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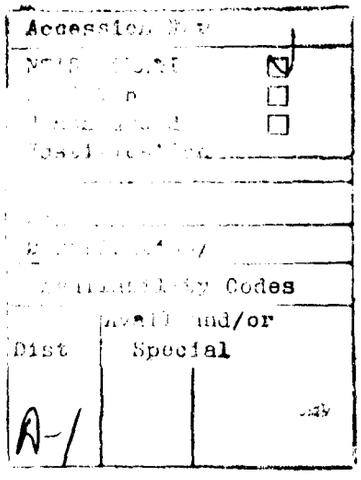

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DESIGN CRITERIA FOR MULTI-LOOP FLIGHT CONTROL SYSTEMS

by

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Abstract

The problems of design criteria and architecture of multiloop flight control systems are discussed for a realized system to achieve precise flight path guidance, safe and economic control of the aerodynamic flow (airspeed, angle of attack and lift coefficient control) and passenger comfort. Joint root locus and quality criteria design will be presented.

The structure of the presented multiloop flight control system consists of nonlinear open loop control for flight performance and flight management purpose, superposed quasi linear state vector feed back and six control surfaces (aileron, rudder, elevator, trim, throttle, direct lift/drag control).

Contents

1. Introduction

Flight control systems are more or less a conventional tool to improve the aircraft characteristics as well as to provide a more precise guidance and control. The range of application is extrem wide. In order to improve the handling qualities and low stability margins of uncontrolled aircraft, damper and stabilizer are state of the art. Flutter control systems may reduce the structure load of the aircraft structure and can improve life cycle time. For many applications in guidance and control the improvement of flight accuracy for air traffic control and 3D/4D navigation is essential. Weapon delivery requires excellent attitude and speed control. Also for safe and economic flights, the control of the aerodynamic flow condition via airspeed, angle of attack or lift coefficient is of great importance. Additonally, many military and all civil aircraft need control systems to improve passenger comfort and the safety margin when flying in adverse wheather conditions e.g. turbulence, wake vortices, wind shear and poor visibility.

Design criteria for adequate flight control systems to fullfill the discussed requirements are contradicting in general and an acceptable compromise has to be found /1/.

These design problems will be discussed for a multiloop flight control system that can achieve a precise flight path guidance and a safe aerodynamic flow control. The structure of this flight control system consist of

- nonlinear open loop control for flight performance and flight management purpose
- superposed linear state vector feed back control
- six control surfaces (aileron, rudder, elevator, trim, direct lift/drag, throttle)

The flight control system as a digital experimental system, is installed in a twin engined propeller driven research aircraft of the Technische Universität Braunschweig. Up to now the system has been tested in cruise flight, approach and landing.

2. Symbols

2.1 Control theory

$\underline{A}$, $\underline{B}$	System matrix
D	observation period
D_c	disturbance vector
G_c	guidance input vector
t	time
σ^2	variance

2.2 Flight mechanic

C^*	handling quality criterion	V	airspeed
C	derevativ	V_K	ground speed
F	Thrust	V_W	wind speed
g	earth acceleration		
H	altitude	α	angle of attack
$\dot{H}$	rate of climb	γ	flight path angle
$\ddot{H}$	vertical acceleration	ϕ	roll } attitude angle (Euler)
n	load factor	θ	pitch } attitude angle (Euler)
m	aircraft mass	ψ	yaw } attitude angle (Euler)
S	wing area	η	elevator displacement
q	pitch rate	δ_f	flap displacement
q_p	dynamic pressure	ρ	air density
u, v, w	orthogonal speed component		

2.3 Indices

c	Command	o	open loop
d	disturbance	w	actuator open loop command
D	drag	α	angle of attack
L	Lift		

3. Control system structure

Design criteria and control system structures are difficult to be presented in general, as they vary due to the application. In this paper we will concentrate the discussion on the precise control of the flight path and the safe control of the aerodyamic flow condition. Flight path and flow condition can vary over a wide range in short time periods.

The basic command inputs in the flight control system are flight path and airspeed. The pilot or an outer loop air traffic control system may vary this command inputs.

To achieve a proper response of the controlled aircraft six control surfaces (actuators) are applied, as there are aileron, rudder, elevator, elevator trim, throttle, and direct lift device (fast landing flap control). For optimum control, all relevant control information has to be fed to all relevant actuators. Therefore the adequate control system for this task is a strongly cross-coupled multi-loop control system.

For the mathematical presentation of general cross-coupled higher order multiloop systems the state space may be adequate. In this space presentation all state element have equal status. It is typical for the aircraft dynamic response that some state element have different status. Generally speaking the aircraft dynamic response can be presented as a cascade system. Each loop of this cascade system has a different and specific response charakteristic. The different loops can be characterised by their frequency domains. Beginning with the highest frequency domain as the inner cascade loop, four different loop can be identified.

1. Structural dynamic

In the relativ high frequency dynamic response of the elastic aircraft flutter control, structural strength reduction and partly loadfactor control as well as gust alleviation are typical applications.

2. Rotational dynamic

In the frequency range of the short period mode, dutch roll and roll mode the handling qualities are of great importance. In this frequency regime an enormous knowledge exists to specify and design special control systems, as there are damper, stabilizer, gust alleviation, direct lift control.

