DESIGN CRITERIA FOR FLIGHT CONTROL SYSTEMS

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ABSTRACT

An aircraft is a well known control process which is nonlinear and strongly cross-coupled. The dynamics of the aircraft response vary over wide a range due to flying tasks and procedures. Even nowadays there exist no general accepted design criteria for flight control systems that will incorporate such contradicting requirements as: accuracy in flight path and aerodynamic flow control, safety, reliability, low direct operation cost, passengers comfort.

The problems of classical control procedures (cascade control, complete state vector feedback) are discussed in contrast to the different design procedures (pole placement, quadratic cost functions). The example for this discussion is a realized and in flight tested flight control system for precise "nap of the earth flights".

CONTENTS

1. INTRODUCTION

In many cases the requirements and design criteria for automatic flight control systems can be described sufficiently and precisely. The system shall be precise due to control task, safe reliable and low in production and maintenance cost. A typical example is a military unmanned vehicle, e.g. a drone. The deviation from a given flight pattern shall be small and the airspeed has to be kept in a preselected range.

A flight control system for a transport aircraft for automatic landing in poor visibility conditions (CAT IIIa) might be another candidate for precise design goals. The maximum and rms deviations from the instrument landing systems glide path are well defined as well as the commanded airspeed and the deviations related to the stall speed. An immense design problem is that human beings are involved in the flight. The pilots expect that flight control systems respond in a similar manner as they do and passengers like a comfortable feeling. The mathematical formulation of the human aspects of design criteria are in principle difficult but solvable. In general a comprise has to found to incorporate the contradicting design criterias.

2. SYMBOLS

C^*	handling quality criterion
C_D	drag coefficient
C_L	lift coefficient
D	drag
E_k	kinetic energy
E_p	potential energy
F	engine thrust
g	earth acceleration
H	height
$\ddot{H}$	vertical acceleration
K_i	weighting factor
$\underline{K}_x$, $\underline{K}_u$	weighting matrix
k	DLC efficiency factor
L	lift
n	load factor
q	pitch rate
Q	quality criterion, cost function
R	distance
$\underline{R}$	feedback matrix
S	wing area
t	time
T	observation time
u_g	horizontal wind component
u	control vector
V_K	inertial speed
$\dot{V}_K$	flight path acceleration
V	airspeed
W	aircraft weight
w_g	vertical wind component
$\underline{x}$	state vector
α	angle of attack
αw	wind angle
γ	flight path angle
Δ	increment
Θ	pitch angle
ρ	air density
η	elevator displacement
σ^2	variance
ω_{sp}	eigenfrequency short period mode
Index	
C	command

3. CONTROL SYSTEM STRUCTURE

For flying an aircraft, different control loops have to be activated. The tasks of this control loops are similar to those of a training programm for a pilot trainee.

I. The first step to take is to stabilize the aircraft in roll, pitch and yaw. In general, training aircrafts have safe flying qualities and they are well damped. In bad damped aircrafts the pilot will be confronted with the additional task to improve the damping of the aircraft. This is necessary as well for civil aircraft in landing approach and turbulence response as for military aircraft for weapon delivery. Flight control systems can more or less assist the pilot in damping and to stabilizing the aircraft.

II. The second flight lecture of a pilot trainee is to keep a constant heading, height and airspeed. To achieve this properly, the aircraft has to be well damped and stabilized. The first training lesson has to be learned.

III. The third step involves holding a desired track. A typical example for a track keeping task is an instrument landing approach. The deviation from the commanded flight path (in centre-line, 3 glide slope) is displayed on a cross-pointer instrument (Fig.1).

The pilot or the automatic flight control system has to keep the displayed deviations as small as possible. Additionally the airspeed must be controlled precisely for safe margins in stall speed and landing roll distance. Fig.2 demonstrates a typical manual instrument landing approach. The flight path deviations are displayed versus the distance from the azimuth transmitter. Prior to touch down oscillations occur in lateral and in longitudinal motion. The well known reason is the raise of the closed control loop gain due to cone effect of the instrument landing system. In this case the natural damping of the aircraft is not high enough and the pilot has no proper instrumentation to increase artificially the damping of the system. This example shows that the inner control cascade has to be well damped and stabilized. The sufficient degree of damping varies from aircraft type to aircraft type and for one specific type from mission to mission. For example, a transport aircraft requires a higher damping ratio then a highly manouevreable fighter aircraft and the degree of artificial damping has to be higher in a precise landing approach with flight path deviation in range of meters compared to cruise flight with flight level deviations in the range of 100 meters.

IV. The fourth lecture implies a precise manouevre flight, where the flight track command value varies with space and time. This is the domain of flight management, including curved approach profiles, 4 D-navigation and optimal flight performance calculations.

In general the task of the pilot or the automatic flight control becomes the more complex the higher the degree of the cascade hierachy is. It is one problem of the design strategy of flight control systems, that each cascade requires its own specific design criteria. On the other hand it is an advantage of the aircraft response characteristics /1,2/ that the characteristics of the inner control loops (lower cascade hierarchy) influences the outer loops but primarely not vice versa. The flow of information runs the opposite direction from the outer loop to the inner loop. A practical design procedure asks for designing the flight control system loop by loop starting with the inner loop. For each loop the specific design criteria may be applied. In an iterativ process even very complex nonlinear and highly cross coupled flight control systems can be designed in two or three iteration steps.

This proposed design procedures has been realized in a precise flight control system for scientific and commercial application. A typical mission is the "nap of the earth" flight for meteorological on board measurement in the contour of orographical obstacles /2/. Due to limited time and space, the discussion will be concentrated on some aspects of the longitudinal aircraft motion.

4. DESIGN CRITERIA

4.1 HANDLING QUALITIES

The higher frequency response of aircraft is very important for handling qualities. Normally the eigenvalues of the roll, short period and dutch roll mode influences the handling qualities very much. A large number of investigations have been made to improve this man-machine problems.

