific engine parameters, as the Engine Pressure Ratio (EPR) for instance, is necessary. Because of limitations in thrust setting defined by EPR- or RPM-limits, it is convenient to close an inner control loop with one of these specific engine parameters as controlled variable. This gives the advantage that nonlinear effects of the FCU actuation system, such as backlash, can be compensated with the inner control loop, utilizing nonlinear control laws including hysteresis compensation algorithms, even much faster than with the smoothly working outer speed control loop. A very accurate thrust control with low throttle activity then results.

For the engine type CJ610 of the experimental test aircraft HFB320 the stationary thrust is defined approximately by:

$$T = \frac{q + p_s}{p_{so}} K_{TEPR} (EPR - 1) \qquad (7)$$

Figure 5 shows the principle of EPR control loop. The thrust command T_c is transformed to an equivalent EPR command by use of equation (7). This signal is then limited according to the permissible maximum and idle-limit. A logical signal EPR_{LIM} indicates limit violations and switches off the integral loop of the speed controller.

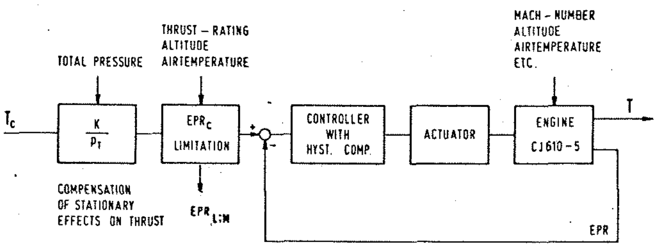


Figure 5. Nonlinear EPR-Control Loop

4.4 The Modes VC and MA

The control loop structure for control of airspeed and altitude by the AFCS modes VC and MA is shown in Figure 4.

The command values v_c and $\dot{v}_c$ required by the controller are provided by a nonlinear command model. If the pilot selects a new airspeed command value on the glareshield controller of the AFCS, the command model computes a slowly changing airspeed command v_c with constant acceleration $\dot{v}_c$. Taking into account the air density prevents the aircraft from accelerating faster and faster with increasing altitude.

The AFCS mode for control of Mach number utilizes the same control loop. The selected Mach number is transformed to an equivalent speed command according to equation (8)

$$v_{CIAS} = \frac{v_{IAS}}{Ma} \cdot Ma_C \qquad (8)$$

and then fed to the controller.

4.5 The Control of the Multiple of the Stalling Speed

For control of the multiple of the stalling speed the same control loop structure is utilized as for speed control. Only the sensor signal of airspeed is substituted by the angle of attack signal. At the first glance this conversion from speed to angle of attack control seems to be inconsistent to the requirement for low throttle activity, because the angle of attack is very sensitive to gusts. But detailed investigations showed that the angle of attack signal can be smoothed by low pass filtering with a time constant of 3 to 5 seconds without significant loss in closed loop stability. Therefore, disturbances of higher frequency are not affecting the throttle activity. Since automatic parameter optimization also showed no significant additional coupling gains, the conversion can be looked upon as successful.

The command value α_C depends not only on the selected multiple k_S, but on all parameters shifting the lift curve c_L with regard to angle of attack. These are the deflection of landing flaps, spoilers, landing gear, etc. Each variation of one of these parameters results in a changing command value of angle of attack and airspeed respectively.

If a multiple k_S is selected a very similar behaviour results compared to that of airspeed control by changing the command value v_c. Increasing the selected multiple results in an increase of airspeed and a decrease of angle of attack. The longitudinal acceleration can be adjusted by the command value $\dot{v}_c$, which is derived from the command model for the angle of attack command. The relationship between both command values $\dot{\alpha}_c$ and $\dot{v}_c$ is approximately derived from the force equation in z-direction. This yields

$$\dot{\alpha}_c = -\frac{4W}{c_{L\alpha} S \rho_H v_{TAS}^3} \dot{v}_c \qquad (9)$$

For realisation in the controller an average value for the weight was used. The quotient therefore is

$$\frac{\Delta\alpha}{\Delta v} \approx -\frac{4W_m}{c_{L\alpha} S \rho_H v_{TAS}^3} \qquad (10)$$

The lift equation provides the following expression for the command value α_c

$$\alpha_c = \frac{1}{c_{L\alpha}} \left[\frac{c_{LMAX}}{ks^2} - c_{Lo} - \Delta c_{LFL} - \Delta c_{LSP} - \Delta c_{LLG} \right] \qquad (11)$$

The terms $c_{L\alpha}$, c_{LMAX}, Δc_{LFL}, Δc_{LSP} depend all on the angle of attack, flap position and spoiler deflections, but some approximations are allowed.