3. Energy dynamic

In the frequency regime of the phugoid and spiral mode, energy transfer is important. Throttle control, speed control and wind shear suspression are typical applications in this area. Additionally some cross coupling effects between lateral and longitudinal motion, e.g. turn flight, are of interest as well as some effects of direct drag and lift control.

4. Flight path management

In the extrem low frequency regime, flight management, 3D and 4D navigation and partly air traffic control dominate this outer cascade loop.

In the past, most of the applied flight control systems are specified and designed for relativly small cascade element (e.g. damper for cascade Nr. 2 and autothrottle control for cascade Nr. 3) as single loop control systems. As the interaction between the cascades can not be neglected, the control efficiency of such single loop control can be improved significantly in applying a multi-loop control structure. For example, the poor control dynamics of conventional flight control system for transport category aircraft in the energy cascade loop require a long stabilized flight profile for approach and landing /2/. Already small energy disturbances e.g. moderatly curved flight path or wind shear can effect such type of control systems very much.

The well known modern control theory /3/ based on a state space presentation of the aircraft may overcome some of the discussed problems. The general problem in application of the modern control theory is the cascade behaviour of the aircraft dynamic, where each cascade loop askes for its specific design procedure. The application of different design procedures in one control systems shall be discussed in chapter 5 more in detail.

The knowledge concerning the aircraft response is in general excellent. The relevant discipline is known as flight mechanics. But only a small part of this knowledge is implemented in flight control systems. This lack of information may cause problems in dynamic response quality and precision.

Most flight control systems use only information to adapt variing parameters as dynamic pressure or Mach number.

The theoretical approach to incorporate flight mechanical knowledge in the flight control system is simple in principle. We assume that the characteristics of total cascade can be described in state space

$$\dot{\underline{x}} = \underline{A}\,\underline{x} + \underline{B}\,\underline{u} \quad . \tag{1}$$

If, for specific manoeuvres, the state vector $\underline{x}_c$ is specified, the required optimal control deflection uc can be calculated in prinziple.

$$u_c = (\underline{\dot{x}}_c - \underline{A}\,\underline{x})\,\underline{B}^{-1} \quad . \tag{2}$$

This ideal equation cannot be solved in general. The phenomen is known as the inversion of the transfer function of time delayed systems.

Most flight control applications eq.(2) can be simplified in a way, that a mathematical solution is possible.

If we observe the information flow in the cascade loops, we find that primary the information will flow from the outer loop to the inner loop. Therefore the dynamic presentation of the outer loop is more important for the knowledge implementation. As the outer loop responds much slower than the inner loops, a quasistationary approximation of eq.(2) may solve the problem. Because the equation of aircraft motion is non linear the approximation of eq.(2) has to be non linear.

With such an quasistationary non linear open loop control the closed loop design is easier. The required feed back gains are small compared with control systems without an adequate open loop control. For example, the aleviation of gust and windshear can be a part of the open loop control.

The less the presentation of the aircraft dynamic in the open loop, the greater are the required feed back gains to fullfill the task. An example for such an open loop control system is given in chapter 4.

4. Non linear open loop control

A more detailed discussion of the loop control shall demonstrate some practical aspects.

The cross-coupling effects between lateral and longitudinal aircraft motion are relative small for conventional transport aircraft. Primary the coordinated turn flight influences the load factor

$$n = \left[\frac{\ddot{H}}{g} + \cos\gamma\right]\frac{1}{\cos\phi} \tag{3}$$

and body fixed rate sensors produce coupled output signals. For example in the output of a pitch rate sensor

$$q_s = \dot{\theta}\cos\phi + \dot{\Phi}\sin\phi\cos\theta \quad . \tag{4}$$

To simplify the discussion, only the longitudinal aircraft motion shall be pointed out more in detail.

There exist two major tasks of the open loop control (see fig. 1 and fig. 2)

- Calculation of the commanded state vector element $\underline{x}_C$
- Calculation of the open loop control surface displacement $\underline{u}_O$

A typical set of state vector elements of a flight control system may be

q	pitch rate
θ	pitch attitude
α	angle of attack
H	altitude
$\dot{H}$	vertical speed
$\ddot{H}$	vertical accelleration
$\dot{\underline{V}}_K$	horizontal accelleration

To achieve a precise control with adequate dynamic behaviour, each state vector element should be compared with a commanded state vector element.

The commanded state vector $\underline{x}_C$ has to be calculated as a function of

the guidance input vector $\underline{G}_C$

H_C	flight path command
V_C	airspeed command

and the disturbance vector $\underline{D}_C$

Φ	roll angle
δ_f	wing flap deviation
ρ	air density
W	aircraft weight
V_W	wind and turbulence velocity

The function between $\underline{x}_C$, $\underline{G}_C$ and $\underline{D}_C$ is part of the flight performance calculation. In general the complete set of the aircraft motion equation (see appendix) is necessary to realize the performance calculations. A simple example shall demonstrate this in a procedure that is well known in the flight mechanics community.

