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SOME AERODYNAMIC/FLIGHTMECHANIC ASPECTS FOR THE DESIGN OF FUTURE COMBAT AIRCRAFT

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Abstract

At an early project state of a future combat aircraft, designed with negative static stability, it is necessary to go through an optimization process in order to minimize the complexity and cost for the control system by avoiding undesirable aerodynamic characteristics. A careful refinement of certain parts of the configuration gives the chance to stay within the limits and to meet the criteria and goals for the desired longitudinal and lateral basic behaviour. - General trends, evaluated from many wind tunnel tests, are presented which show the influence of changing LEX size, shape of fuselage nose, slats, vertical tails etc. - Concerning maximum attainable negative static margin one limit is set by the time to double amplitude after a gust disturbance. Looking at some typical existing and projected combat aircraft the paper discusses the fact and the consequences that the same Time To Double leads to different (attainable) static margins.

Symbols:

AR	aspect ratio
C_l	rolling moment coefficient, body axis
C_m	pitching moment coefficient
C_n	yawing moment coefficient, body axis
$C_{n\beta_{dyn}}$	$= C_{n\beta}\cdot\cos\alpha - \frac{J_z}{J_x}\cdot C_{l\beta}\cdot\sin\alpha$; parameter for prediction of spin resistance
$C_{m_{Rec}}$	pitch recovery moment
LEX	leading edge extension
SM	static margin; negative static stability [% c]
S_{Ref}	reference area
T_2	time to double amplitude
α	angle of attack
β	sideslip angle
ζ	rudder deflection
ν	vertical tail cant angle
Λ_{LE}	sweep of leading edge of wing
δ_H	horizontal tail deflection

1. Introduction

Future combat aircraft will be designed with some amount of longitudinal static instability to fulfil the high performance requirements within the whole flight regime. The negative static margin in combination with new operational modes of the aircraft (direct lift and sideforce, fuselage aiming etc.) and the enlargement of the usable flight envelope into the high angle of attack regions lead to extreme requirements for the control and stabilization system of the aircraft. This again causes high complexity, large actuator performance and size and high costs of the control system. Therefore it should be one aim of the configuration-finding and optimization process to reduce the necessary effort for this part by avoiding undesirable aerodynamic characteristics.

A careful refinement of the chosen configuration using variation techniques in wind tunnel tests improves the basic qualities of the aircraft and gives the chance for a relative simple design of the control system. The purpose of this paper is to show some general trends evaluated from many wind tunnel experiments with various configurations and to give some hints how to achieve the desired longitudinal and lateral characteristics.

2. Lateral/Directional Characteristics

Concerning the lateral and directional motion the task of the optimization process for reducing the control and stabilization effort is to provide natural static yaw and roll stability up to high angles of attack. Positive $C_{n\beta}$ and negative $C_{l\beta}$ are the usual parameters which are of significant importance for a good basic lateral behaviour. Spin resistance is characterized by a positive $C_{n\beta dyn}$ which should be achieved throughout the whole angle of attack range whereas the possibility of controlled flight in this region is dependent on sufficient effectiveness of the all movable vertical tail or rudder. Another aspect worthwhile to be looked at is the tendency for yaw or roll departure at zero sideslip. - The following excerpt of results from many low speed wind tunnel tests with a variety of configurations points out some general trends how to influence and improve the parameters and aspects mentioned above.

Fig. 1 shows the difference between two typical twin and single vertical tail configurations in yawing and rolling moment coefficients at 10 degrees sideslip angle and the corresponding $C_{n\beta dyn}$- plotted versus angle of attack. The twin vertical tail with 25° degrees cant angle improves the basic stability throughout the whole incidence range without changing the qualitative characteristic of the curves. In spite of this the rudder effectiveness (Fig. 2) of the same configurations points out the advantage of the single vertical tail which produces a constant rudder effectiveness up to high angles of attack. Even at low incidences the twin verticals with twice the area give only 60 % more effectiveness and the degradation proceeds very rapidly with growing alpha. - Changing the cant angle of a twin vertical tail configuration can be a proper mean to influence lateral and directional stability as shown in Fig. 3. There seems to be a general trend that lateral characteristics could be improved with growing cant angle;

but there is of course a limit especially for an aft-tail configuration because of interference effects between horizontal and vertical tail. - An example for the forward - and - aft movement of a vertical tail and the typical influence on the sideslip data is illustrated in Fig. 4. At low angles of attack the rearward position provides the expected advantages. At higher alpha ranges the whole characteristic is changed and the foreward position produces better sideslip values in the yaw as well as in the roll axis. - All the examples discussed before, where vertical tail configurations are varied, show that these changes in the rear part of the airframe can mainly influence the quantitative but not the qualitative character of the curves.

