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COMPUTER AIDED FLIGHT TESTING OF A DIGITAL AUTOPILOT ON BOARD A RESEARCH AIRCRAFT*)

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Abstract

A modern structured digital autopilot which will serve several purposes in the future has been developed for the DO 28 research aircraft. Several flight mechanical derivatives of the DO 28 are not exactly known. Therefore an off-line design of the autopilot only on the ground computer cannot lead to satisfactory results. A suitable on-board data system enables final optimizations of the controller during flight. Different software tools are used for trouble shooting and observing the experimental autopilot. The possibilities of on-line examination and modification allow a development within a rather short time frame.

1. Introduction

At the Technische Universität Braunschweig aeronautical research is performed in the field of air safety problems. A special research program "Sicherheit im Luftverkehr" (Safety in Air Traffic) has been set up for this purpose. This research is financed by the Deutsche Forschungsgemeinschaft (German Society for the Advancement of Scientific Research). A part of this program explores dangers to aircraft during take-off and landing (see also ICAS-84-5.10.1). In this context it is the aim to develop an experimental digital autopilot with state feedback and with variable coefficients. For practical flight testing the Technical University of Braunschweig in 1980 acquired a DORNIER DO 28 SKYSERVANT as a research aircraft. (FIG. 1)

Why an autopilot with variable coefficients? A simultaneous demand for high precision in speed and flight path automatically leads to a high degree of throttle activity. The additional demand for a high passenger comfort is a contradiction in terms and can only be obtained by a compromise. For the design of an autopilot it is helpful to formulate a quality criterion. It contains all terms, which are important to the behaviour of the autopilot. Several publications have shown that the deviations in speed, flight path as well as the throttle activity belong to the important terms of a quality criterion for a modern flight controller.(1,2) The weight among the single terms may be different, depending on the situation of flight. If there is sufficient altitude, there may be more weight on the passenger comfort, but during final approach care must be taken to avoid large glide-path deviations. Apart from noncompensated rests of the cone effect, state of the art autopilots are supplied with constant coefficients and therefore don't change their behaviour depending on the flight situation as pilots would do this. It can be supposed that a flight controller, which reacts like a pilot, will be better accepted by the crew, even during critical situations.

FIG. 1 : The DO 28 Research Aircraft

The idea of a flight controller with variable coefficients is to change its attributes depending on altitude or slant range. First experiences with such an autopilot have been obtained in off-line simulations. They aren't completed until today and will take some more time. The meantime was used to integrate a modern structured flight controller with state feedback and constant coefficients, which will be modified to an autopilot with variable attributes in the future. Subject of this paper is to present the procedures and tools which were used to operate the autopilot during the testing phase and which were designed regarding the requirements of the future releases of the flight controller.

In this paper the term "autopilot" refers to the algorithm of a flight controller for the longitudinal motion of the aircraft with elevator and throttle as final control elements.

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List of Symbols and Names

ACP	Autopilot Control Panel
a_x	aircraft fixed x-acceleation
a_y	aircraft fixed y-acceleation
a_z	aircraft fixed z-acceleation
$C_{\theta\eta}$	feedback coefficient from pitch angle to the elevator
$C_{q\eta}$	feedback from pitch rate to the elevator
$C_{\dot{q}\eta}$	feedback from pitch acceleration to the elevator
CRT	Cathode Ray Tube
DME	Distance Measuring Equipment
	elevator position angle
η_c	elevator position reference
F_c	forward feed of thrust
f_c	autopilot thrust command
γ	flight path angle
H	altitude
H_c	altitude reference
ΔH	altitude deviation
INS	Inertial Navigation System
I/O	Input/Output
K	Feedback parameter for root locus
MP	manifold pressure
MP_c	commanded manifold pressure
ϕ	bank angle
PCM	Pulse Code Modulation
q	aircraft fixed rate of pitch
q_r	aircraft fixed rate of pitch minus coss coupled turn rate during coordinated turns at constant altitude
$\dot{q}_r$	pitch acceleration, differential of q_r
r	aircraft fixed rate of turn
θ	pitch angle
V	true air speed
V_c	commanded true air speed
ΔV	air speed deviation

2. Some Problems of Autopilot Development

A result of modern control theory is the following: the best controller for any system can be obtained if all states of the system are fed back to all actuators. This requires the knowledge of a state model from this system and makes it necessary to calculate all reference states according to the primary references.

In the past, an autopilot with state feedback has already been realized on the same DO 28 aircraft at the Bodenseewerk Gerätetechnik (BGT), Überlingen, FRG. It was developed for the purpose of steep approaches and short landings.(3) The development resulted into the so called FRG 70. It demonstrated that an autopilot structure which includes cross coupling between throttle and elevator has essential advantages against conventional autopilots with separated autothrottle- and elevator-loops.

After this flight control system has proved that the principle of state feedback can be advantageously applied to autopilots, it is now intended to perform more scientific research in this field.

The FRG 70 was designed with the help of off-line simulations and optimizations. Unfortunately there are flight-mechanical derivatives which until today are either unknown or not known with satisfactory precision. Especially the influence of propeller thrust to lift and the elevator structural dynamics are not exactly known. This means that the state model of the aircraft is not correct and the simulation contained uncertaincies. Corrections of the coefficients during flight test were necessary.

Similar problems exist today. Several sensors have been changed or added in the meantime. There is a new on-board computer system and sensor data processing is different. Parts of the autopilot have a different structure, because the advantages of other and better sensor signals have been incorporated. Therefore the coefficients of the old FRG 70 cannot be simply applied to the new autopilot.