The required lift L is in equilibrium with the weight W of the aircraft and the load factor n

$$L = nW \quad . \tag{5}$$

The lift is a function of dynamic pressure

$$q_p = \frac{\rho}{2} V^2 \tag{6}$$

wing area S and lift coefficient C_L

$$L = \frac{\rho}{2} V^2 S C_L \quad . \tag{7}$$

The lift coefficient itself is primary a function of angle of attack α and flap deflection angle δ_f

$$C_L = C_{Lo}(\delta_f) + C_{L\alpha}\,\alpha \quad . \tag{8}$$

The combination of equation (5) to (8) gives the element α_c of the commanded state vector x_c

$$\alpha_c = 2 W_d n_c \left[V_c^2 S C_{L\alpha} + C_{Lo}(\delta_f) C_{L\alpha}^{-1} \right]^{-1} . \tag{9}$$

The commanded airspeed V_c is an element of the guidance vector. The weight W_d is an element of the disturbance vector. The load factor n_c has additionally to be calculated in relation to eq.(3).

An example for the open loop throttle control may be derived from the "drag equation" of the aircraft (see appendix). The required thrust is:

$$F_c = W \left[n \frac{C_D}{C_L} - n \frac{w_W}{V} \cos\gamma - \left(1 + n \frac{u_W}{V}\right) \sin\gamma + \frac{\dot{V}_K}{g} \right] . \tag{10}$$

The drag lift to drag ratio is a function of the angle of attack, flap position and Mach number. The load factor n is in relation to eq.(3) a function of vertical accelleration $\ddot{H}$, roll angle Φ and flight path angle γ. The effect of vertical wind w_{Wg} (e.g. downburst) is as well implimented as horizontal wind u_{Wg}. Horizontal wind influences the required thrust only in climb or descend conditions. The effect of required thrust in a windshear situation shall be discussed more in detail. In windshear the airspeed V of an aircraft shall be constant ($\dot{V} = 0$) for safety reasons. As the ground speed V_K is a superposition of windspeed V_W and airspeed

$$\underline{V}_K = \underline{V} + \underline{V}_W . \tag{11}$$

The time derevation is

$$\dot{\underline{V}}_K = \dot{\underline{V}} + \dot{\underline{V}}_W .$$

With $\dot{V} = 0$ the requirement exists, that $\dot{V}_K = \dot{u}$. This means, that in a windshear situation the aircraft has to be accelerated or decelerated in the same way as the wind itself. We introduce this effect into eq.(10). For small flight path angle γ we get

$$F_c = W \left[n \frac{C_D}{C_L} - n \frac{w_{Wg}}{V} - (1 - n \frac{u_{Wg}}{V})\gamma + \frac{\dot{u}_{Wg}}{g} \right] . \tag{10a}$$

These equations are the basis for a precise and effective open loop control.

With the todays computer power in digital flight control systems these coupled non linear equations can be calculated in real time without any significant problems.

The modern control theory /3/ gives precise answers concerning the optimal structure of linear feed back: All state vector elements $\underline{x}$ have to feed back to all actuators. The practical problem is to define the six elements of the state vector and to measure the state variables. These very interesting problems can only be mentioned without going into details.

The state vector size depend on how many cascade loops are necessary to present the aircraft characteristics. In most cases the actuator dynamics must be added yet. In contrast to this the sensor dynamic may be neglected.

The aircraft measurement technics /4/ are well developed so that most state vector elements can be measured directly. On the other hand the modern control theory provides powerfull methods to observe unknown state vector elements. The design of observers /5/ for flight control systems is a very interesting task. The designer has to find a compromise between expensive sensors and moderate system knowledge.

Figure 1 shows a block diagramm of all essential control loop elements.

5. Design criteria and procedure

For a given control system structure the control parameters have to be calculated. To design a non linear open loop control is relativly simple. The set of nonlinear equations can be solved for example with a numerical minimum variance methods /6/.

In contrast to the open loop control, the closed loop control design can in theory be very complicate. The todays design procedure for complex flight control systems is more art then an application of a proper theory. I shall illustrate this private statement more in detail.

The design criteria in the "rotational dynamic cascade" are well formulated in handling qualities criteria of aircraft. An excellent example of handling qual' requirements is the well known military specification MIL 8785 /7/. Most of handling quality criteria can be expressed as eigenvalues and eigenvectors of relevant modes (short period, dutch roll, roll mode). The MIL 8785 gives clear rul where the eigenvalues (roots) have to be placed.

In contrast to the adequate root method of the rotational dynamic cascade the design of the energy dynamic cascade and parts of the flight management cascade can be formulated only unsufficiently by eigenvalues. Problems of speed and flight path deviation as well as of throttle activity may be formulated by variances of deviations. For example the difference between the commanded airspeed and the measured airspeed is a clear and simple measurement for speed control accuracy. The variance of the speed derivation is $\Delta V = V_C - V$

$$\sigma_V^2 = \frac{1}{D} \int_t^{t+D} \Delta V^2 \, dt \tag{12}$$

is easy to calculate. Throttle activity is an important human factor in flight control design and acceptance. A high throttle activity bothers both pilot and passengers /1/. Some additional research is required to formulate an adequate mathematical equation to describe throttle activity. A sufficient measurement is thrust rate $\dot{F}$

$$\sigma_{\dot{F}}^2 = \frac{1}{D} \int_t^{t+D} \dot{F}^2 dt \; . \qquad (13)$$

Passengers or pilots comfort is an additional important human factor, both in civil and military aviation. In general it is difficult to find an acceptable mathematical formulation for human factors. The well known C*- Criteria /8/ for short periods response design represents passenger comfort quite well.