The actual value k_{SI} of the multiple of the stalling speed is displayed to the pilots during the flight tests

$$k_{SI} = \left[\frac{c_{LMAX}}{c_{Lo}+c_{L\alpha}\alpha+\Delta c_{LFL}+\Delta c_{LSP}+\Delta c_{LLG}}\right]^{\frac{1}{2}} \tag{12}$$

If the multiple k_S is kept constant but the landing flap position is changed for instance, air speed and angle of attack are changing in the same direction. Extension of the landing flaps increases the maximum lift coefficient c_{LMAX} . Therefore, a higher lift coefficient is permitted corresponding to a lower air speed. At the same time the angle of attack decreases, too. That means for throttle control that at first the thrust is to be reduced to perform the deceleration. Then for compensation of the additional drag of landing flaps a higher thrust setting is necessary.

An appropriate thrust presetting is performed at speed changes, if the commanded rate $\dot{v}_C$ depends only on changes of maximum lift coefficient c_{LMAX} or of the selected multiple k_S . Therefore, the commanded value α_C is divided in two parts α_{C1} and α_{C2} with

$$\alpha_{C1} = \frac{c_{LMAX}}{k_S^{\,2} c_{L\alpha}} \tag{13}$$

$$\alpha_{C2} = \left[c_{Lo}+\Delta c_{LFL}+\Delta c_{LSP}+\Delta c_{LLG}\right]/c_{L\alpha} \tag{14}$$

$$\alpha_C = \alpha_{C1} - \alpha_{C2} \tag{15}$$

Figure 6 shows the control loop structure utilized for this control mode.

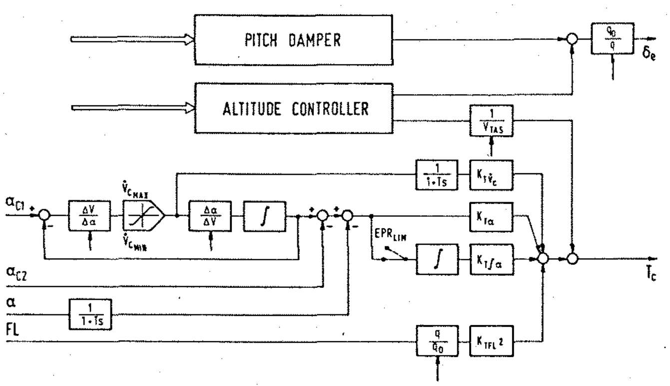


Figure 6. Control Loop Structure for Coupled Altitude and Angle of Attack Control

The angle of attack signal reacts very fast not only to gusts, but changes also if the normal load factor increases due to vertical flight path or turn maneuvers. This results in increasing airspeed even then, when the safety margin to the stall speed is large enough. This unsatisfactory behaviour can be avoided if the airspeed is the controlled variable and the controller shown in Figure 4 is utilized. The command value v_C in this control mode is easily derived, if the actual multiple of the stalling speed is measured and computed.

$$v_C = k_S\left(\frac{v_{IAS}}{k_{S1}}\right) \tag{16}$$

The quotient of the measured values for airspeed and multiple of the stalling speed shows all changes of the normal load factor, too. Thus, it is indispensible to filter out all high frequent oscillations due to gusts or flight maneuvers. Without regard to turn maneuvers transport aircraft fly only at short time intervals with an increased load factor, and in general it is not convenient to increase the airspeed for that reason. Therefore, the quotient is to be low pass filtered with a time constant of about 50 to 100 seconds.