Many constraints and limitation have to be considered: too slow response, too poor or well damping and pilot induced oscillations. They are a function of eigenvalues and eigenvectors and may be displayed as pole-zero configuration. Even relativ complex response problems e.g. turbulence response can be described as eigenvalues. A large experience of simulator runs and flight test with a great variety of aircraft types already exist /3,4/. The optimal aircraft response, the correlated eigenvalue and eigenvector distribution are fairly well known. A worldwide accepted measurement of pilot opinion and feeling is the Cooper - Harper - rating scale /3,5/. A typical example of eigenvalue distribution and correlated pilot rating you will find in the well known "thumb print" cur (Fig.4). The response of an aircraft to a control column-input is of great importance for handling qualities. The pilot requires an acceptable correlation of pitch rate q change in angle of attack α and load factor n as response to a stick force command (Fig.5). Especially the load factor response per stickforce is important. This response can be expressed as short period mode frequency ω_{sp} versus load factor per angle of attack variation. The range of acceptable handling qualities is relativ small. The C*-criterion /6/ presents a different approach to describe the aircraft response to a control column input. Pitch rate q and load factor at the pilots seat n*are weighted by a typical speed V*

$$C^* = n^* g + V^* q \qquad (1)$$

The acceptance of the C*- criterion is still controversary. The handling qualities criterion can be applied to the uncontrolled aircraft /7/. The pilot is in general only interested in a proper response of the aircraft including the flight control system. Therefore the handling qualities criteria give detailed information for an optimal eigenvalue and eigenvector distribution of the damped and stabilized aircraft.

4.2 GUIDANCE ACCURACY

For track keeping procedure and manoeuvre flight the guidance accuracy can be expressed in terms of deviation from the commanded flight path ΔH (Fig.6) and the commanded aerodynamic flow condition. The variance σ^2 of the deviation calculated for the observation period T is a simple measurement

$$\sigma_H^2 = \frac{1}{T} \int_t^{t+T} \Delta H^2 dt \qquad (2)$$

The aerodynamic flow condition can be described by the lift coefficient C_L, the angle of attack α or the airspeed. Lift coefficient is a precise measurement of the aerodynamic flow condition. Normally pilots are trained in using airspeed as the measurement for the aerodynamic flow condition. The lift equation

$$L = nW = \frac{\rho}{2} V^2 S C_L \qquad (3)$$

gives the correlation between airspeed and lift coefficient (Fig.7)

$$C_L = \frac{2}{\rho} \cdot n \frac{W}{S} \cdot \frac{1}{V^2} \qquad (3a)$$

For low airspeed or high lift coefficient the C_L-value control will be more precise than airspeed control /8/.

For high dynamic pressure airspeed control should be privileged. A typical crossover airspeed for a conventional transport aircraft with a wing load of W/S = $3600 Nm^{-2}$ at sea level acts in a range of V = 160 kts. Again, C_L-control will be an advantage for landing approach and cruise flight in high altitude.

In an application for a flight control system /2/ the basic control parameter for the aerodynamic flow condition is the lift coefficient. The lift coefficient can be measured directly by pressure ports at the wing /9/. In commercial transport aircraft wing pressure probes are not available. As the next best measurement ranges the angle of attack, where a close correlation to the lift coefficient exists (Fig.8). As the pilot has in general no experience with controlling lift coefficient or the angle of attack, it is worthwhile to command and display the airspeed and calculate the correlated lift coefficient. Minimizing the variances of flight path and airspeed deviations would be desirable. Concerning the cross coupling effects, it is not possible in general to minimize height deviation variance σ_H^2 and airspeed deviation variances σ_V^2 at the same time. A compromise has to be found, which may be formulated in a quality criterion Q

$$Q = \sigma_H^2 + K_0 \sigma_V^2 \qquad (4)$$

where K is the weighting factor. We have to face the problem of fixing the weighting factors. The simple question what is more undesirable: a height deviation of 10 ft or a speed deviation of 1 kts is very difficult to answer and depends on the mission. In landing approach prior to touch down the height deviation is of more importance than in a cruise flight. An energy consideration can give the potential answer. We can expect a desirable response of the aircraft if deviations in kinetic energy ΔE_k caused by speed deviations are approximately equal to deviations in potential energy ΔE_p caused by flight path deviations /10,11/.

$$\Delta E_g = W \, \Delta H \qquad (5)$$

$$\Delta E_K = \frac{W}{g} V \, \Delta V \qquad (6)$$

With $\Delta E_g = \Delta E_K$

$$\Delta H = \frac{V}{g} \Delta V \qquad (8)$$

the equal variances are

$$\sigma_H^2 = \left(\frac{V}{g}\right)^2 \sigma_V^2 \qquad (8a)$$

and therefore the weighting factor is

$$K_0 = \left(\frac{g}{V}\right)^2 \qquad (8b)$$

With increasing airspeed the weighting of speed deviations have to be reduced.

4.3 PASSENGER COMFORT

For all civil transport aircraft and for most military aircraft the pilots work load and the passenger comfort are essential for the acceptance of an airplane and its flight control system. The passenger comfort as a design parameter is difficult to formulate in a mathematical expression. Two major parameters shall be discussed in more detail: throttle activity and vertical acceleration at the passenger or pilots seat.

For a precise control, actuator activity is required in general. The throttle or the engine thrust is a control surface to modify the energy situation of an aircraft. The control of energy related parameters as height deviation and speed deviation produce undesired throttle activity, especially in turbulence and wind shear.

Typical aircraft engines are designed primarely for steady state conditions and not as a high frequent operating actuator. Throttle activity can reduce the life cycle time of the engines and can increase the fuel consumption. More important as a design criteria are the psychological reasons related to throttle activity. It is well known that throttle activity bothers the passengers. Especially less experienced and anxious passengers feel unsafe if the engine noise changes. This effect will be increased if the cabin pressure changes simultaniously due to the engine revolution speed. With respect to airports-neighbours frequently changing noise is less acceptable than constant noise of the same intensity.

A quite different aspect of throttle activity will concerns the pilot. Experienced pilots are able to move the throttle rarely. For a known situation, e.g. a glide slope intercept, an experienced pilot can control the aircraft only with one throttle setting. Only unexperienced pilots move the throttle frequently. A flight control system with high throttle activity responds like a trainee pilot. A captain flying such an aircraft might not be accepted by his colleagues.