$$C^{*2} = \ddot{H}^2 + (V_p \, q)^2 \qquad (14)$$

$$\sigma_{C^*}^2 = \frac{1}{D} \int_t^{t+D} C^{*2} \, dt \qquad (15)$$

As difficult as the correct mathematical formulation of the relevant effects in the energy dynamics cascade is the weighting of these effects. The simple question what is more undesirable: a speed deviation of 1 knot or a flight path deviation of 10 ft is very difficult to answer. Due to the flight envelope different weighting are worthwhile. A practical approach is the equal weighting of the relevant energy-deviations

- kinetic energy $\Delta V \cdot V$
- potential energy ΔH

This energy weighting produce acceptable flight test results /9/.

More difficult is weighting the precision (H, V) on one hand and the human factors (throttle activity, passenger comfort) on the other hand. Many experience in calculation, simulation, flight test and operation are necessary to fix the weighting factors.

When the weighting factors $\underline{K}$ have been fixed, variance of the control qualtiy Q

$$Q = \int \Delta \underline{x} \, \underline{K}_x \, \Delta x^T \, dt + \int \Delta \underline{u} \, \underline{K}_u \, \Delta u^T \, dt \qquad (16)$$

can be minimized with different powerfull procedures.

Recording many application, a fixed set of weighting factors is not adequate for the total flight regime. Each area of the flight envelope requires its specific weighting matrix. The superposed calculation of different flight regimes and a joint minimisation of the quality criteria can give sufficent results. Todays powerfull computer are the necessary tool for this job.

As problemized earlier, complete flight control system requires different design procedures, root methods for the inner cascades and minimum cost methods for the outer cascades. No theory exists to solve both problems at the same time. If we use the different characteristics of the cascade we wiil find, that the control parameters of the inner loops affects strongly the dynamic characteristics of the outer loop but not vice versa. The control parameter sensivity move in the opposite way compared to the control information. Based on this axiom, we design complex multiloop control systems step by step.

The first step is the design of the inner loop (flutter suspression, damper, stabilizer) with root methods based on aircraft handling quality specifications. In a second step the outer loop control parameters are calculated by cost function minimization, where the inner loop control parameters are fixed. In most applications two or three iterative circles including flight test are sufficient.

6. Flight Test results

The results of the discussed design procedure for complex multiloop flight control systems shall be demonstrated for a realized flight control system for scientific applications. This flight control system has been developed in the Institut for Guidance and Control, Technical University Braunschweig /10/. The design targed was an extrem precise flight control system for flying nap-on-the-earth profiles to measure wind, windshear and turbulence on board of the aircraft.

The test aircraft is an institute owned, twin engine propeller aircraft (fig. 3). The aircraft is fully equiped with sensors, digital and analog computer and actuators for elevator, aileron, rudder, horizontal fin trim, throttle and direct lift (fig. 4). In the presented version of the flight control system, the aerodynamic flow condition was measured via the angle of attack. The task of air data computing, flight augmentation and thrust control will be done in one central computer (Typ Norden, DEC PDP11 compatible). The sample rate is 23 cycles per second.

Figure 5 demonstrates the high accuracy of the flight control system in smooth air. In a 9 minutes flight period, the maximum altitude deviation was less then 1 m. The altitude deviation is in the range of the resolution of the barometric altimeter. Figure 6 shows the aircraft response in altitude, airspeed and thrust at the begin of a

turn flight in moderate turbulence. In figure 7 the aircraft energy situations were heavily disturbed by setting the landing flaps. An altitude-acquire manouevre shows fig. 8 for strong turbulence. An automatic landing is demonstrated in fig. 9. Typical for this test aircraft is the gust sensitivity of the uncontrolled aircraft due to the low wing load and on the other hand its high pitch angle variation due to tail-wheel landing gear.

An older version (with a simple open loop control) is shown in fig. 10 in an curved MLS-approach /11/ passing a moderate wind shear.

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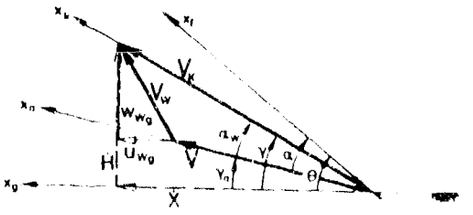
Apendix

A1 Aircraft equation of motion (translational) (simplified)

$$m \dot{V}_k = F - D + L \sin \alpha_w - W \sin\gamma \qquad (A1)$$

$$n G = L \qquad (A2)$$

A2 Velocity vector geometrie



$$\underline{V}_K = \underline{V} + \underline{V}_W \qquad (A3)$$

$$\sin\alpha_w = -\frac{w_W}{V}\cos\gamma - \frac{u_W}{V}\sin\gamma \qquad (A4)$$

A3 Thrust equation (superposition of eq (A1), eq (A2), eq (A4))

$$F = W\left[n\frac{C_D}{C_L} - n\frac{w_W}{V}\cos\gamma - \left(1 + n\frac{u_W}{V}\right)\sin\gamma + \frac{\dot{V}_K}{g}\right]$$