Sometimes it may be a problem that the connection between the elevator servo drive and the elevator itself contains a little slackness, which is of different magnitude depending on the the elevator position angle. This effect can be kept in bounds if the autotrim keeps a small force on the elevator.

3. The DO 28 SKYSERVANT and its Flight Test Equipment

3.1 Sensors and Servo Drives

The sensor equipment of the research aircraft includes a normal primary IFR-instrumentation which is electrically independent from the flight test equipment. A DELCO Carousel IVA Inertial Navigation System (INS) is operated from the cockpit and is interfaced to the on-board data system. The following sensor signals are available in the computer:

- a_x, a_y, a_z from aircraft-fixed accelerometers
- p, q, r from aircraft fixed rate gyros
- static and dynamic pressure
- total and static temperature
- angle of attack and angle of sideslip
- elevator, aileron, rudder, flap and throttle position
- ILS information like glidepath and localizer deviation
- radio altitude
- DME-distance
- Engine parameters like RPM and manifold pressure
- inertial navigation data:
  latitude along track acceler.
  longitude wind angle

ground speed	drift angle
true heading	attitude angles Θ, Φ, ψ
true track	desired track
vertical acceler.	cross track distance

The control surfaces of the DO 28 are driven by electromechanic servos. They receive analog position commands from the data processing system and are supplied with internal feedbacks of speed and position. All servos may be quickly disconnected by the pilots and can be manually overrided if the disconnect fails.

3.2 Data processing system

The DO 28 aircraft is used for different purposes and therefore equipped with a rather universal data system.

Central part of this system is a powerful 16-bit Minicomputer, a NORDEN 11/34 with floating point hardware and two mil-spec floppy disc drives (See FIG. 2). The NORDEN 11/34 is a military version of the PDP 11/34 (Digital Equipment Corporation). Via a MUDAS communication processor it has access to all sensor data and control surfaces (MUDAS = **M**odular **U**niversal **D**ata **A**cquisition **S**ystem, Dornier System, Friedrichshafen, FRG). MUDAS contains all signal converters and relieves the main processor from collection and distribution of I/O data.

The main computer is operated from the seat of the flight test engineer in the back of the aircraft. His CRT-terminal is combined with a small printer. It permits the generation of a flight test protocol.

For the purpose of documentation and data evaluation on the ground, a PCM data recorder has been installed. It can sample 32 channels with a rate of 92 Hz. PCM-modulator inputs may be accessed either directly or via NORDEN/MUDAS. PCM data is later read in on a ground computer system, where it can be filtered, reduced, classified or plotted. Some of these plots are shown in chapter 6.3.

3.3 Autopilot Control Panel

An Autopilot Control Panel (ACP) is situated in the cockpit which is interfaced directly to the terminal line of the main computer. For reasons of safety, data exchange between main computer and ACP is performed with check-summed data blocks. There must be a request at the ACP for at least every 500 ms, otherwise it will put the pilots on the alert, because there must be something wrong with the main computer.

From the view of the pilot, the control elements and displays of this control panel are not very different from those of a normal autopilot. The operator can select modes, input command values, or read some status data from a display. However, regarding the fact that the ACP is an I/O device for an experimental software of the main computer,