This brief description of the situation clarifies that adequate low throttly activity is a need. The problem we have to face is, that mathematical formulation is difficult and no sufficient solution exists. All unnecessary throttle motion is undesired in contrast to some quick throttle settings in a glide slope intercept and in a wind shear situation. Throttle rate F, especially the higher frequency motion can be an approach of a measurement for throttle activity.

The vertical acceleration at a passengers seat $\ddot{H}_p$ is an additional component of passenger comfort. It is well known that vertical acceleration due to turbulence is of more influence at the rear seats compared to the front seats of an aircraft. In general the first class passengers are seated in areas where vertical acceleration is comparable low. Additionally pitch rate q may disturb the pilot and in rare cases the passengers. Pilots are trained to keep the pitch attitude constant or to move it with precise procedures, e.g. the rotation during take-off. Oscillations or random motion in pitch attitude are undesired. The pilot can observe the pitch motion in good visibility as well as on instrument flight rule conditions. Passengers may observe this effect only until the horizon is visible.

Vertical acceleration at the passengers seat $\ddot{H}_p$ and the pitch rate q are candidates of the C*-criterion (equ.1). In a modified version of the C*-criterion, acceleration and pitch rate can be formulated as passengers discomfort

$$\tilde{C}^{*2} = \ddot{H}_p{}^2 + (V_p\ q)^2 \qquad (1b)$$

At the speed V both effects are equal.

4.4 QUALITY CRITERION

Handling qualities, guidance accuracy and passenger comfort have to be incorporated in one quality criterion. Due to the cascade characteristic of an flight control system, the feedback of angular rate and Euler angle to elevator aileron and rudder are elements of the inner stability augmentation system. This system has to be designed first due to handling qualities criteria. In general a desired pole-configuration is preselected. Independly the outer loop concerning the autopilot and autothrottle control can be designed. The control plant is the aircraft including the stability augmentation system.

The design criteria concerning guidance accuracy and passenger comfort can be incooperated in the quality criterion

$$Q = K_1 \frac{1}{T} \int_t^{t+T} H^2 dt + K_2 \frac{1}{D} \int_t^{t+T} \Delta V^2 dt + K_3 \frac{1}{D} \int_t^{t+T} \tilde{C}^{*2} dt + K_4 \frac{1}{T} \int_t^{t+T} \dot{F}^2 dt \qquad (9)$$

The design procedure is in general very simple: All relevant feedback gains have to be varied to minimize the quality criterion. With powerful parameter optimizing procedures the job can be done easily and quickly /12/. An increase of formal complexity can be obtained, when standard "optimal procedure", as there are the solution of the Riccati differential equation /13/, are used. This procedure requires the complete feedback of the state vector $\underline{x}$ to the control vector $\underline{u}$

$$\underline{u} = \underline{\underline{R}}\ \underline{x} \qquad (10)$$

The relevant quality criterion is

$$Q = \underline{x}\ \underline{K}_x\ \underline{x}^T dt + \underline{u}\ \underline{K}_u\ \underline{u}^T dt \qquad (9a)$$

where $\underline{K}_x$ and $\underline{K}_u$ are the weighting matrices. A significant problem is the fixing of the weighting factors. It might be possible to convert the weighting factors of equ.(9) into matrix form of equ.(9a). Only one argument of the integral in equ. (9) is part of the state vector elements (ΔH). All other arguments are nonlinear combinations of different state vector elements. Therefore the matrices $\underline{K}_x$ and $\underline{K}_u$ are totally filled with elements that are strongly depended from each other. A systematic variation of the matrix elements is practically impossible.

The major problem in designing a flight control system is to prepare an adequate set of weighting factors. When the weighting factors are fixed, the optimization procedure is simple and well known.

The elements of the quality criterion represents a conflict situation. In general, a raise of a weighting factor will reduce the correlated quality element and will increase all other quality elements. For example, an improvement in flight path accuracy will increase the undesired throttle activity and vice versa.

Simulator runs and flight tests /11/ with varied weighting factors have shown that a strong correlation exists between accuracy in lift coefficient control on one hand and pitch rate (pilot discomfort) on the other hand. The kinematic angular equation /11/

$$\Delta\alpha + \Delta\gamma - \Delta\Theta = \alpha w \qquad (10)$$

gives a physical background to this problem. Vertical gusts influences the wind angle α_W directly and cause a response in angle of attack ($\Delta\alpha$), flight path angle ( ) and pitch attitude ($\Delta\Theta$). If the flight path control is precise, deviation in are negligible small. The high frequent disturbances of the angle of attack caused by vertical turbulence can only be avoided by undesired pitch attitude variation. A sufficient set of weighting factors leads to the compromise keeping on one hand the angle of attack variation small for low and medium frequencies due to safety reasons and to avoid on the other hand the undesired higher frequent pitch attitude variations.

Another important relationship exists between flight path accuracy and throttle activity. The required thrust F_C is a function of drag (drag to lift ratio C_D/C_L), flight path angle γ commanded horizontal acceleration $\dot{V}_K$ and vertical wind w_g.

$$F_C = W(C_D/C_L + {}_C + w_g/V + V_K/g) \qquad (11)$$

Higher frequently flight path variation, vertical turbulence and wind shear /8/ lead to quick thrust variation, and therefore to undesired throttle activity. A sufficient set of weighting factors provide an acceptable frequency distribution between elevator and throttle. An optimal flight control system follows the principle to control the higher frequent disturbances of flight path and airspeed via the elevator and to use the throttle only if a lower frequent variation of the total energy is necessary. A simulator run of a curved landing approach of a STOL aircraft, automaticly controlled by the integrated flight control system FRG 70 /14,11/ demonstrates the desired frequency distribution between elevator and throttle in a situation with moderate turbulence and severe wind shear. The commanded function of flight path H and angle of attack are given in Fig.9 as well as the disturbances. A simplified version of the block diagramm of the integrated flight control system FRG 70 is shown in Fig 10. The aircraft motion as a response due to guidance and disturbances input functions (Fig.9) will be demonstrated in Fig.11. It is of interest to see how variation of commanded flight path (curved approach), commanded airspeed (decellerated approach and automatic landing) will influence the quality criterion (cost function) in contrast to disturbances (turbulence, wind shear Fig.11).

change in flight path command	3%
change in angle of attack command	3%
wind shear	10%
horizontal and vertical gust	84%
	100%

Table 1: Portions of the r.m.s. cost value

This r.m.s. relation is realistic for curved flight path, medium turbulence and strong wind shear. Under heavy turbulence and a conventional rectiliniar flight path, the relative r.m.s. cost value due to gust increases from 84% to 95% Therefore the performance of gust alleviation appears to be a very important property of an integrated flight control system.