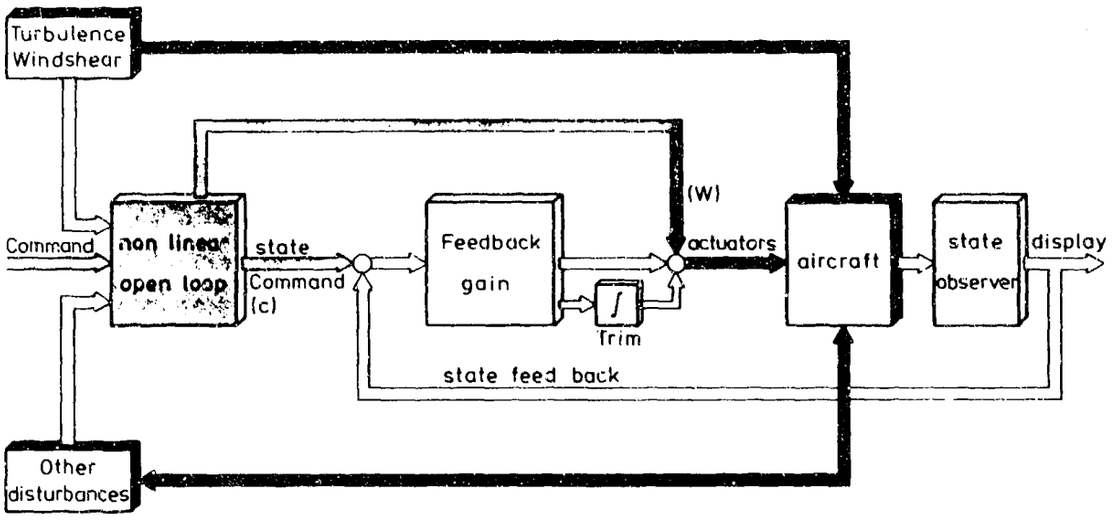


fig. 1 Block diagramm of the control loops

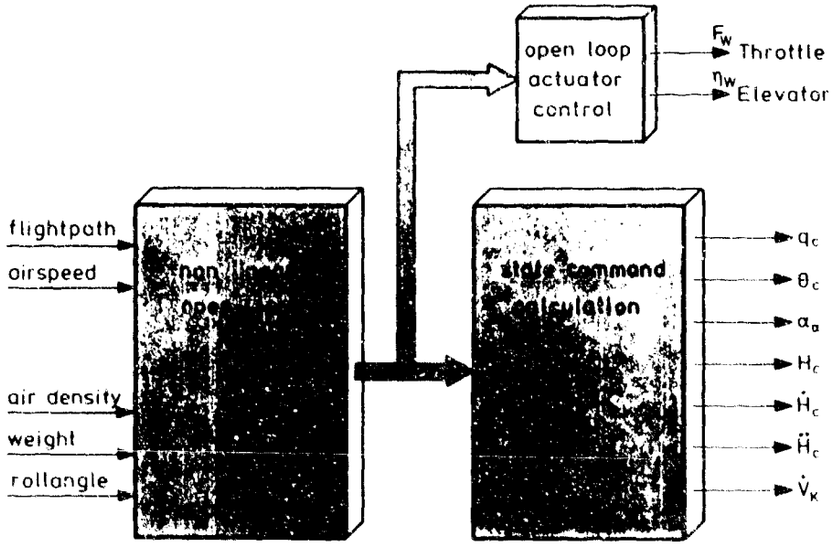


fig. 2 Non linear open loop control state and state command calculation