Besides that it was decided that only for selected multiples less than 1.4 the speed is to be increased in turn maneuvers. This yields for the speed command computation algorithm:

$$v_{C\geq 1.4} = k_S\left(c_{LMAX}\right)^{-\frac{1}{2}}\left[v_{IAS}\left(c_L\cos\Phi\right)^{\frac{1}{2}}\right]_{FILTERED} \tag{17}$$

$$v_{C<1.4} = v_{C\geq 1.4}\left(\cos\Phi\right)^{-\frac{1}{2}} \tag{18}$$

4.6 The Go-Around Mode

With the control mode for the automatic go-around maneuver the angle of attack for the steepest climb is commanded and controlled by the elevator. To prevent the aircraft from further descending and to assure a very fast transition into climb after starting this mode, the maximum permissible engine thrust is commanded immediately and a pull-up command is fed to the elevator. This washed out elevator command is derived from the thrust command. The loop using the longitudinal accelera-

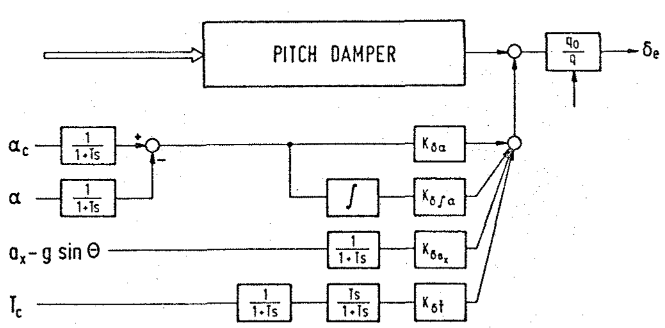


Figure 7. Control Loop Structure for Angle of Attack Control for the Automatic Go-Around Mode

tion provides that surplus thrust results primarily in an increasing altitude. Besides that this loop provides a very stable pitch attitude particularly in rough air. The control loop structure is shown in Figure 7.

5. Flight Test Results

A flight test program was conducted using the DFVLR experimental aircraft HFB320. The test system is shown in Figure 8.

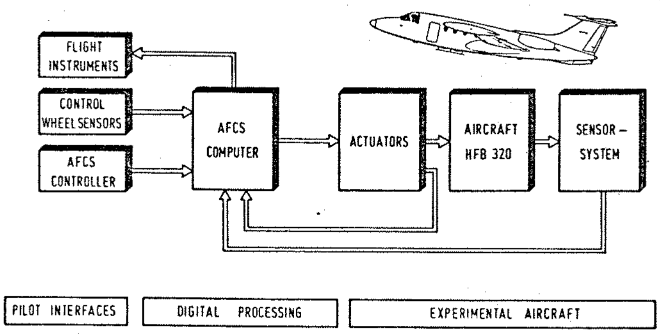


Figure 8. Experimental Test Flight System

The main objective was to test the algorithmus for control and command computation, the AFCS modes management logic and newly developed hardware during flight. Because of intensive ground test of the system by use of nonlinear simulation no major deviation in the control performance did show up. Nearly all simulation results were confirmed. Within 90 flight hours all control system functions were tested and approved in the speed range of 130 through 290 kts. The following figures show some flight test results regarding to the speed control modes. They are chosen to demonstrate the effectiveness of the control loop structure in particular with regard to the open loop control of throttle and elevator.

Figure 9 shows two acceleration phases from 200 kts to 250 kts and further up to 290 kts. The commanded acceleration is preset in the computer at 1.5 kts/sec. The maximum speed error occurs during the second acceleration phase, when the upper EPR-limit is reached. Its value is about 5 kts and the maximum altitude deviation is less than 15 ft. The EPR-trace shows very clearly the appropriate thrust setting during acceleration and steady flight condition.

Figure 10 shows two altitude changes carried out utilizing the ALT ACQ mode in combination with the speed mode VC: A descent maneuver with 1900 ft/min and 40° flap extension and a following climb maneuver with 1000 ft/min climb rate combined with a flap retraction from 40° to 20°. The maximum altitude deviation of about 20 ft occurs during the parabolic sections of the flight path. The flap retraction causes no remarkable deviation of speed and altitude.

Figure 11 shows that the extension of flaps nearly causes no deviation of speed and altitude, although the drag is strongly dependent on the flap position. The nonlinear gain K_{TFL} provides the adjustment of the thrust whereas the gain $K_{\delta T}$ compensates the pitch moment due to thrust. The control loops for maintaining speed and altitude are effectively relieved.

Figure 12 shows a flight phase with stepwise reduction of the selected multiple k_S at a constant flap deflection of 40 degrees utilizing the AFCS modes VS and ALT HOLD. With the reduction of the selected multiple k_S the airspeed decreases from 150 kts to 123 kts and the angle of attack increases from 0.5 to 5.0 degrees. Altitude deviations are less than 15 ft. The EPR curve shows very clearly the necessary thrust reduction during the deceleration phases and the smooth thrust changes in the steady flight condition.