A much more powerful device to achieve significant changes in the directional and lateral parameters especially at stall and poststall conditions is the optimization of the forebody. This includes all parts of the configuration in front of the basic wing leading edge like strakes, canards, fuselage noses and air intakes. The interference effects of these components are so severe that a proper or inproper arrangement or size can lead to a very good or extremly bad $C_{n\beta dyn}$ - behaviour at higher angles of attack. Some of the most interesting trends which of course need not be valid for all imaginable configurations, are presented in the following figures. - The influence of variing the fuselage nose cross section from flat, elliptic to round is shown in Fig. 5. Flatter shark noses tend to produce strong restabilization in yaw at higher alphas but at the same time there occurs a remarkable loss in roll stability. Therefore the resulting $C_{n\beta dyn}$-Parameter points out an overall advantage for the round fuselage nose cross section because the rolling moment coefficient due to sideslip is the dominant part in prediction of the spin tendency in post stall regions.

Adding a small strake to a fuselage nose with a round cross section gives the chance to improve the directional stability similar to the trend of an elliptical nose without having the disadvantage of losing stability in the roll axis. Fig. 6 shows the effect of such a nose strake which improves all sideslip parameters. Another advantage of using this device is pointed out in Fig. 7; yaw departure tendency at zero sideslip at higher angles of attack is remarkably diminished.

Fig. 8 presents the results of a variation of LEX-size for a tailless configuration. It can be seen that it is possible to find an optimum LEX for good basic sideslip characteristics. The LEX-off and 6 % LEX configurations lead to spin suspicious $C_{n\beta dyn}$-values at high incidences, whereas the 4 % LEX seems to give favourable interference and an overall positive $C_{n\beta dyn}$-Parameter. - A closed coupled canard should have an effect similar to a LEX. Used as a trim and pitch control device it normally has a relatively large area (5 % to 10 % of the reference area); so in all tests known to us a canard configuration shows the typical effects of a too large LEX: At low angles of attack a canard stabilizes whereas at high alphas it produces a strong destabilization. Another effect of a canard is a strong nonlinearity in rolling moment versus sideslip angle within the critical angle-of-attack range. Fig. 9 shows this effect at $\alpha = 35^{\circ}$. Without canard the rolling moment is an essentially linear and a stable function of β. With 'canard on' there exists an extreme instability within the range of $\beta \sim \pm 6^{\circ}$. At higher β the curve of lateral stability seems to show that there might be some hysteresis effects, but unfortunately the tests were not run in both directions of β. These effects seem to be typical for close-coupled canards. The leading-edge vortex of the leeward wing is reinforced by the tip vortex of the canard, while the leading-edge vortex of the foregoing wing is not. Thus, this vortex breaks down first resulting in a strong lateral instability. This would also explain the restabilization at higher side-slip angles. Both tip-vortices of the canard would then not be rolled in. Long coupled canards don't show this effect because the tip-vortices of the canard are too far away from the leading-edge vortices, so they can't be rolled in.

A possibility to improve this unfavourable behaviour of a canard configuration is shown in Fig. 10 where a slat is added to the outboard parts of the cranked wing. This device gives a strong stable contribution in the roll axis and leads to a much better $C_{n\beta dyn}$-curve compared to the basic configuration.

Summarizing the small excerpt of the wind tunnel testing done at Dornier facility, it can be said that a good basic lateral and directional stability at medium and high angles of attack is mainly a matter of forebody optimization. Even the commonly assumed trend that increasing leading edge sweep leads to worse sideslip characteristics can be overwhelmed by a careful refinement of the configuration in the area in front of the basic wing leading edge. Fig. 11 and 12 give two examples for an optimized aft-tail and tailless configuration with different wing sweeps, inlet and LEX arrangements.

3. Static longitudinal characteristics

The favourable pitch characteristics to be aimed at in the very first design loops of an aircraft with negative static margin, are summarized in Fig. 13: A stable break after stall, pitch down due to sideslip and an instability level which doesn't exceed the design instability for trimmed cases should be the topics for optimization work. A certain amount of pitch-recovery-moment must be provided at high angles of attack which sets the limit for the usable longitudinal instability. A reasonable number could be settled by a minimum pitch down acceleration capability of about 0.3 rad/sec^2. If pitch thrust vectoring is installed the requirement for the aerodynamic pitch device can probably be reduced to $C_{mRec} \leq 0$ with full flaps down and so the permittable negative static margin could be enlarged. - Nonlinear high lift capacity is often combined with pitch-up tendencies at moderate angles of attack. Therefore the design instability value, which is chosen for optimal performance at lower and medium lift coefficients will be significantly increased at higher angles of attack. Furthermore pitch-up characteristics reduce the nose-down pitch control capacity. All this may lead to the fact that approach and flight phases near maximum lift become the layout condition for the control system though the requirements for actual maneuver design could be lower. - The desired basic qualities can be achieved by a series of configuration changes as shown by windtunnel results of a variable model.