Experienced pilots control an aircraft in a similar way but not so precisely, as the integrated flight control system does. Flight test have shown that pilots feel comfortable and safe with this type of control system response. Detailed flight test results are demonstrated in the Appendix.

The weighting factor are dependent from the aircraft response and the flight control systems structure. The set of sufficient weighting factors varies for example, if a precise nonlinear open loop control system in incooperated in the flight control systems and the feedback gain can be reduced. In this situation, it is easier to find a compromise between the conflicting parameters of guidance accuracy and passenger comfort /2/ . Another example presents the incooperation of an additional direct lift control device (DLC) in a strongly cross-coupled integrated flight control system. Taking strong influence of gust alleviation into account, the important question is: How is the reduction of the r.m.s. cost value of a control system including DLC compared to a system without DLC, when the input functions, the quality criterion and the aircraft are the same?

Theoretical studies and simulator runs have shown that the change of lift to drag ratio of the direct lift device is an important parameter /14/.

$$k = 1 - \frac{C_{D\delta}}{C_{L\delta}} \cdot \frac{C_L}{C_D} \qquad (12)$$

In Fig.12 the ratio Q of r.m.s. cost values in an optimal integrated control system with and without DLC is plotted versus k (see equ.9), a function of the drag to lift ratio of the DLC device. The strong influence of the drag to lift ratio on the relative r.m.s. cost value Q is obvious. The best control quality, which is represented by the minimum point in Fig.12 can be obtained with k ≈ 3 and Q = 40%. This optimal amount of cost reduction and the corresponding improvement in control qualities are rather high. The desirable value of k = 3 can be realised with drag spoilers only. The smallest reduction of cost value (maximum in Fig.4) is obtained by Q = 90%. and k = -4. A value k = -4 can occur when landing flaps are used. The amount of cost reduction is so small, that the additional expense for the DLC system is not worthwhile. In case of a conventional autopilot and a DLC subsystem using landing flaps, the result can be even worse than with an integrated control system using no DLC (Q ≥ 100%). This explains some disadvantages experienced by such DLC systems.

The advantage of DLC can also be used to modify the weighting of the compromise. If the flight path accuracy is sufficient even without DLC, the undesired throttle activity can be reduced by increasing the weighting factor when DLC is applied. The low frequency drag control of the DLC will relieve the throttle from the control job.

The discussed examples demonstrate that to fasten the weighting factors is the decision of the engineer and therefore very subjectiv. Experiences have shown that the fasten of few weighting factors can be easier than the great number of feedback gains. Design problems can be transformed to another deseign level, where design problems may be solved easier and quicker, and where a good physical interpretations of the problems is possible.

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APPENDIX

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 ben developed in the Institute for Guidance and Control, Technical University Braunschweig /2/. The design target was an extreme precise flight control system for flying nap-of-the-earth profiles to measure wind, wind shear and turbulence on board of the aircraft. The block diagramm of this flight control system is shown in Fig.13. The test aircraft is an institute owned, twin engine propeller aircraft (Fig.14). The aircraft is fully equiped with sensors, digital and analog computers and actuators for elevator, aileron, rudder, horizontal fin trim, throttle and direct lift (Fig.15). 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 by one central computer (Typ Norden, DEC PDP11 compatible).The sample rate is 23 cycles per second.

Fig.16 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. Fig.17 shows the aircraft response in altitude, airspeed and thrust at the beginning of a turn flight in moderate turbulence. In Fig.18 the aircraft energy situations were heavily disturbed by setting the landing flaps. An altitude-acquire manouevre shows Fig.19 for strong turbulence. An automatic landing is demonstrated in Fig.20. 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.

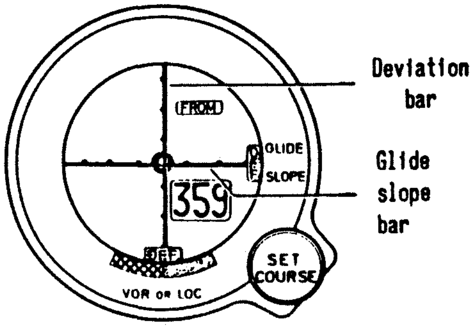

Fig. 1 Crosspointer indicator

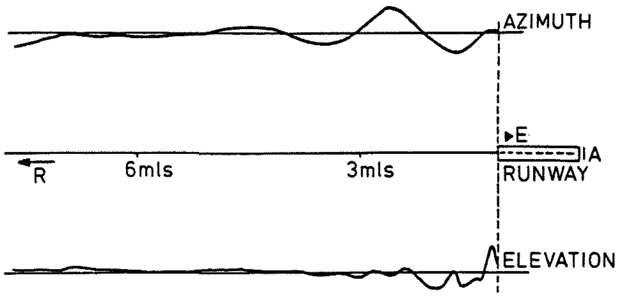

Fig. 2 Manuel MLS approach (Transall, no visual information for the pilot)