The stepwise extension of landing flaps is shown in Figure 13. At a selected multiple of 1.3 both airspeed and angle of attack decrease, but the actual multiple of stalling speed is nearly constant.

The turn maneuver (Figure 14) using the HDG ACQ mode, is carried out with a maximum bank angle of 25°. At the beginning of the turn with a selected multiple of 1.6 the actual multiple decreases due to the change of the normal load factor. The controller increases the thrust and the aircraft accelerates slowly. At the end of the turn the actual multiple just reaches the commanded value. The behaviour of the controller shows that the task is fulfilled even very slowly. But it was really not necessary to increase the speed further, since the airspeed was fast enough. This disadvantage can be avoided using the airspeed as the controlled variable instead of the angle of attack.

Figures 15 to 18 show some flight test results with the control mode VS using airspeed control. Figure 15 is very similar to Figure 12. Stepwise reduction of the selected multiple at constant flap deflection results in a decrease of airspeed. The upper trace shows the computed speed command v_C, which decreases very slowly with about 1 kt per minute at all the time caused by the weight reduction due to fuel consumption. The speed deviation is less than 2 kts also during the deceleration phases initiated by reduction of the selected multiple.

Extension and retraction of landing flaps at a constant selected multiple of 1.4 are shown in Figure 16. According to the flap setting the airspeed is changing, but the speed deviation is always less than 3 kts.

Figure 17 shows a turn maneuver carried out with the HDG ACQ mode. Before starting the turn the aircraft accelerates due to a change in the selected multiple of 1.3 to 1.4. During the turn the airspeed is kept nearly constant and the actual multiple decreases according to the bank angle.

In Figure 18 a similar turn maneuver is shwon now carried out with a selected multiple of 1.3. As mentioned before the multiple of the stalling speed shall be kept constant, if the selected multiple is less than 1.4. For this purpose the aircraft accelerates or decelerates respectively according to the bank angle.

Figure 19 shows a transition from the descent to the climb performed with the go-around mode. At the beginning of this mode the thrust increases immediately and the aircraft pitches up. The landing flaps are automatically retracted from 40 to 0 degrees and the speed rises until the desired steep climb is reached. After retraction of flaps a very stable pitch attitude results, while airspeed and vertical speed increase further. The climb is terminated by Control Wheel Steering.

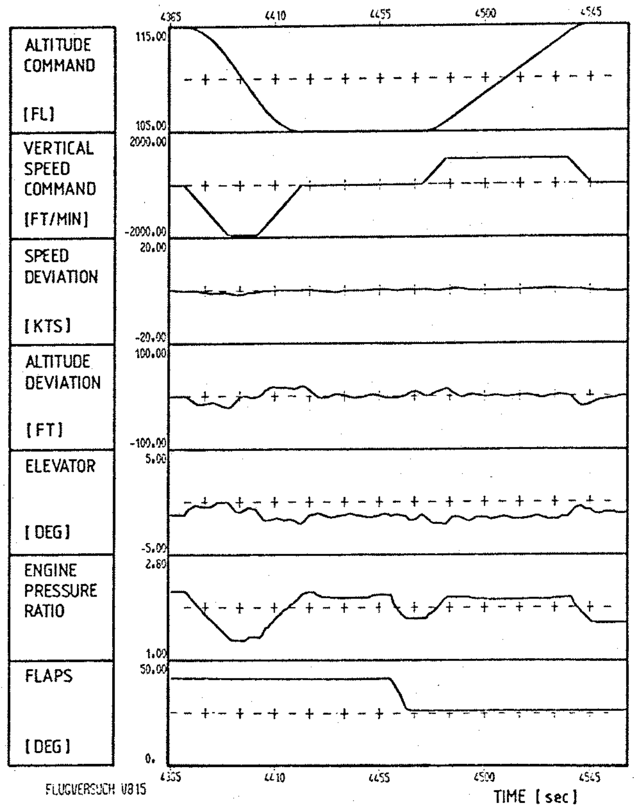


Figure 10. AFCS Modes VC and ALT ACQ; Descent and Climb between FL 105 and FL 115 at Constant Speed