Fig. 14 gives a rough overview of pitching moment behaviour of wings near and after stall [1]. Dependent on aspect ratio and sweep two regions can be identified where stable or unstable break at maximum lift could be expected.

Fig. 15 shows the influence of LEX-size variation on the pitch recovery moment of a tailless aircraft with 10 % design instability at low angles of attack. Pitch-up tendencies due to the LEX-vortex reduce the available recovery moment with increasing LEX-size; so with a fixed requirement for the pitch-down acceleration the maximum usable instability is reduced. The same problem will occur with configurations with higher leading edge sweep. If a certain instability level is wanted because of trim drag advantages, one is forced to reduce the LEX area down to negative LEX'es. A not very obvious, but nevertheless big influence on recovery moment and attainable negative static margin has the choice of the proper vertical tail configuration. Fig. 16 and 17 illustrate the loss in pitch down capability when replacing the single vertical by a twin tail. For the tailless as well as for the aft tail configuration the flow breakdown at higher angles of attack produces a download between the two vertical fins and therefore a positive contribution to the pitching moment coefficient. Our wind tunnel experience shows that the problem cannot be avoided by reducing the vertical tail cant angle to zero.

Pitch due to sideslip at higher angles of attack is also affected by the choice of LEX size and vertical tail configuration as illustrated in Fig. 18 and 19. A favourable negative $C_{m\beta}$ at stall condition can probably lower the requirements for the revocery moment and remove problems for the lay-out of the control system.

One of the most important factors for the design of the control system is the steepness of the C_m-α-slopes for trimmed flight conditions. If somewhere in the whole angle of attack range the trimmed $C_{m\alpha}$ exceeds the design $C_{m\alpha}$ for maneuver this point might become the (undesired) lay-out case for the flight control system. So the "optimum" $C_{m\alpha}$-function versus angle of attack should have a tendency to less instability at higher alphas. This would probably remove some of the problems at landing and take off flight phases as well as at high-angle-of-attack maneuvering. Fig. 20 gives an impression of trimmed $C_{m\alpha}$ versus angle of attack looking at typical combat configurations. Aft tail airplanes seem to come closest to the desired $C_{m\alpha}$ slope whereas higher swept wings and especially canard configurations tend to have an increased $C_{m\alpha}$-level at higher angles of attack.

4. Dynamic longitudinal characteristics

The necessary amount of control power for stabilizing an unstable aircraft is not only related to the chosen instability value, characterized by the factor $C_{m\alpha}/C_{L\alpha}$, but also to other configuration depending values as moments of inertia, wing area, mean aerodynamic chord and the pitch damping derivatives. All these parameters of the unstable aircraft contribute to a 'Time to double Amplitude' after an angle-of-attack distortion caused for example by a gust. If you want to stabilize this system you need a certain amount of pitch acceleration in order to counteract the disturbance and to provide good ride and handling qualities. Fig. 21 shows a graph where the 'pitch acceleration required' is plotted versus 'Time to Double Amplitude'. Dependent on the 'Time delay' of the whole control system including the budget from sensor measurement to the production of pitch acceleration, one gets a hyperbolic increase of required control power with decreasing 'Time to Double' (T_2). As for our experience the minimum allowable T_2 is reached when approaching six times the 'Time Delay' of the whole system. A reasonable number for the time delay, which represents the state of art, seems to be around 40 msec. Therefore a 'Time to Double' of about 250 msec should be the limit for maximum possible negative static margin. Fig. 22 shows for a typical tailless combat aircraft that the minimum T_2 will occur at high subsonic speeds just before the starting shift of neutral point. Therefore the maximum allowable negative static margin according to the minimum possible 'Time to Double' will be defined in this Mach number region. At low mach numbers the T_2 is remarkably larger. Because of the poor aerodynamic effectiveness this will be the layout point for the deflection rates if you don't use thrust vectoring devices.

To give a better feeling how the static margin and the 'Time to Double' differ for the various configurations, Fig. 23 shows the values for some existing and projected aircraft. It is remarkable that the CCV-Starfighter with 20 % negative static margin has a more uncritical 'Time to Double' than the 12 % unstable F-16. Looking at the selection of the four presented configurations it is evident that the 250 msec-limit is a value which represents the feasable state of art. Going below this limit will probably cause too severe problems in providing good handling and ride qualities and lead somewhere to 'time delay' limits of the whole signal flow.

5. Conclusions

Closing the design loop from desired negative static margin for optimum trim drag via wind tunnel optimization for getting favourable basic sideslip and pitch characteristics to the limits of instability given by the required recovery moment and minimum allowable 'Time to Double', Fig. 24 and 25 show the possibility to find an 'optimum' configuration that stays within the limits, fulfils most of the desired characteristics and last but not least comes close to the point for minimum trim drag.