fig. 3 The DO 28 research aircraft

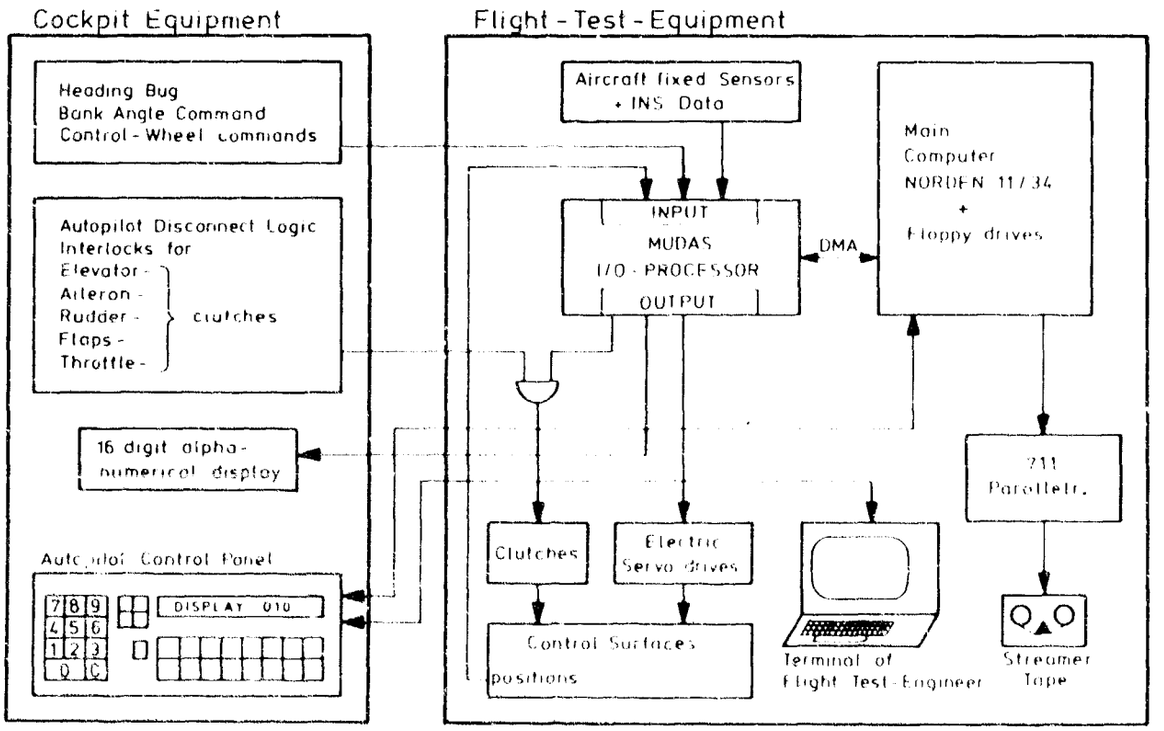


fig. 4 Equipment of the DO-28 research aircraft

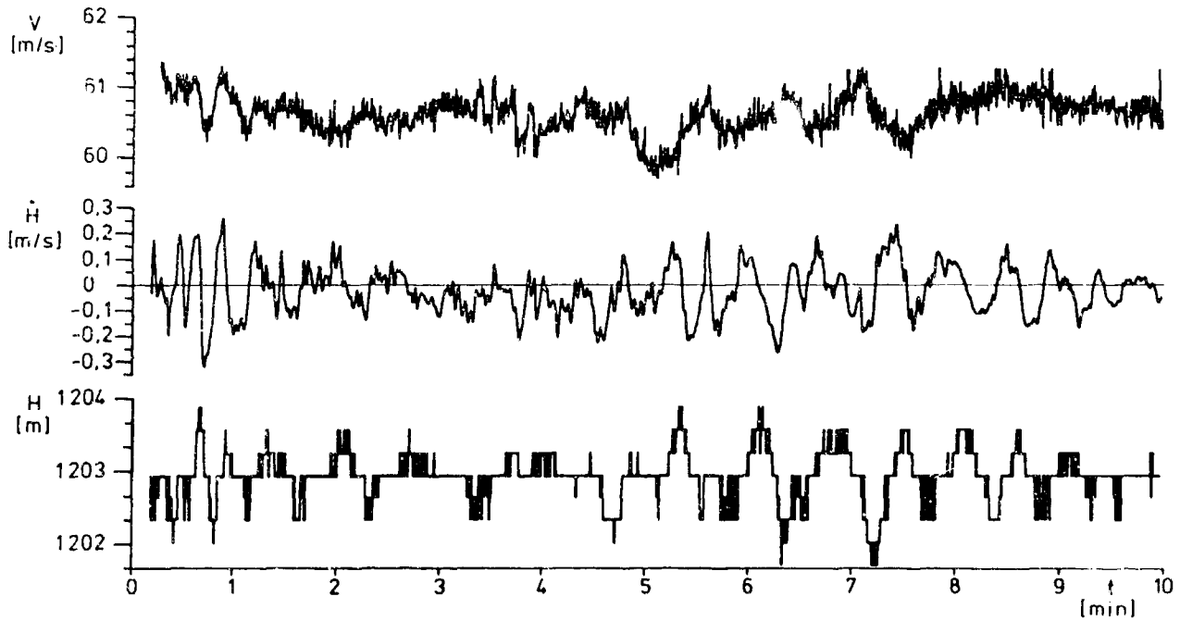


fig. 5 Altitude and speed hold (calm air)