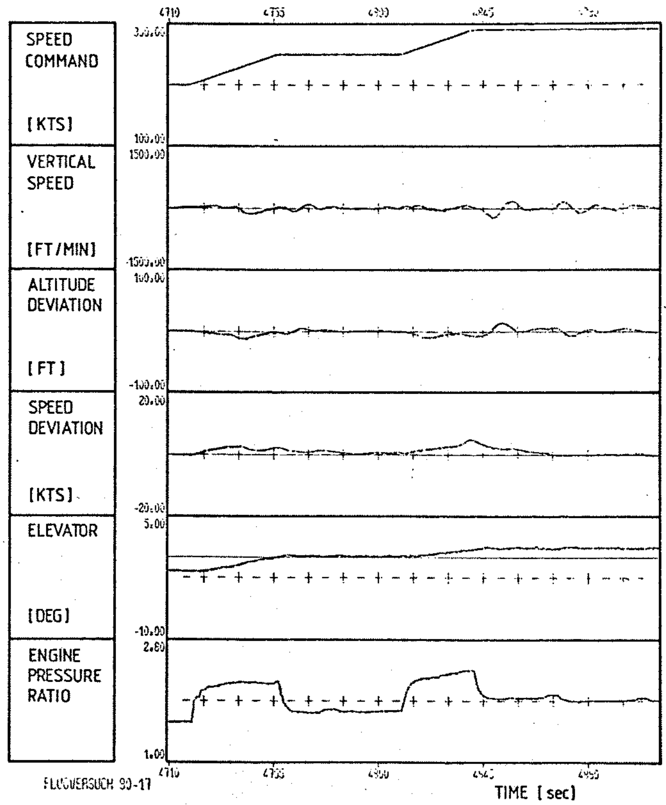


Figure 9. AFCS Modes VC and ALT HOLD; Commanded Speed Change from 200 kts to 290 kts

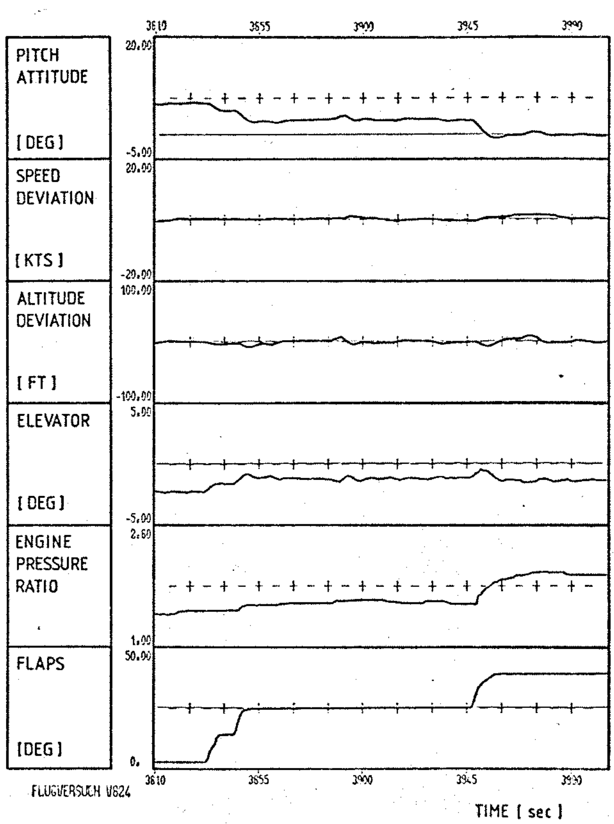
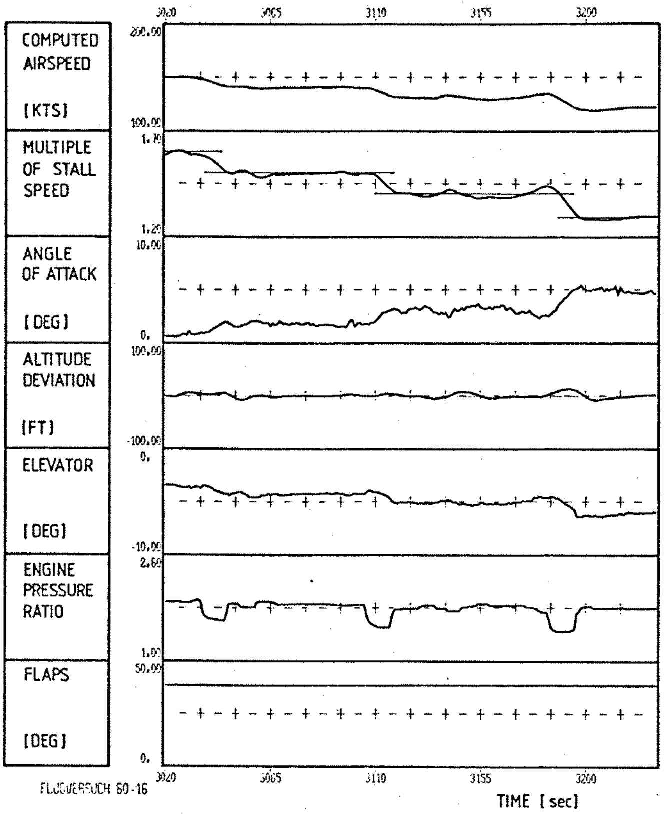