The figures give an example for a tailless configuration which meets both limits (C_{mRec} and T_2) in the same point when adding a 4 % LEX and a single vertical tail and therefore provides maximum attainable instability for good performance. The lateral and directional stability seems to be sufficient with positive $C_{n\beta_{dyn}}$-values throughout the whole angle of attack range, as illustrated in Fig. 25 below (Minimum $C_{n\beta_{dyn}} \sim .2$ [rad^{-1}]), in spite of the fact that the LEX should be a little smaller for optimum sideslip data. - In addition the rudder effectiveness of the single vertical tail gives a good yaw control especially at higher angles of attack.

The proposed characteristics and limits, to be aimed at in an optimization process within the early design state, are a rough guide line which should lead to useful results and a first step towards the final configuration of a future combat aircraft. Depending on the design goals, desired angle of attack range, use of thrust control devices etc. the different (favourable) requirements may be modified but in order to get a relative simple control system and in order to lower the costs of the whole aircraft one should always come close to the characteristics discussed above.

6. Acknowledgement

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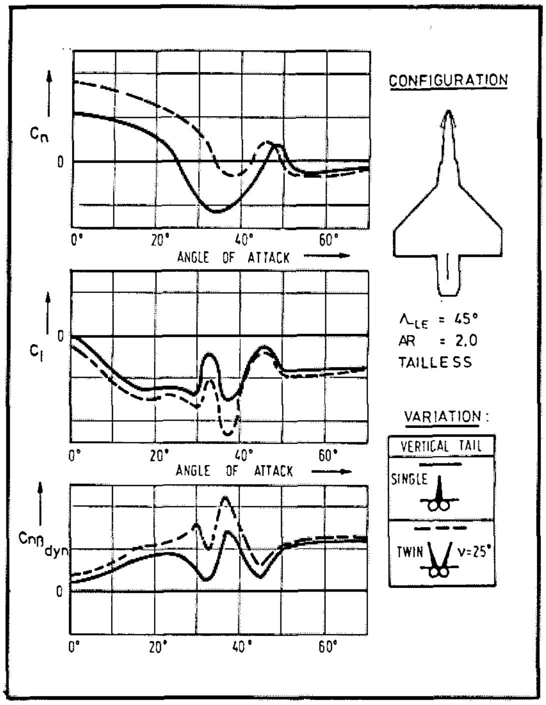