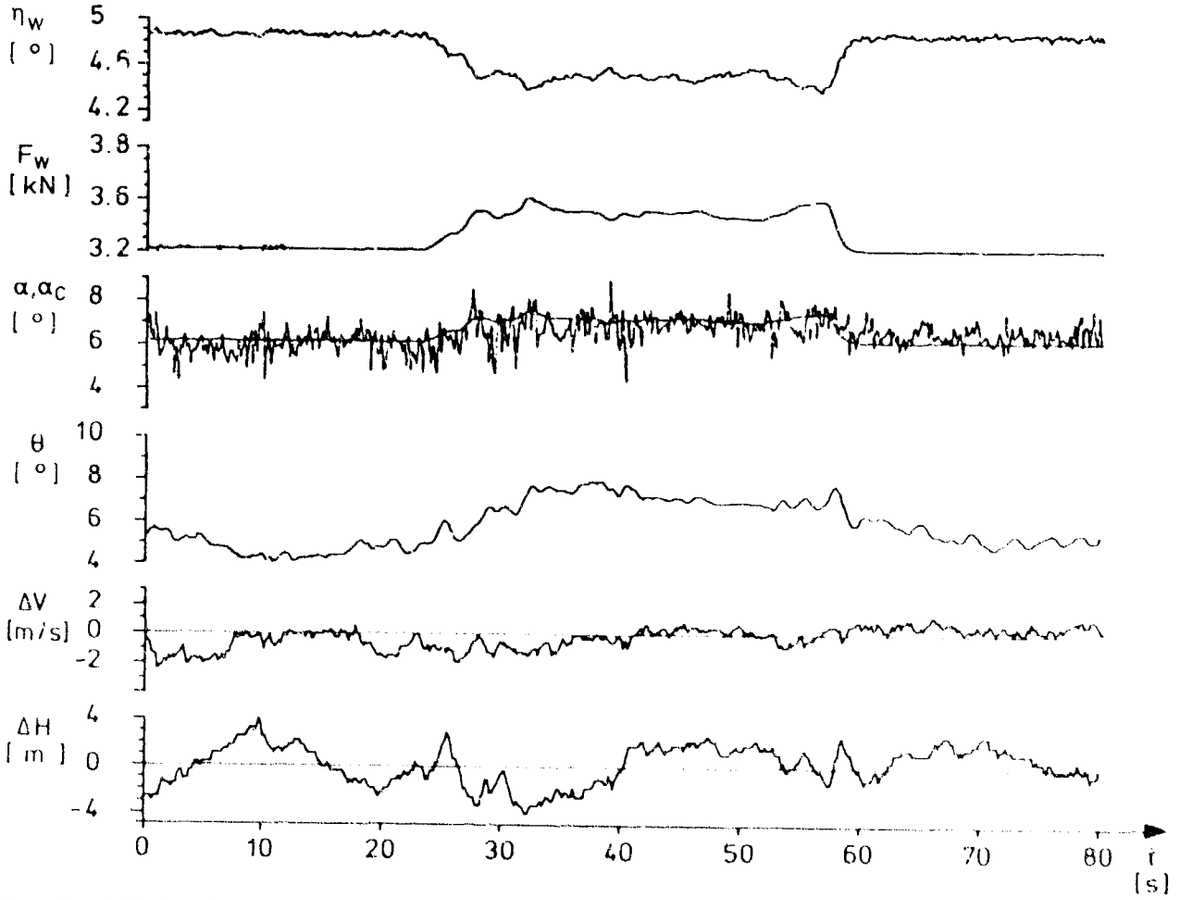


fig. 6 Altitude and speed hold in turn flight (moderate turbulence)