Figure 11. AFCS Modes VC and ALT HOLD; Extension of Landing Flaps from 0° to 40°



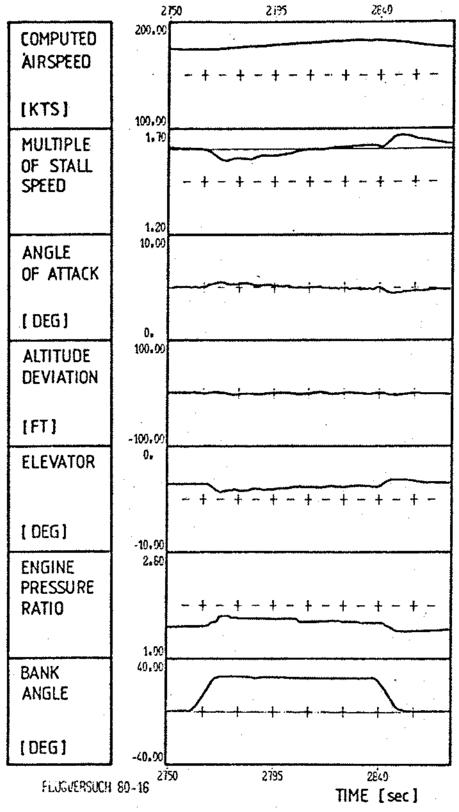
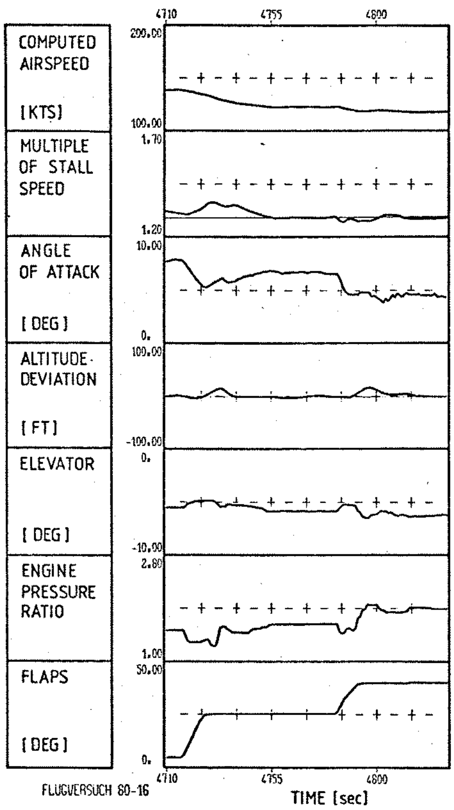


Figure 12. AFCS Modes VS (α-control) and ALT HOLD; Commanded Deceleration by Selection of k_s = 1.6 - 1.5 - 1.4 -1.3

Figure 14. AFCS Modes VS (α-control), ALT HOLD, HDG ACQ; Automatic Heading Change at a Constant Multiple k_s = 1.6