Fig. 1 LATERAL / DIRECTIONAL STABILITY; $\beta = 10°$
EFFECT OF VERTICAL TAIL CONFIGURATION

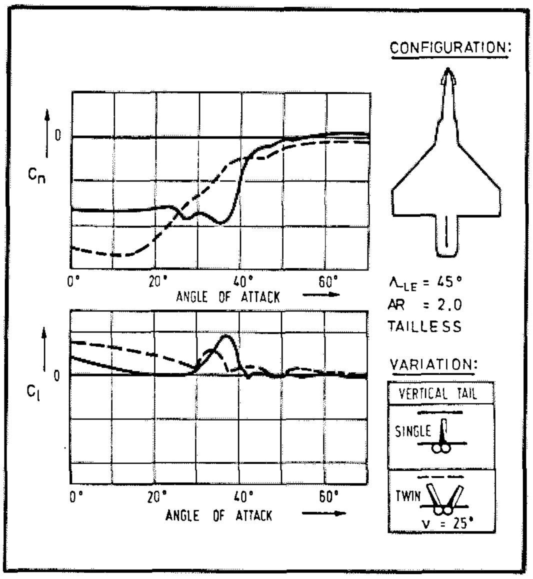

Fig 2 RUDDER EFFICIENCY, $\zeta = -36$, $\beta = 0°$
EFFECT OF VERTICAL TAIL CONFIGURATION

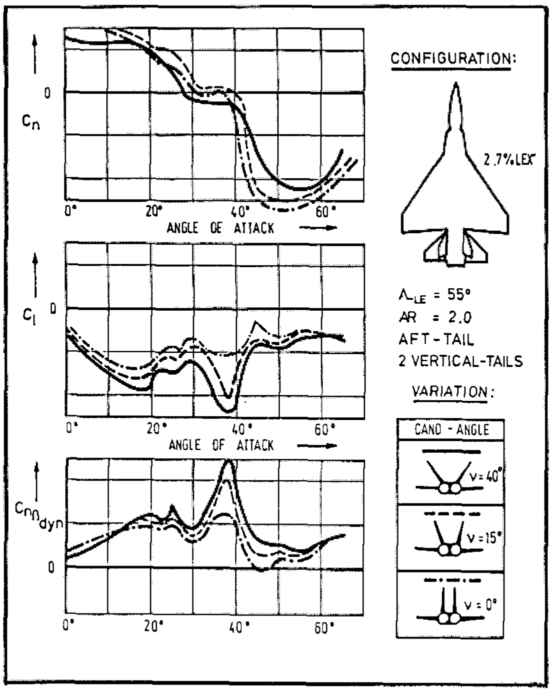

Fig. 3 LATERAL / DIRECTIONAL STABILITY; β = 10°
EFFECT OF VERTICAL TAIL CANT ANGLE v

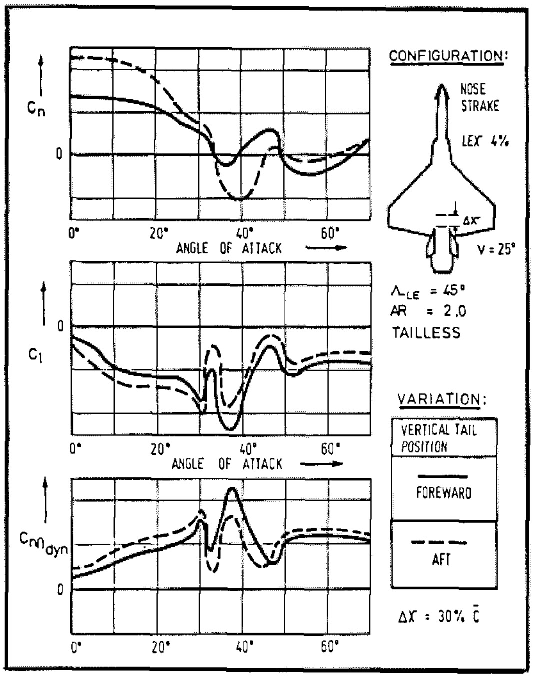

Fig. 4 LATERAL / DIRECTIONAL STABILITY β = 10;
EFFECT OF VERTICAL TAIL x- POSITION

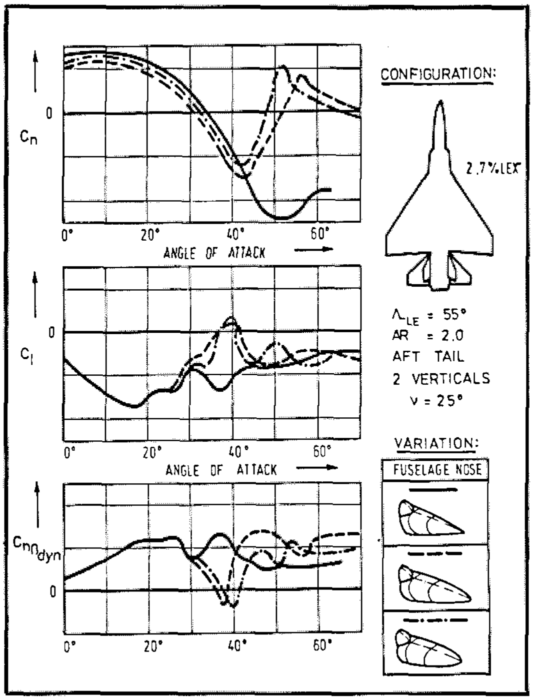

Fig. 5 LATERAL / DIRECTIONAL STABILITY; β = 10°