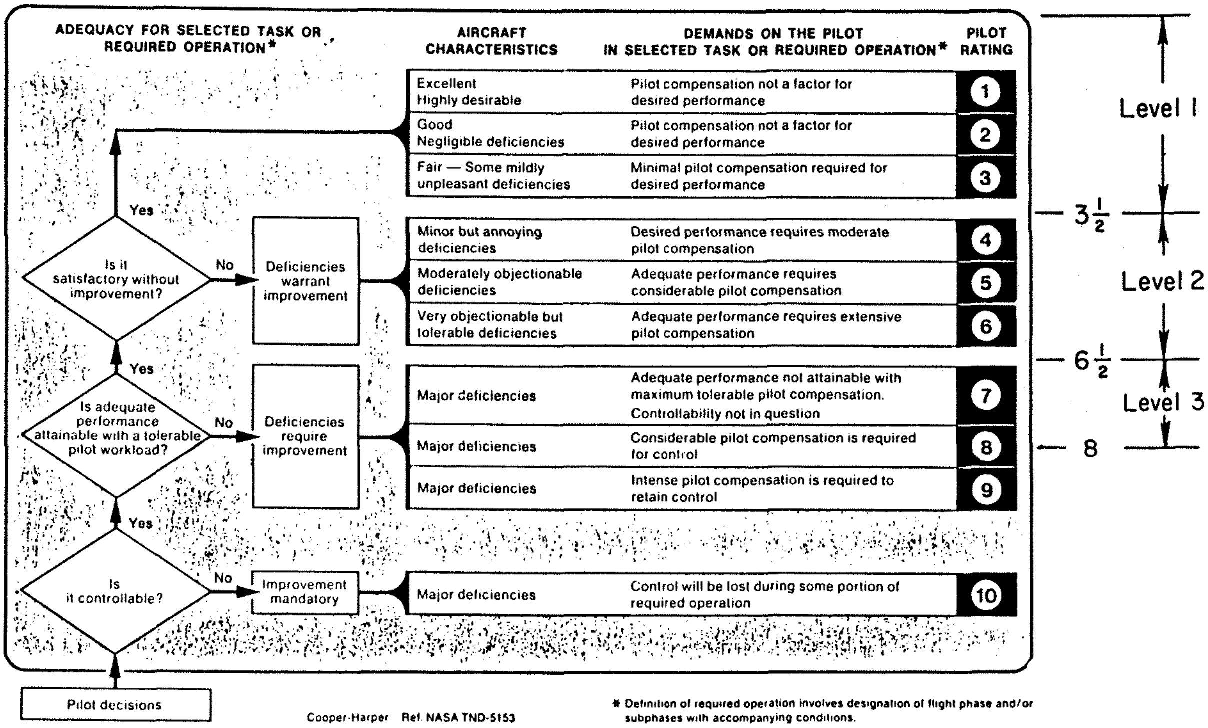

Fig. 3 Definition of Flying Quality Levels [3]

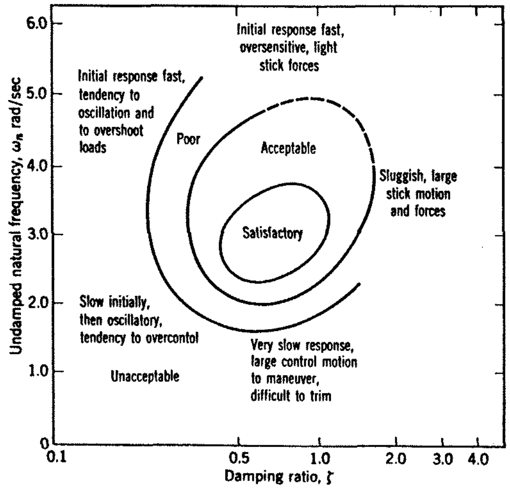

Fig. 4 Longitudinal short-period oscillation-pilot opinion contours [4]

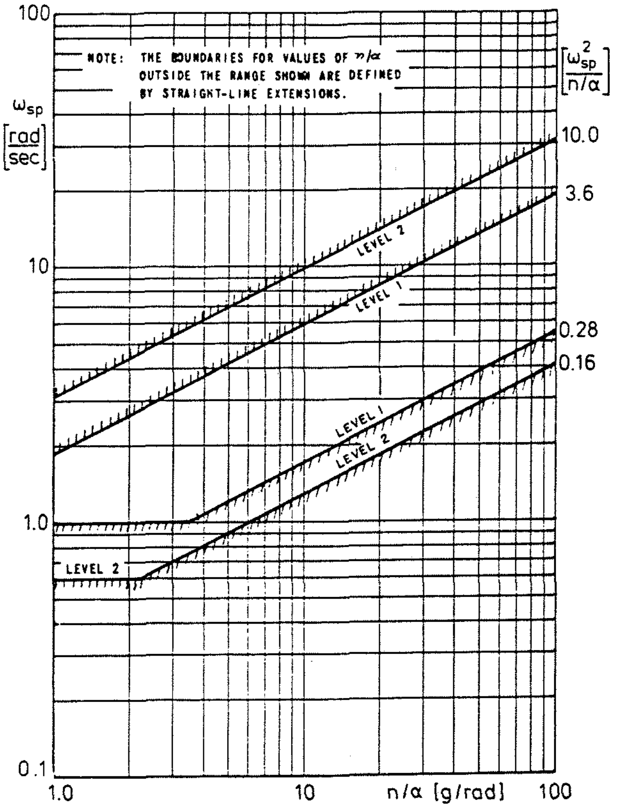

Fig. 5 Requirements for short-term pitch response to pitch controller ($\dot{\omega}_{sp}$ vs. n/α) [3]