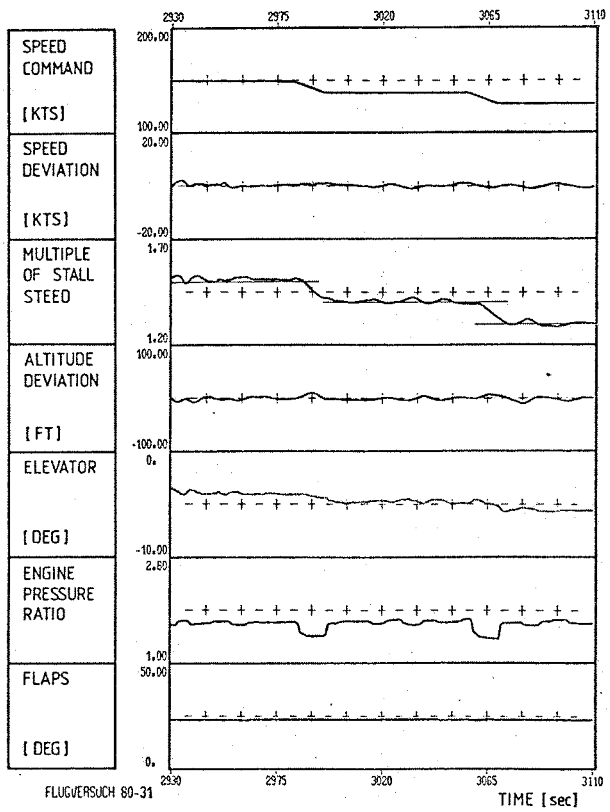


Figure 13. AFCS Modes VS (α-control) and ALT HOLD; Extension of Landing Flaps at a Selected Multiple k_s = 1.3

Figure 15. AFCS Modes VS (IAS-control), ALT HOLD; Commanded Deceleration by Selection of k_s = 1.5 - 1.4 - 1.3

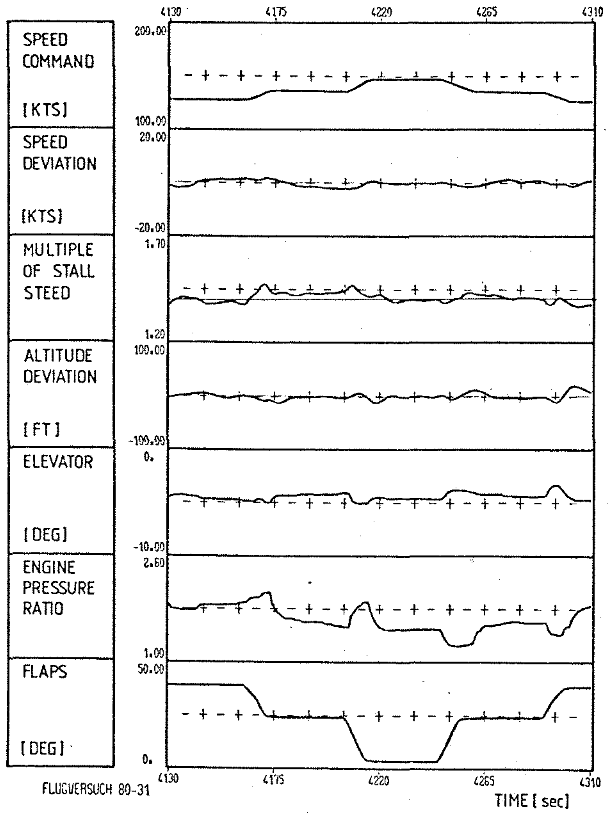


Figure 16. AFCS Modes VS (IAS-control), ALT HOLD; Retraction and Extension of Landing Flaps at a Selected Multiple k_s = 1.4

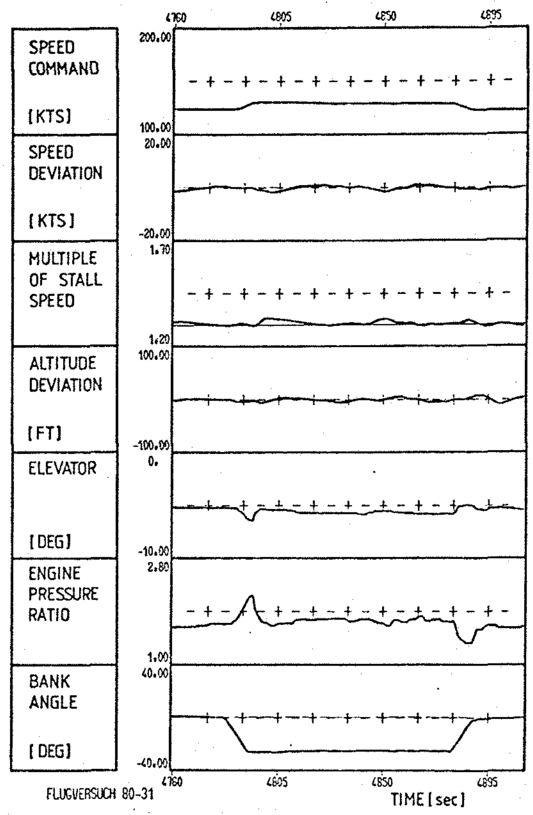


Figure 18. AFCS Modes VS (IAS-control), ALT HOLD, HDG ACQ; Automatic Heading Change at a Selected Multiple k_s = 1.3