EFFECT OF FUSELAGE NOSE CROSS SECTION

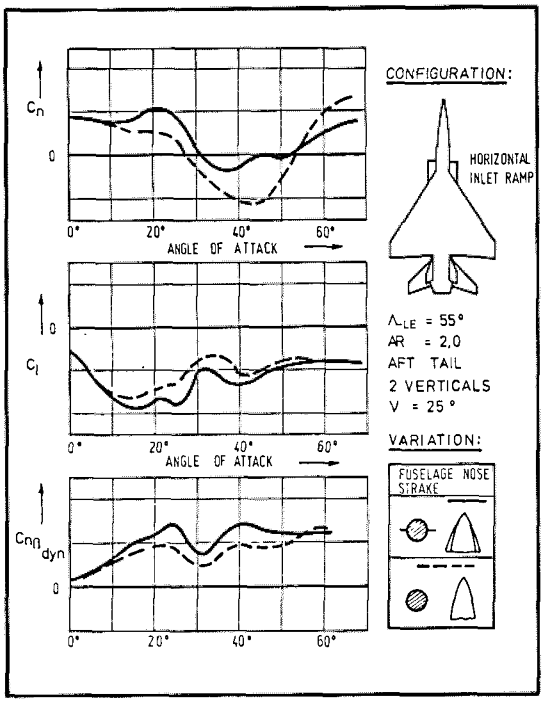

Fig. 6 EFFECT OF A NOSE STRAKE ON
LATERAL / DIRECTIONAL STABILITY
β = 10°

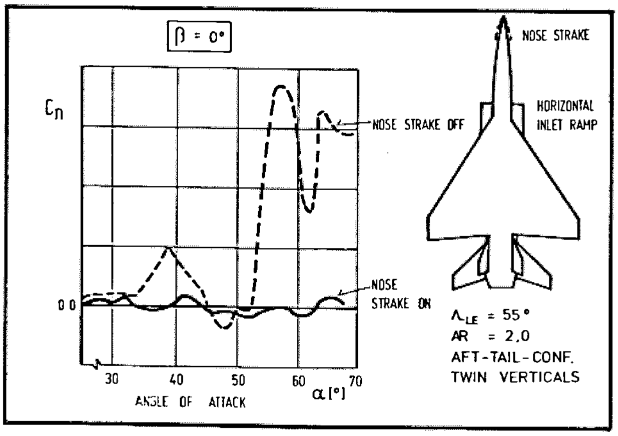

Fig. 7 EFFECT OF NOSE STRAKE ON YAW DEPARTURE

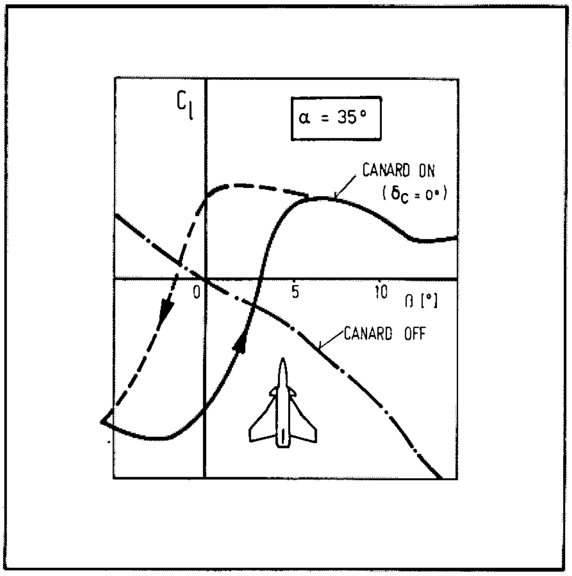

Fig. 9 NONLINEARITY IN ROLLING DUE TO SIDESLIP OF A CANARD CONFIGURATION

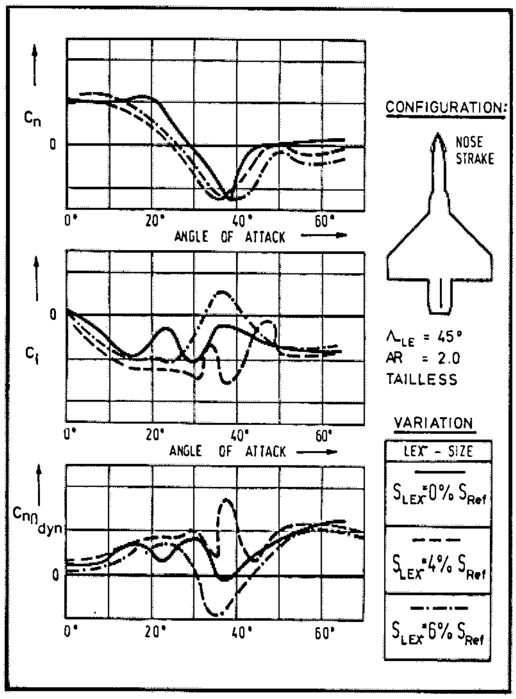

Fig. 8 EFFECT OF LEX SIZE ON LATERAL / DIRECTIONAL STABILITY, $\beta = 10°$

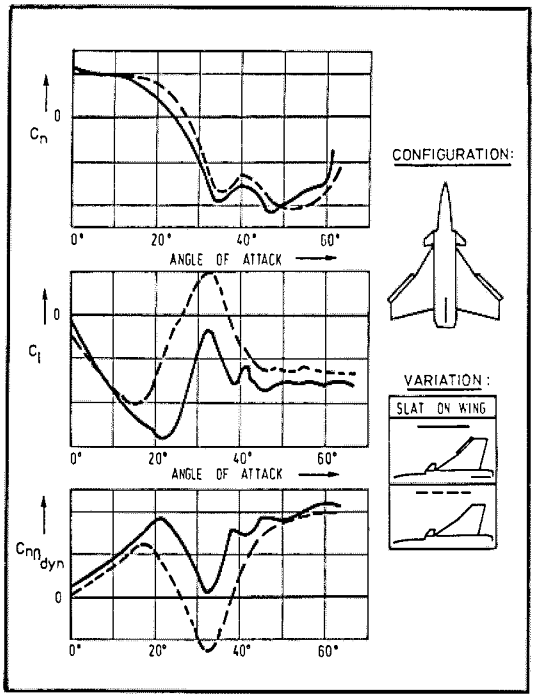