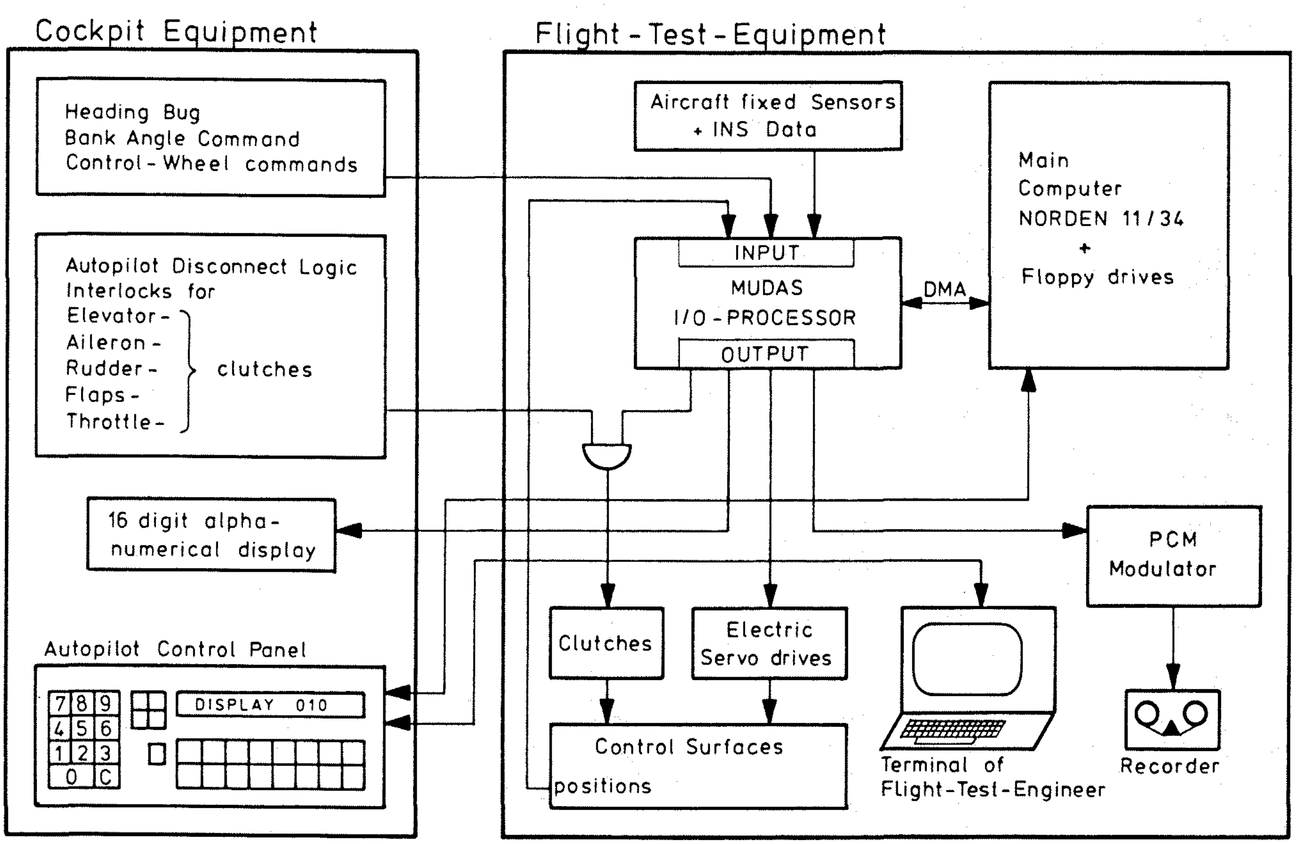

FIG. 2 : The Flight Test Equipment of the Research Aircraft

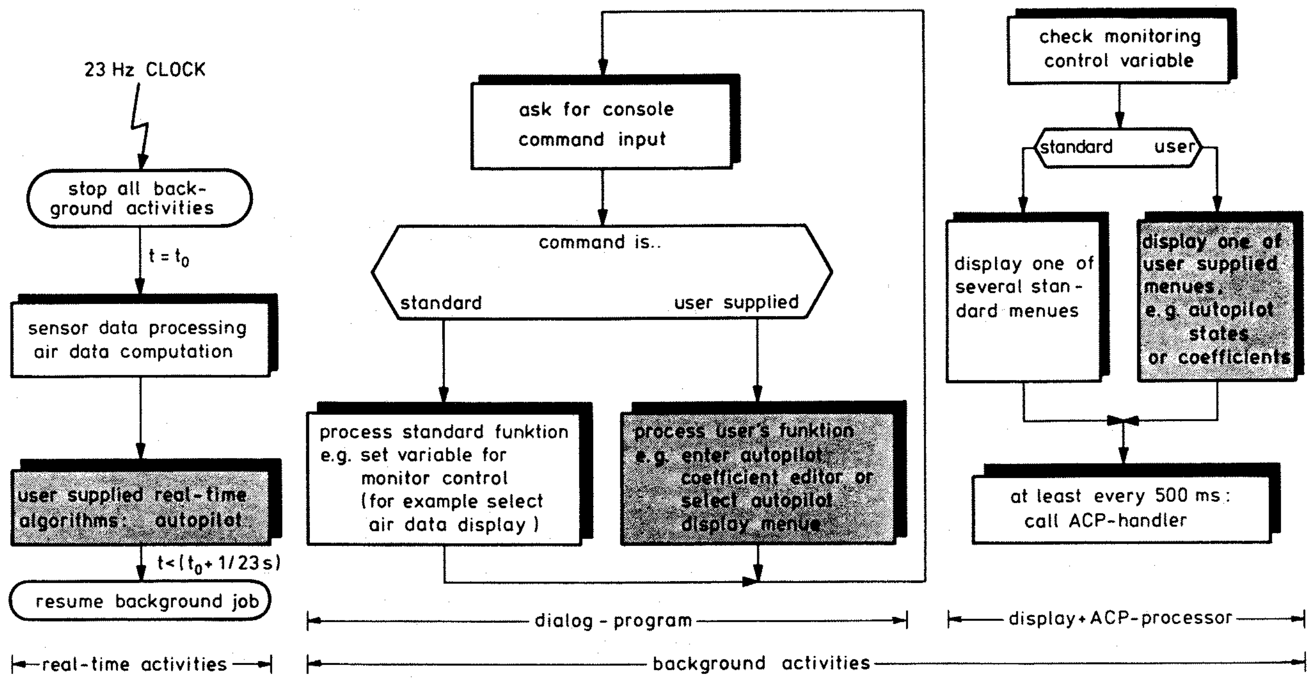

FIG. 3: Structure of the On Board Softwaresystem

it is internally organized like a user-programmable intelligent I/O processor. This means that the behaviour of the ACP is defined by an initial load of a mode-attribute-table and a mode-compatibility-table. The following attributes are defined for each of 14 possible modes:

- priority and compatibily to other modes, which may be active when this mode is selected
- units, limits, input format and number of command values.
- unit and format of display values

This concept has the advantage of good flexibility. The ACP can be used to control the autopilot. It is able to operate different tasks of the main computer without the necessity of changes in its hardware or firmware. Only a new data set must be loaded from the main computer. A data set is generated on a ground computer with the help of a dialog orientated install-program. After an install-session, the new data set is copied to a diskette from the aircraft computer.

4. Integration of the experimental autopilot into the data processing system

4.1 On-line processing of sensor data and autopilot algorithms

The aircraft is used in several projects. To reduce the workload for similar problems in different applications, a program structure for aircraft data processing was defined and is obligatory for all users.(4) Generally it divides software into real-time processes and low priority processes. FIG. 3 demonstrates the software of the main-computer system. All real time processes are repeated with a frequency of 23Hz and must be computed within a rigid time frame of less than 1/23 s. The low priority background tasks use the remaining time shares. Their repetition frequency results from their program length and from the rate of capacity utilization of the real-time task.