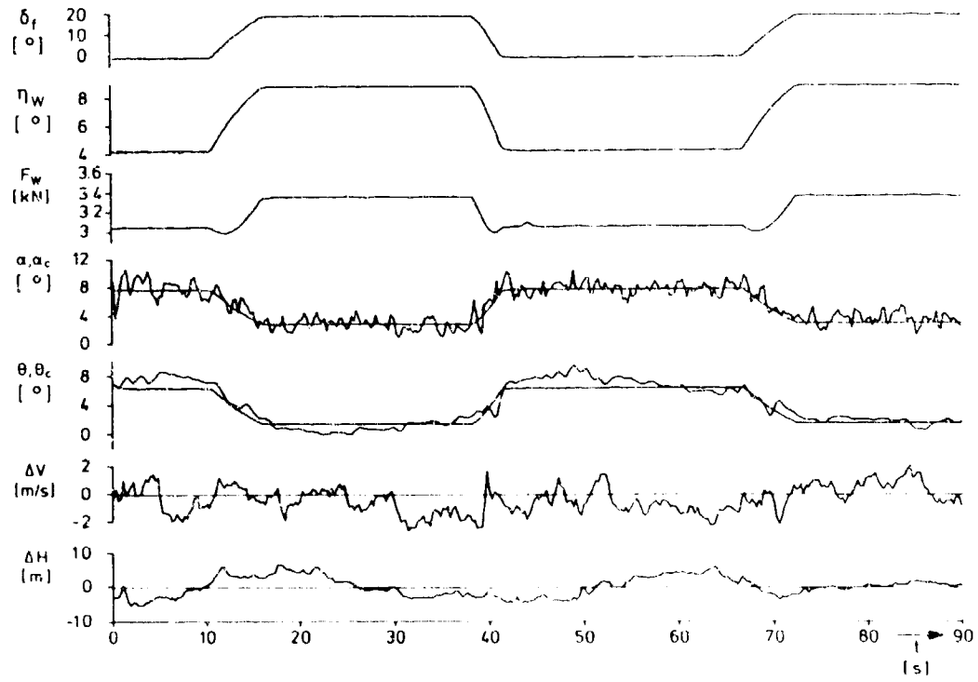


fig 7 Altitude and speed hold at flap setting

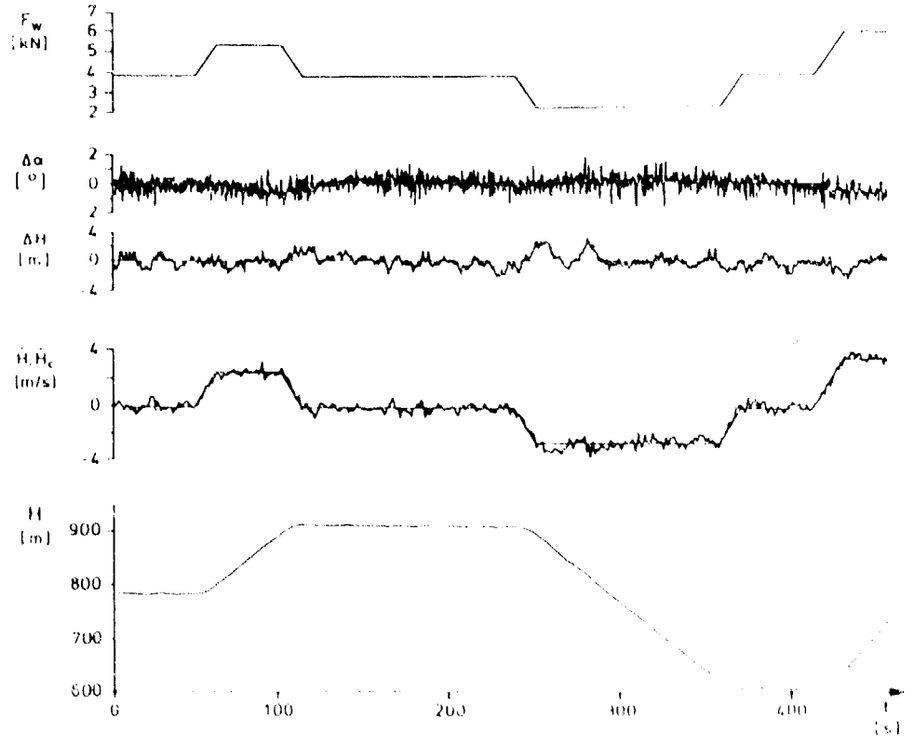


fig 8 Altitude acquire (strong turbulence)

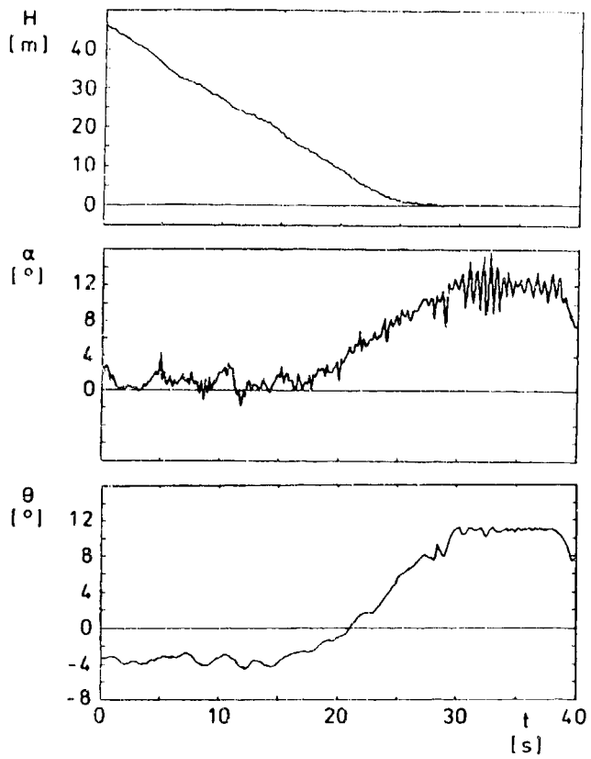


fig. 9 Automatic landing
(flap position $\delta_e = 52°$)

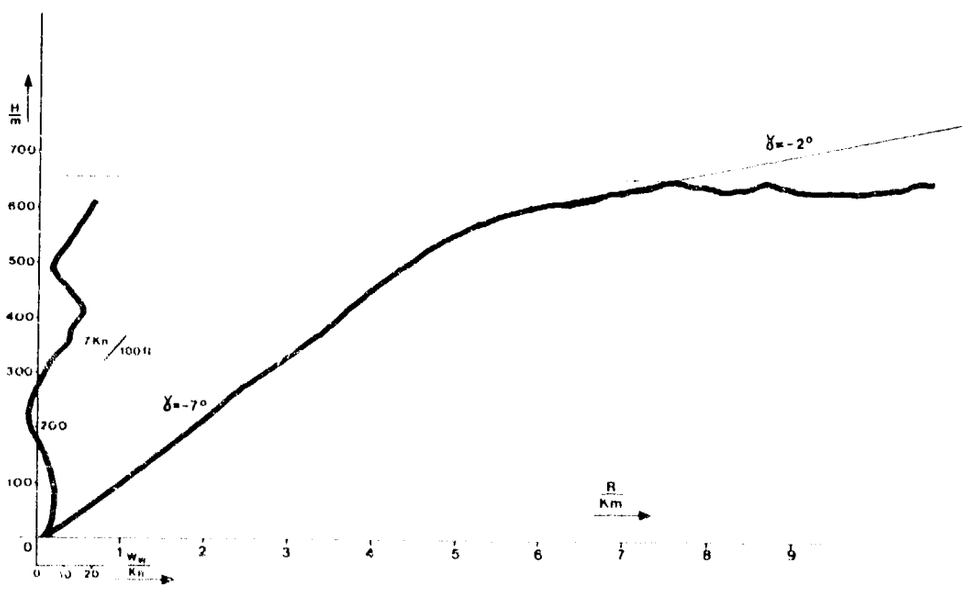


fig. 10 Curved MLS approach (passing a moderate windshear)