Fig. 10 LATERAL / DIRECTIONAL STABILITY ; $\beta = 10°$; EFFECT OF A WING SLAT ON A CANARD CONFIGURATION

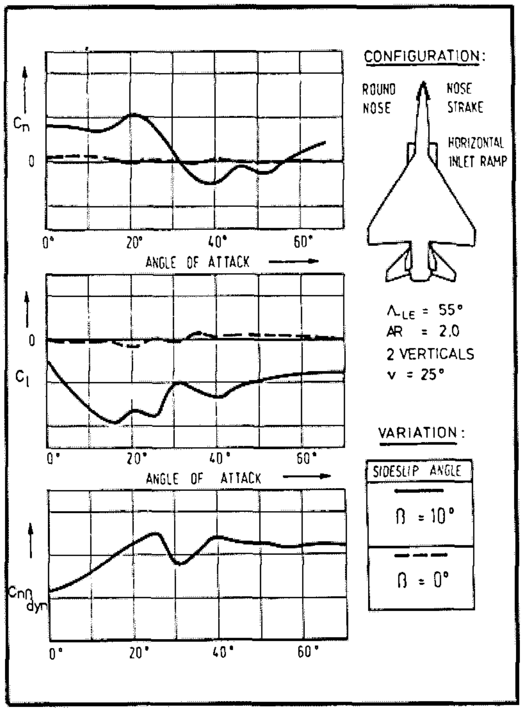

Fig. 11 LATERAL / DIRECTIONAL STABILITY; EXAMPLE FOR AN OPTIMIZED AFT TAIL CONFIGURATION

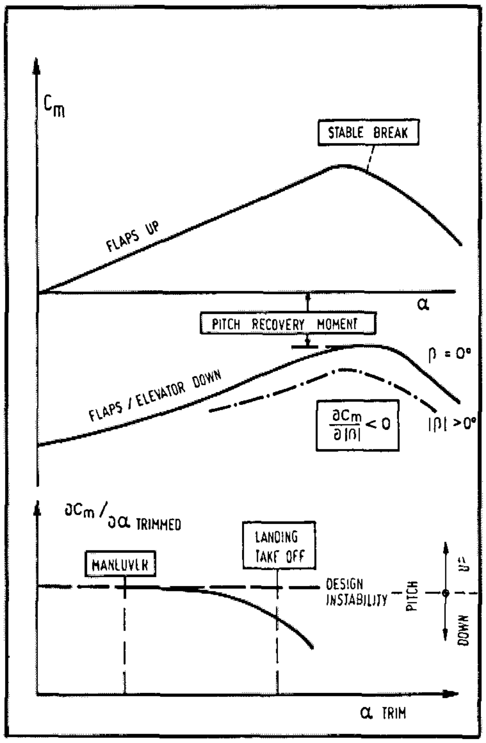

Fig 13 FAVOURABLE PITCH CHARACTERISTICS OF AN UNSTABLE CONFIGURATION

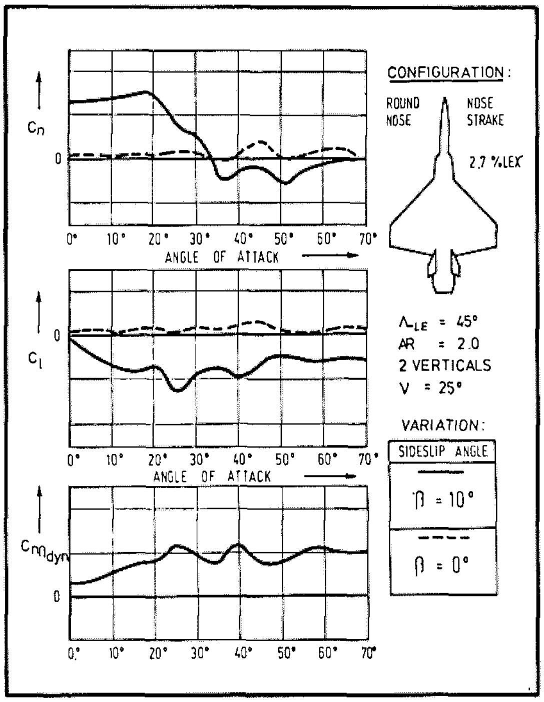

Fig 12 LATERAL / DIRECTIONAL STABILITY; EXAMPLE FOR AN OPTIMIZED TAILLES CONFIGURATION

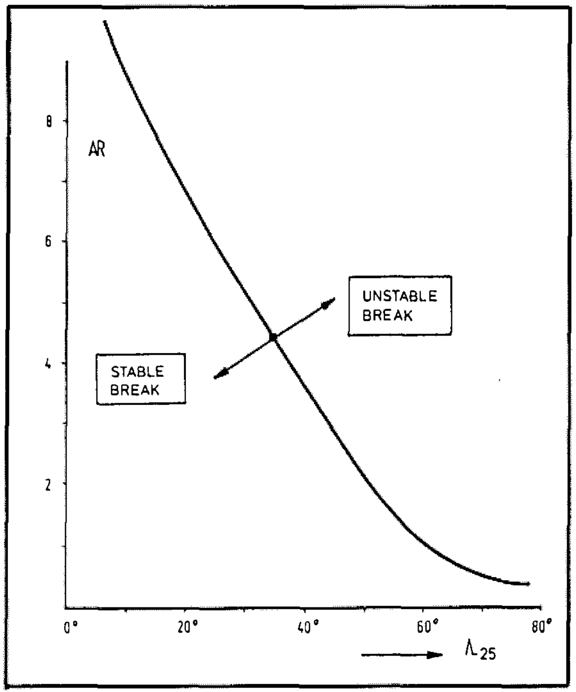