For the purpose of shorter development time and easier documentation all programs except some small and time critical modules are written in the high level language FORTRAN IV.

All processes are divided into standard parts and into user-dependent parts. All standard parts are supplied to the user through an object library. The standard real-time task includes processing of all sensor data into engineering units. The air data computing is also included within this part. For example a Luenberger observer is synthesizing a precise vertical speed signal from static pressure and INS-vertical acceleration.(5) All of these values are to be accessed in COMMON data areas.

The standard part of the background-process handles a dialog with the Autopilot Control Panel, as well as the dialog with the terminal, which takes place in the dialog-window of the CRT. A special monitoring process is steadily renewing an operator-selected menue in the so-called monitor-window of the CRT screen. The standard instruction set of the background job enables the flight test engineer to look into all primary sensor data, as well as into all results of processed standard signals.

The autopilot algorithm is embedded into the system as a user-subroutine which is called from the real-time task after all standard data is processed. Communication with the ACP takes place via COMMON data areas, which are read or written by the so-called ACP-handler. It is assigned to the standard part of the background job, because it is not so important, whether the reaction on a pilot-input follows about 100 ms later or not.

4.2 Diagnostic Software Tools for the Flight Test Engineer

The later descibed autopilot is an experimental flight controller. It was frequently changed in the past and will be changed in future. This requires some tools for efficient testing and quick error recognition. The autopilot algorithm can be tested off-line with a rather good reliability for later on-line application. It is an economical demand to test as many program parts as possible by the simulation on the ground computer. However, not all sections can be satisfactorily checked because the actual aircraft hardware can not be completely interconnected to the ground computer. For example, integration of autopilot mode switching must be reassured in the aircraft. For this reason, the flight test engineer should be able to look into all states of the autopilot and its control logic. Several special display-menues have been programmed for this purpose. One of them shows I/O signals of the autopilot and furthermore the contents of different internal states like integrators. Another one presents the logical status of the autopilot and its communication with the ACP. Last not least the states of control surfaces and engines can be observed, if the operator wants this.

A special command, which is included in the standard instruction set, gives the possibility to print a hardcopy of the actual CRT-contents. This hardcopy always contains the actual time of day. Time is also written to the PCM-recorder, so that printed data can be related to PCM data during later evaluation on the ground.

These tools first were destinated for quick trouble shooting and observation, if there are problems during flight test. In fact they already helped and will help to find a high percentage of logical programming errors during first program tests on the development computer in the laboratory, where the aircraft hardware is simulated.

As described in the introduction, a final tuning of the autopilot's coefficients must be possible in flight. A special editor for changing parameters has been integrated into the user's background program (see FIG. 3). It allows the operator to modify coefficients in a way, as if he would turn an analog potentiometer. After selection of the desired parameter, the operator may define an increment with a magnitude of his choice. Then he can increase or decrease the parameter by repetitive pushing of terminal keys. Each keyclick adds/subtracts another increment to/from the desired coefficient. It also may be inverted, cleared or reentered. This editor has been very useful during former flight tests and is one of the most important aids for an effective on line optimization. The programmer may add the on-line calculation of a quality criterion. The results are displayed and offer a help to estimate the quality of the autopilot.

5. Structure of the Longitudinal Loops of the autopilot

FIG. 4 demonstrates the principle of the longitudinal part of the DO 28 autopilot. All important states are fed back to all actuators, as there are throttle and elevator. Direct lift control (DLC) is not realized in the current autopilot but may be included in the future. Hence it follows that the flaps are not incorporated in the state feedback. Important information, which results from commanded inputs, is forward-looped to improve the system response to changes in reference signals. Therefore the dimensioning of feedback gains can be mainly performed according to the demands of disturbance response. An example is given by the thrust-command $F_c(\gamma, V_c)$, which depends on commanded speed and flight path angle. It will be described in chapter 6.3 .

A forward-looped signal according to $1/\cos\Phi - 1$ is added to the elevator. This is the usual way to consider the additional lift-requirement during coordinated turns.

Feedback of the rotational states θ, $\dot{\theta}$, and $\ddot{\theta}$ can be regarded as an internal phugoid damper. These states are only coupled to the elevator because a feedback to thrust does not produce large effect on phugoid damping. -feedback is filtered by a washout with a time constant of about 25s. The reason is the following: no stationary part of θ should be added to the elevator for the purpose of damping, because the phugoid damper must enable the aircraft to find another stationary pitch angle, if weight or speed is changing. Instead of $\dot{\theta}$, $\ddot{\theta}$ the terms q_r, $\dot{q}_r$ are used. They consider the effects of rate-gyro cross coupling between q and r during coordinated turns.

Altitude and speed (H_c, V_c) are the reference inputs for this flight controller. Both must be steady and differentiable functions of time. FIG. 4 shows that a special command-value generator determines commanded H_c and V_c by differentiation.

The source of H_c and V_c depends on the selected mode. During "ALTITUDE HOLD" both are constant. When entering "ALTITUDE ACQUIRE", H_c is a low-pass filtered ramp, while during an automatic landing, H_c will be determined from the glide slope deviation.