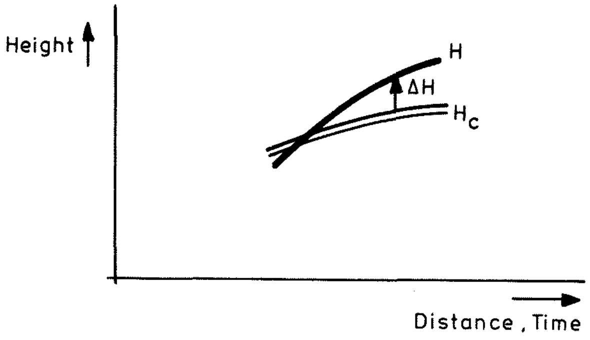

Fig. 6 Flight path deviation

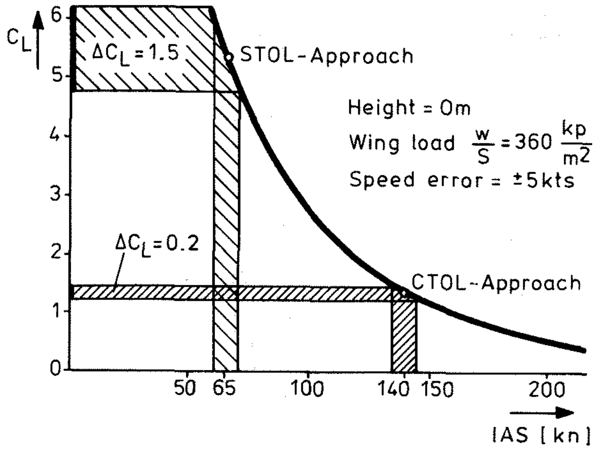

Fig. 7 Airspeed and C_L-Value errors

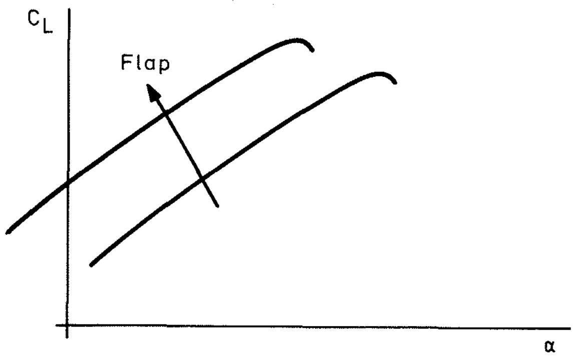

Fig. 8 Lift coefficient versus angle of attack

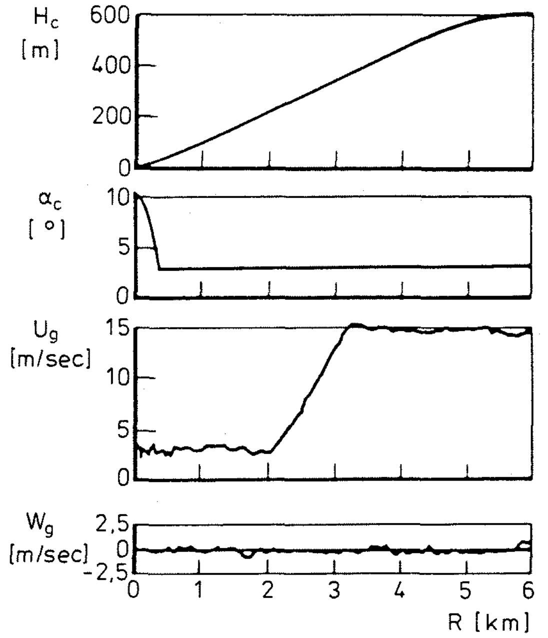

Fig. 9 Guidance and disturbances input for a simulator run [11]

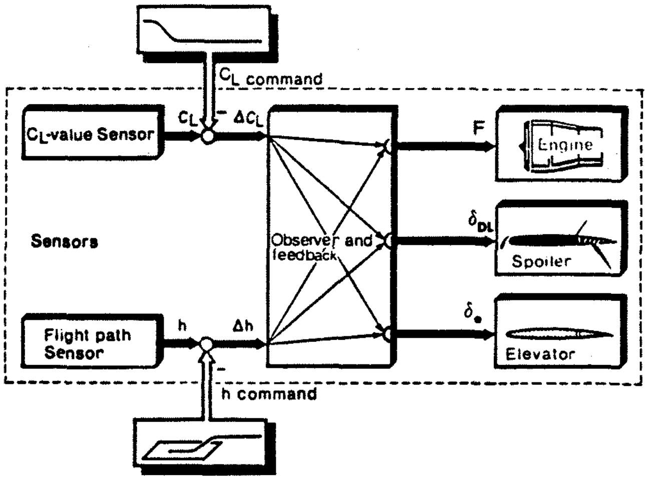

Fig. 10 Simplified blockdiagramm of the integrated flight control system FRG 70 [11]

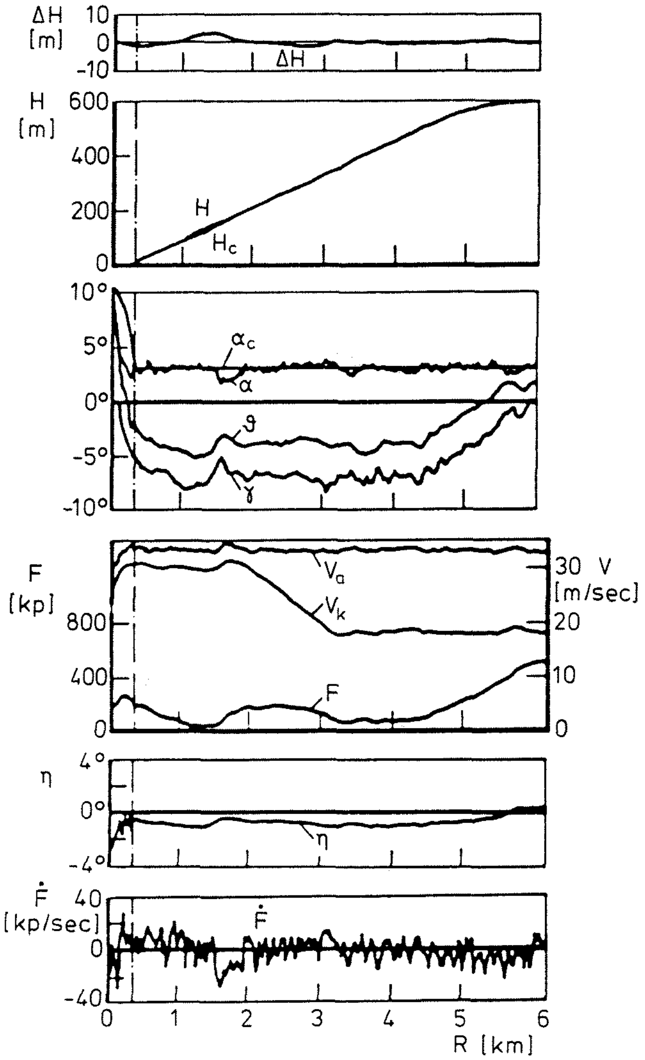

Fig. 11 Aircraft response (Simulation) [11]