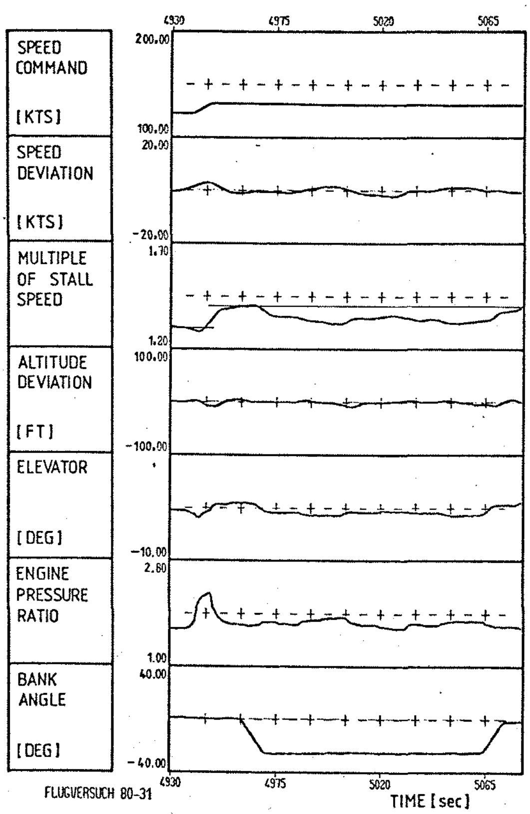


Figure 17. AFCS Modes VS (IAS-control), ALT HOLD, HDG ACQ; Automatic Heading Change at a Selected Multiple k_s = 1.4

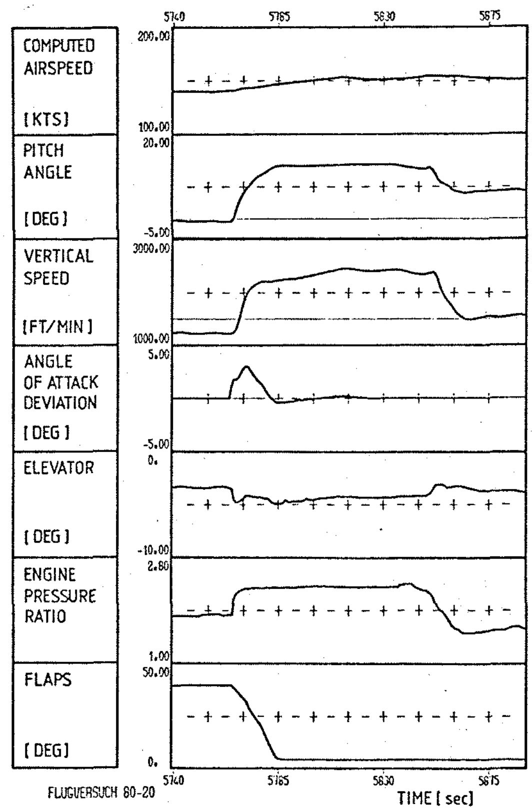


Figure 19. AFCS Modes GA Starting in Descent with 40^{o} Flap Setting

6. Summary

The increasing operational requirements placed on flight control systems for transport aircraft can be achieved economically only by use of an integrated digital system. Such systems also provide the means for new automatic modes and functions and new design features of the control system. Knowledge of aircraft and engine characteristics and dynamical behaviour can be exploited to develop nonlinear powerful algorithms for improvement of control accuracy.

By use of the control system described in this paper which is characterized by

- coupled multivariable feedback control
- nonlinear feedforward open loop control
- direct compensation of disturbances and
- inner EPR control loop

the requirements on high accuracy of airspeed and angle of attack control as well as low throttle activity can be met satisfactorily.

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