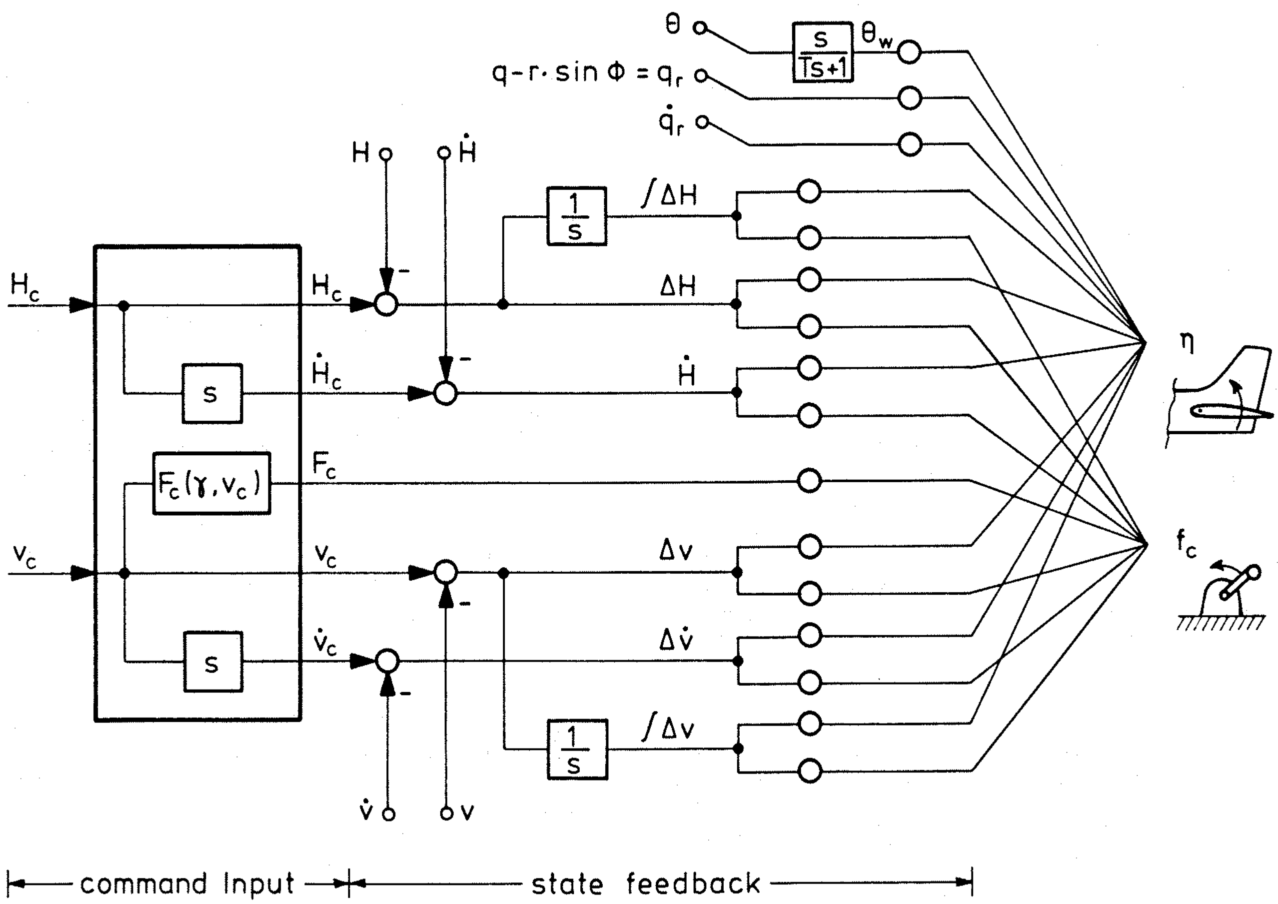

FIG. 4 : Structure of the Longitudinal Part of the Experimental Autopilot

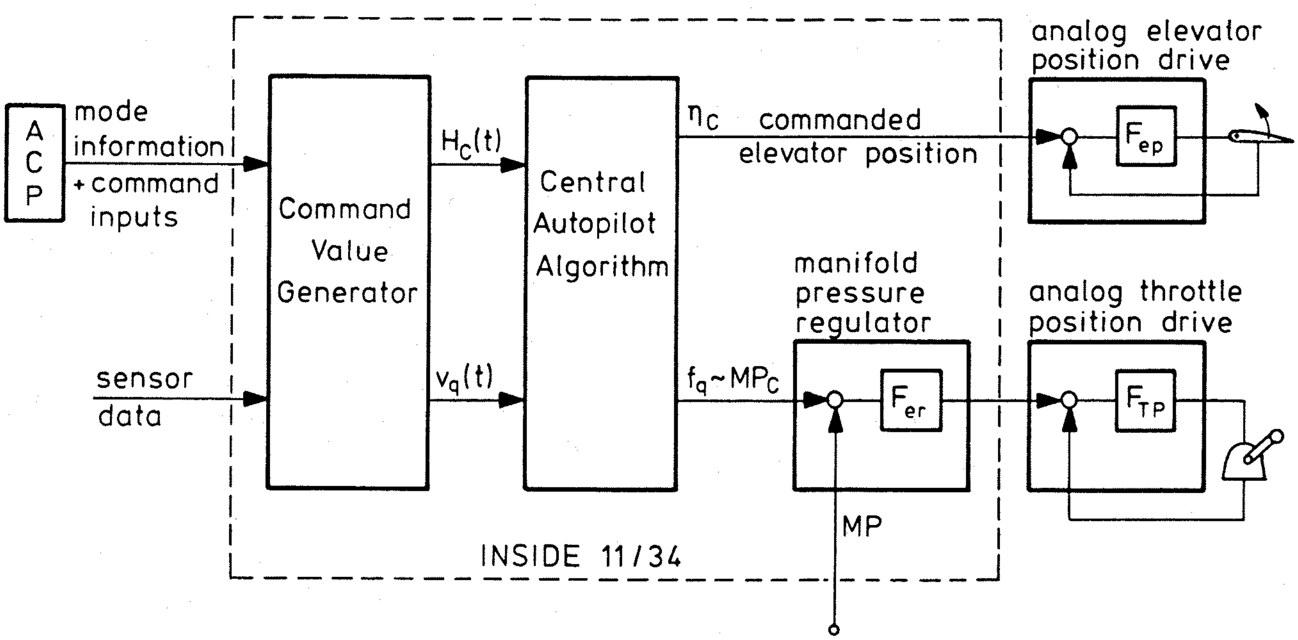

FIG. 5 : Integration of the Autopilot into the Aircraft

FIG. 5 describes the integration of this autopilot structure into the aircraft. The elevator position command is immediately connected to the elevator servo system. Instead of guiding the thrust command directly to the throttle position servo, it is used as a command input MP_c to a manifold pressure controller (see FIG. 5). Like the autopilot it is also realized in the main computer and regulates manifold pressure MP using the throttle position servo. Thrust and manifold pressure are in a good proportional relationship as long as the propeller speed is kept constant. This frees the autopilot from several non-linearities, which exist between throttle position and thrust. They are:

- dependence of the effectivity of the engine's super-charger from ambient static pressure

- mechanical hysteresis between throttle lever and engine manifold pressure

6. Procedures of Autopilot Testing

6.1 Optimization of the Phugoid Damper

The base for a satisfactory behaviour of the aircraft with higher autopilot modes is a good pitch and phugoid damper. The longitudinal damper is active in all modes of the autopilot. However, if the principle of state feedback is applied, the damper can be regarded as a separated inner cascade of the control system, which is responsible for rotational stability. As described in chapter 5, it is realized by feedback of θ, q_r, and $\dot{q}_r$ to the elevator. For an ideal, lag-free elevator system only θ and q_r are required for a good longitudinal damper. Theoretically rather high feedback gains, e.g. $C_{\theta\eta}$ = 10 rad/rad, are possible. In a real aircraft there are unfortunately several pole pairs of the elevator servo system, which restrict feedback gains. Perhaps the later assumed model of the elevator system is not correct. If there are effects of structural dynamics, the behaviour of the elevator cannot be exactly described by discrete poles.