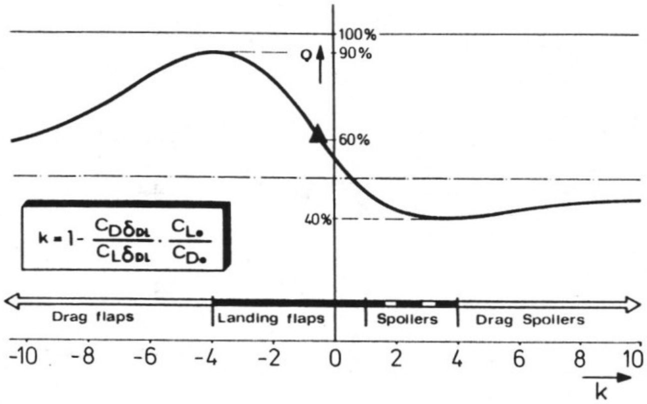

Fig. 12 Control quality as a function of the drag to lift ratio

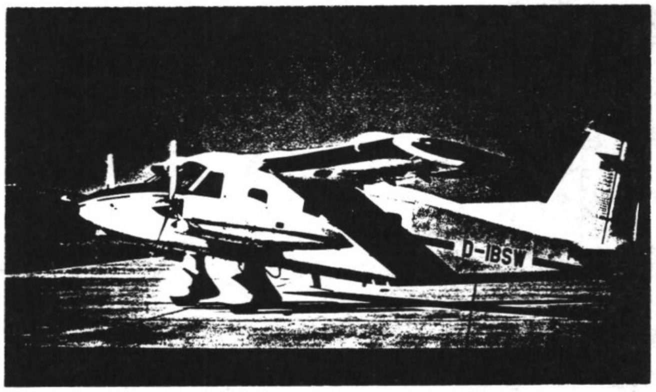

Fig. 14 The DO-28 research aircraft

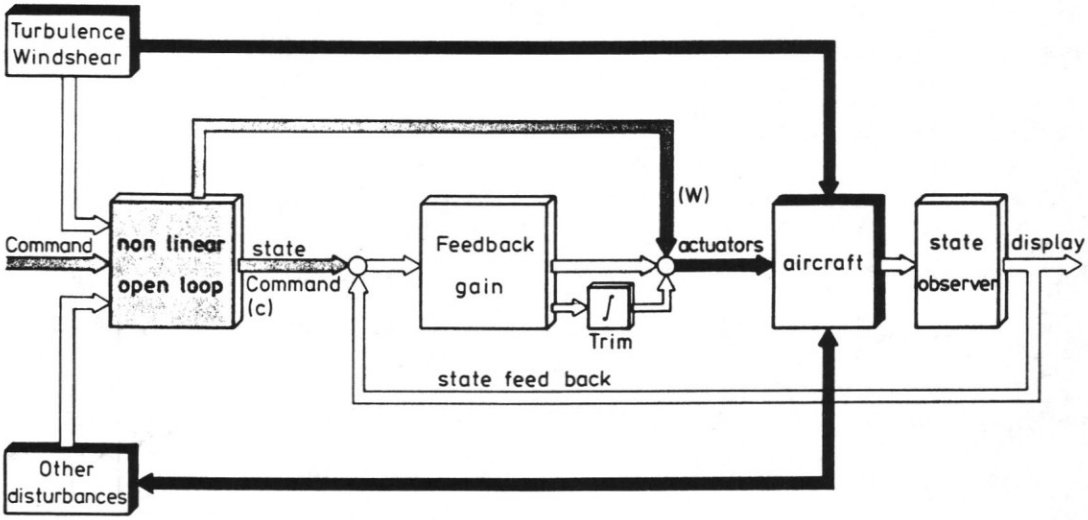

Fig. 13 Block diagramm of the control loops

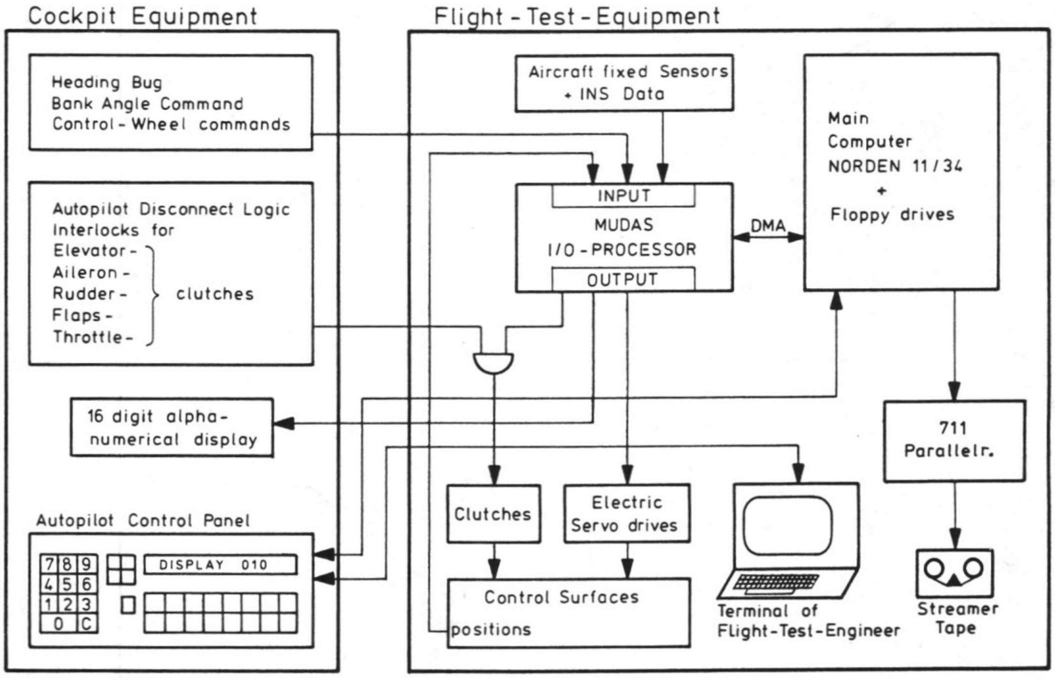

Fig. 15 Equipment of the DO-28 research aircraft

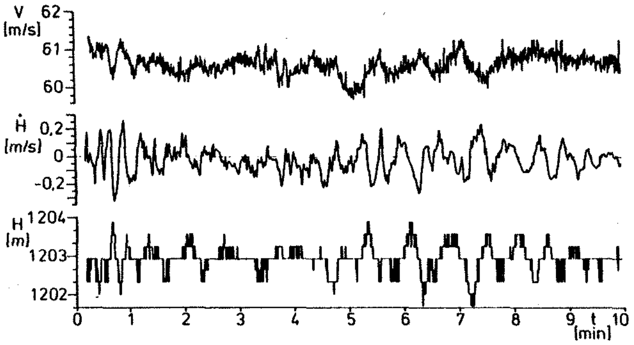

Fig. 16 Altitude and speed hold (calm air)