To develop a strategy for an on-line optimization of the damper, it is necessary to understand the effects of different feedbacks. For a brief discussion a hypothetical pole-zero distribution of the longitudinal aircraft motion is assumed (see FIG. 6) : A pole pair (P) represents the phugoid, another pole pair of higher frequency and two zeroes belong to the short period mode oscillation (S), and two pole pairs (E) represent the dynamics of the elevator system. FIG. 6a shows the influence of a growing θ-feedback. It is the most effective part for suppressing the phugoid mode. FIG b demonstrates that the influence of growing q_r primarily dampes the short period. Both of the above described feedbacks have the effect that some other poles become destabilized and therefore are limited. Feedback of $\dot{q}_r$ (FIG. 6c) may stabilize the dominant pole pair of the elevator with the same limitations in respect to the remaining poles, which may be caused by elasticity or anything else.

If a simulation-optimized parameter set doesn't fit during flight test, the simulated aircraft state model contains inaccuracies and the damper must be modified in flight. In the present case the damper has been optimized by the following iterative strategy:

A stationary state of the aircraft is assumed, e.g. horizontal flight. All coefficients of the autopilot are cleared to zero. When the autopilot is activated, the present values of pitch-angle elevator position, throttle position and manifold pressure are taken as reference values. First the coefficient $C_{\theta\eta}$ is slowly increased until the limit of stability is reached. Now $C_{q\eta}$ will be modified, stability can be recovered, and $C_{\theta\eta}$ can be increased again. When there is no further improvement during this process, $C_{\dot{q}\eta}$ is changed and

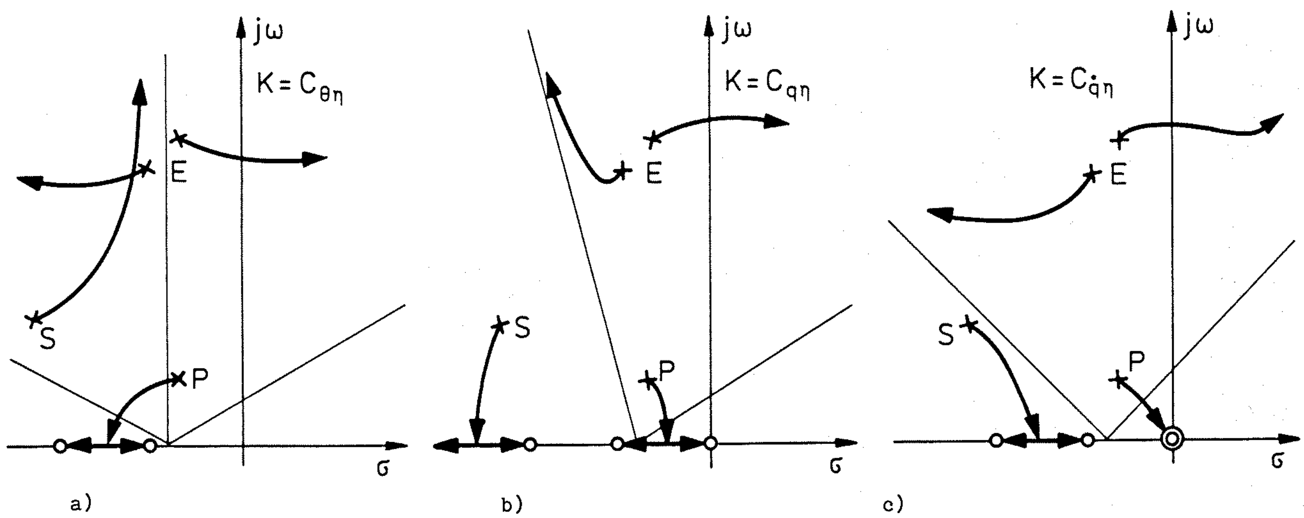

FIG. 6 : Influence of Different Elevator Feedbacks on the Poles of a Hypothetical Aircraft Dynamics

has the effect of more stability. The iteration with $C_{\theta\eta}$ and $C_{q\eta}$ can be repeated once more and so on. Within a time frame of 20 minutes a damper can be optimized, which shows good results. The left part of FIG. 7 shows the pitch angle after a phugoid manoeuver which has been excited by an elevator input. The right part demonstrates a phugoid manoeuver of the aircraft without damper.

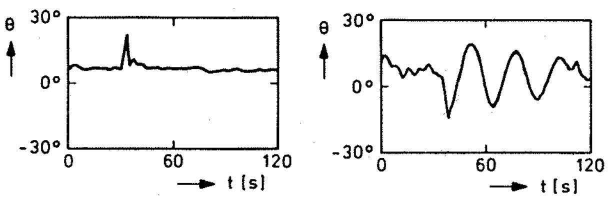

FIG. 7 : Phugoid Responses of the DO 28 with and without longitudinal damper

6.2 Altitude Hold Mode

As long as the airspeed is kept above the speed of minimum drag, ALTITUDE HOLD is a mode, which can still be realized without thrust control. The phugoid damper is assumed to be active. The strategy of dimensioning feedback of altitude deviation ΔH, integrated ΔH and vertical speed is similar to the strategy described in chapter 6.1 . However, the altitude regulator can be looked upon as a cascade above the phugoid damper. Because of the damper the attributes of the aircraft have less effect on the dimensioning of the exterior cascades. Knowing the damped aircraft's response to elevator inputs, this means that the altitude regulator could be pre-dimensioned on the ground. Only a fine tuning was necessary during flight test. FIG. 8 shows an aircraft turn with a bank angle of 30 degrees with the autopilot in ALTITUDE HOLD. Altitude deviation is always less than 5 m.

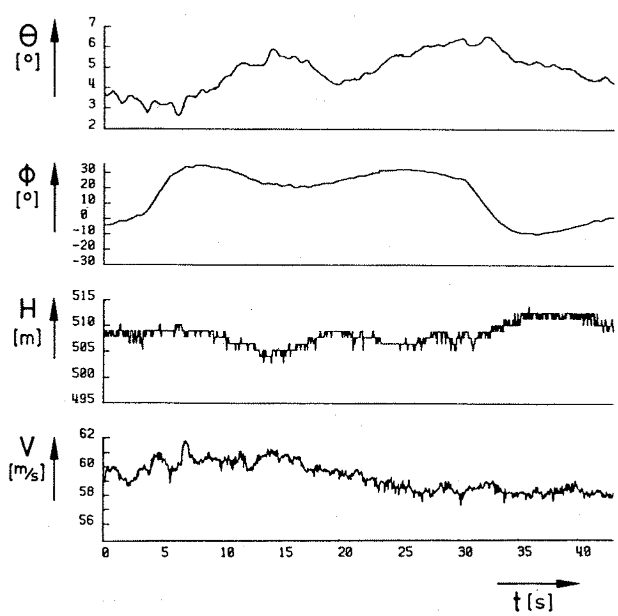

FIG. 8 : Turn Manoeuver in Altitude Hold Mode

6.3 Integration of throttle control

Several autopilot modes require both the control of glidepath and speed. This can only be performed, if throttle control is integrated into the autopilot. There are two important parts of throttle control: feed-forward of thrust-reference which results from commanded states and thrust feedback from actual states of the aircraft. With a constant flap-configuration thrust requirement is mainly a function of commanded speed and flight path angle. During this autopilot development the intention was to determine these requirements first and then to optimize different state-feedbacks according to a given quality criteria. The following procedure should be performed:

Climbs and descents are flown with the above described autopilot controlling a flight-path with constant climb or descent rate. Selected mode is ALTITUDE ACQUIRE with deactivated throttle control. The pilot operates the engines and has the task to keep the airspeed on the reference value. Manifold pressure and selected propeller speed are recorded. Several manoeuvers like this are flown with different speeds and different flight path angles. Evaluation of the recorded data will be a base for a formula or algorithm which should enable an on-line estimation of thrust requirement from commanded speed and flight path angle.