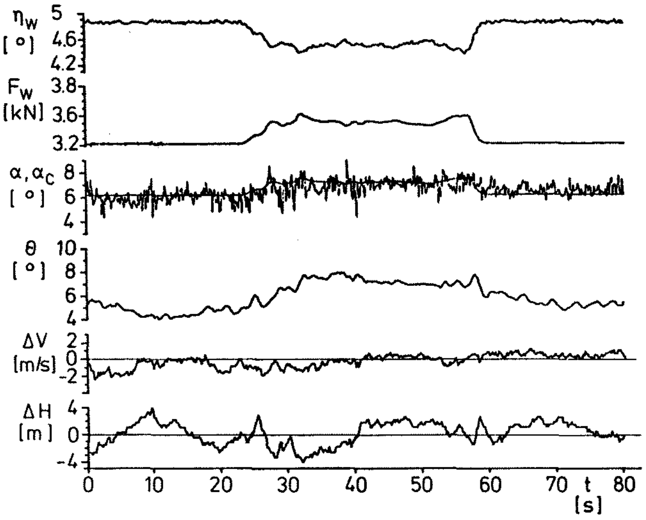

Fig. 17 Altitude and speed hold in turn flight (moderate turbulence)

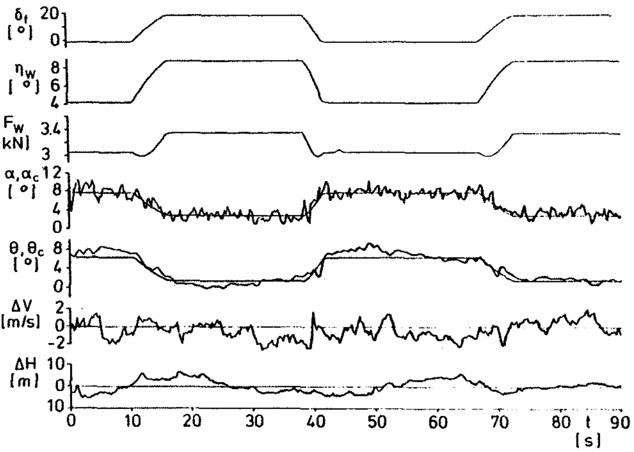

Fig. 18 Altitude and speed hold at flap setting

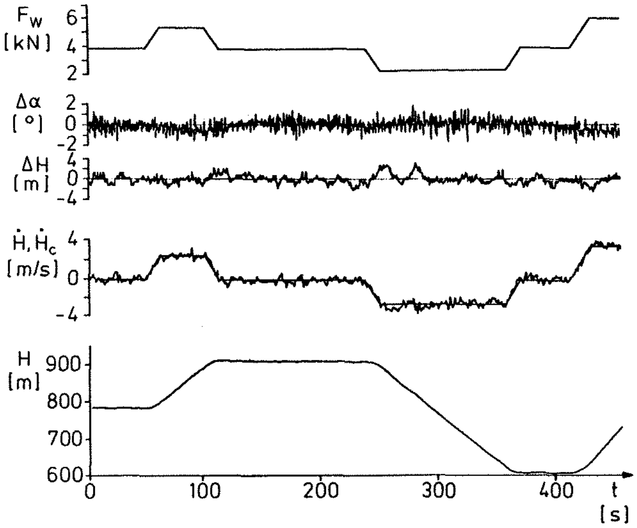

Fig. 19 Altitude acquire (strong turbulence)

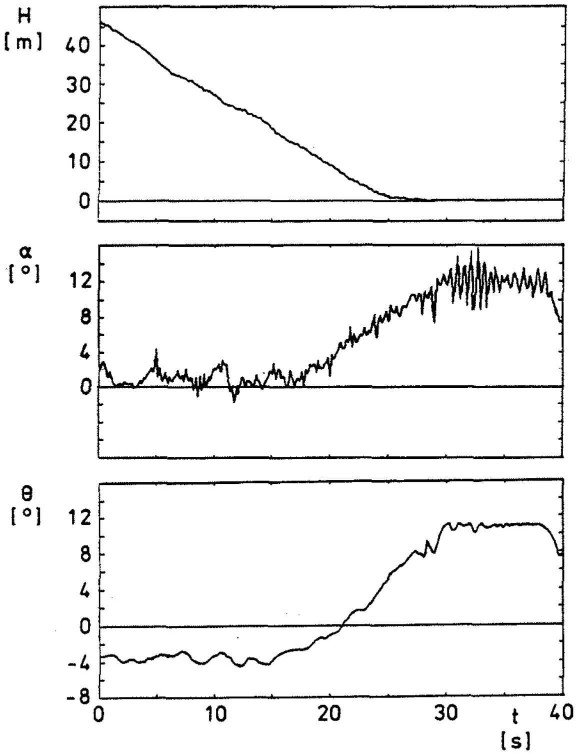

Fig. 20 Automatic landing (flap position $\delta_e = 52^{\circ}$)

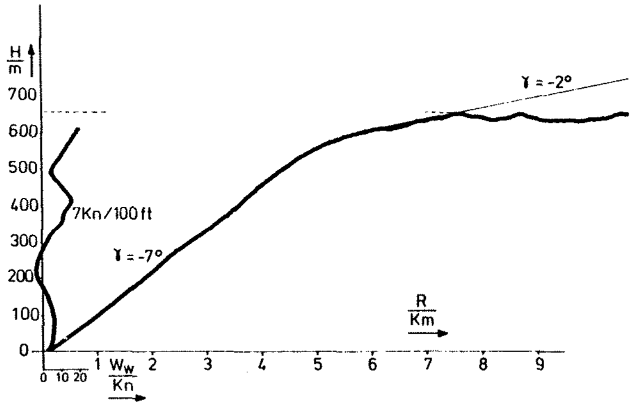

Fig. 21 Curved MLS approach (passing a moderate windshear)