FIG. 9 shows recorded altitude and vertical speed from a whole flight test like the one just des-

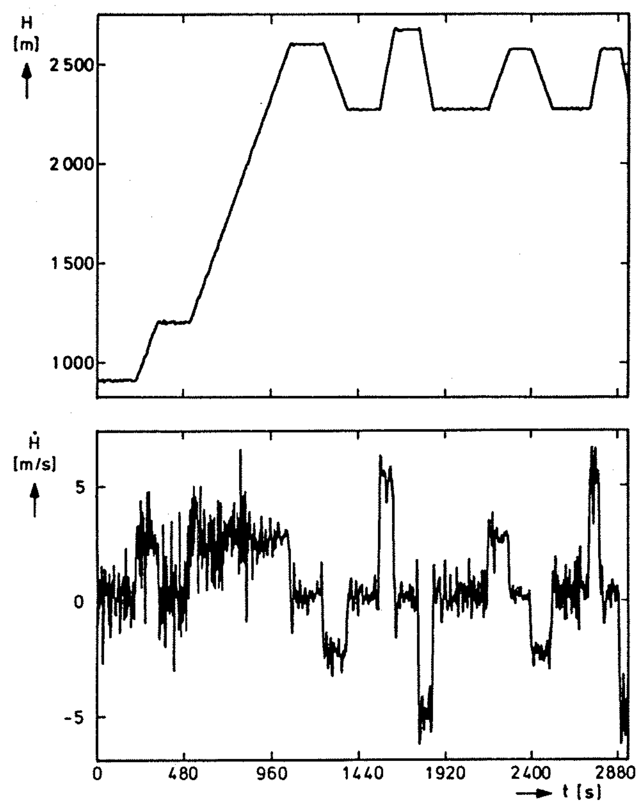

FIG. 9 : Flight Test Manoeuvers for Determination of Thrust Requirements

cribed. On this day there was an unstable athmosphere, a typical weather for soaring with thermal updraft up to 6m/s. In this case the pilot's task to keep air speed constant is very difficult. The autopilot is exactly following a constantly increasing altitude command. If there are vertical winds, which will cause altitude deviations, the autopilot immediately converts these altitude errors into speed errors. This is a general problem of autopilots with separated controllers for altitude and speed. For this reason a long climb was undertaken until there was less vertical turbulence at higher altitude.

Two complete changes from one flight path angle to another are demonstrated in FIG. 10. Even under these better conditions the pilot has difficulty to keep an exact speed. He can't work as he would like to do, because he has no access to the elevator. Normally a pilot corrects short-time speed errors with the elevator and uses the throttle only to adjust long term speed deviations.

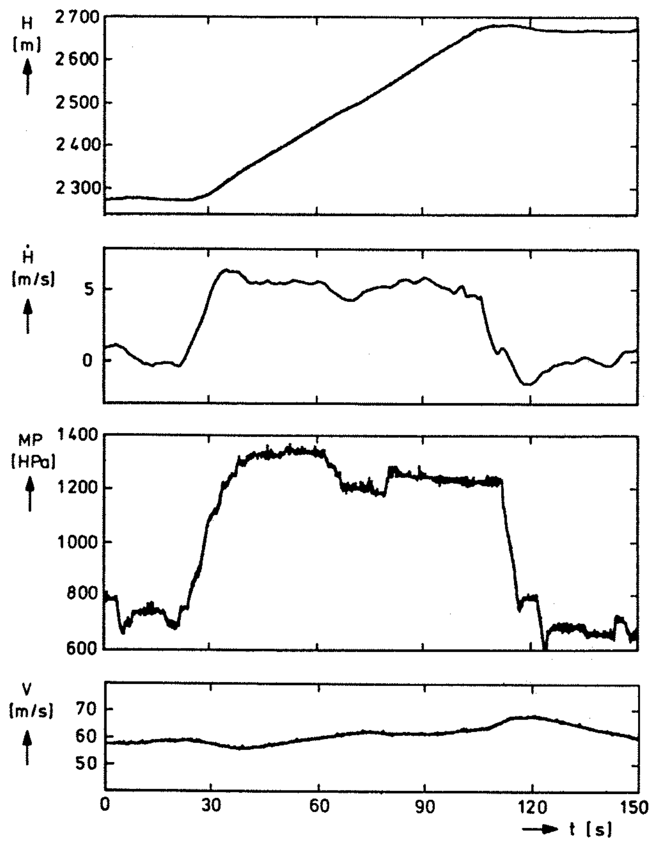

FIG. 10 : ALTITUDE ACQUIRE MODE , H = const.

It can be concluded that it is not realistic to obtain a reliable data set during a single flight. After this experience the strategy of throttle control integration was modified to an iterative process:

After data evaluation from the above described flight a first rough algorithm for thrust forward-loop control was formulated. The next flight test was performed to optimize the most important state feedbacks for a cross-coupled autopilot. If it works satisfactorily, the above described manoeuvres are repeated, but now with an autopilot controlled throttle system. The autopilot should be able now to perform an improved speed control because it has better information than the pilot before. If these conditions are met - the flight test engineer is able to review whether or not - a more reliable data set can be obtained after this flight. The iteration process had not already entered its last loop at the copy deadline of this paper, but it can be stated that it converges.

7. Conclusions

The in-flight integration of different parts of an experimental digital autopilot for the longitudinal aircraft motion has been described. A strategy for an iterative optimization of forward loops and feedbacks of the flight controller was demonstrated. After this optimization process a cross-coupled autopilot has been dimensioned, which works satisfactory in flight test and which is "good" with respect to the on line calculated quality criterion. An identification of the phugoid damped aircraft should be one of the next steps. It is the aim to realize the same feedbacks during an off-line simulation, which were found during flight. If such an agreement can be obtained, it would enable a realistic, systematic off-line optimization of the autopilot according to different quality criteria. The availability of different coefficient sets for diverse requirements is a prerequisite for a flight controller with situation dependent behaviour.

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