Fig 14 BEHAVIOUR OF PITCHING MOMENT AT $C_{L_{max}}$

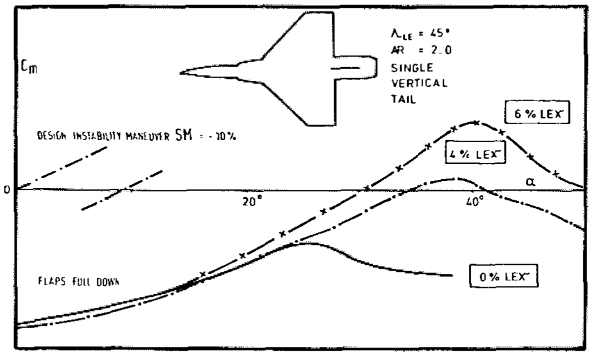

Fig 15 EFFECT OF LEX SIZE ON PITCH - RECOVERY MOMENT

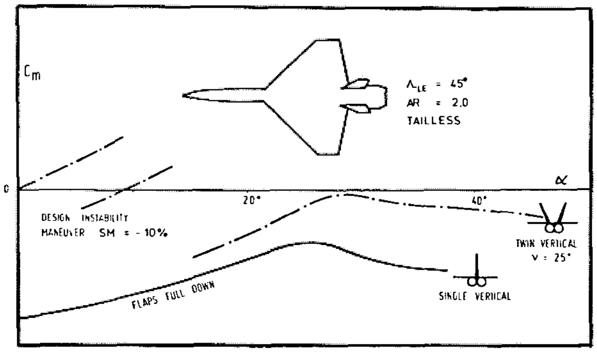

Fig 16 EFFECT OF VERTICAL TAIL CONFIGURATION ON PITCH RECOVERY MOMENT

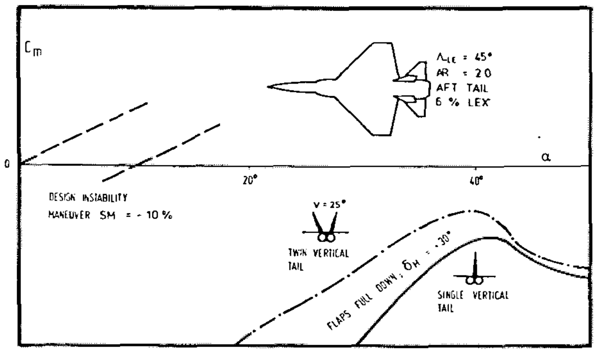

Fig 17 EFFECT OF VERTICAL TAIL CONFIGURATION ON PITCH RECOVERY MOMENT

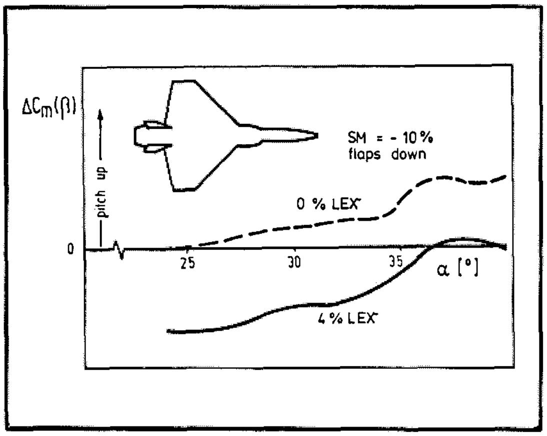

Fig 18 PITCH DUE TO SIDESLIP; EFFECT OF LEX

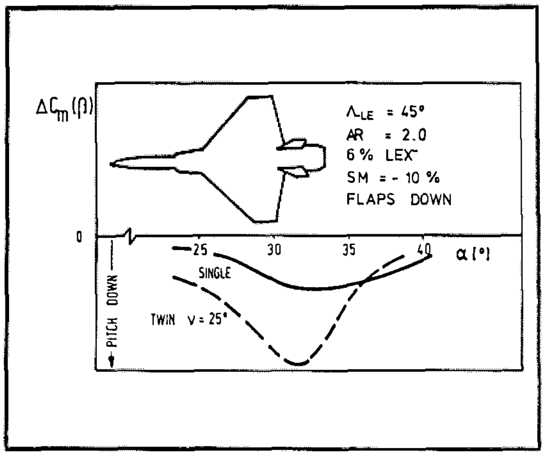

Fig 19 PITCH DUE TO SIDESLIP; EFFECT OF VERTICAL TAIL CONFIGURATION

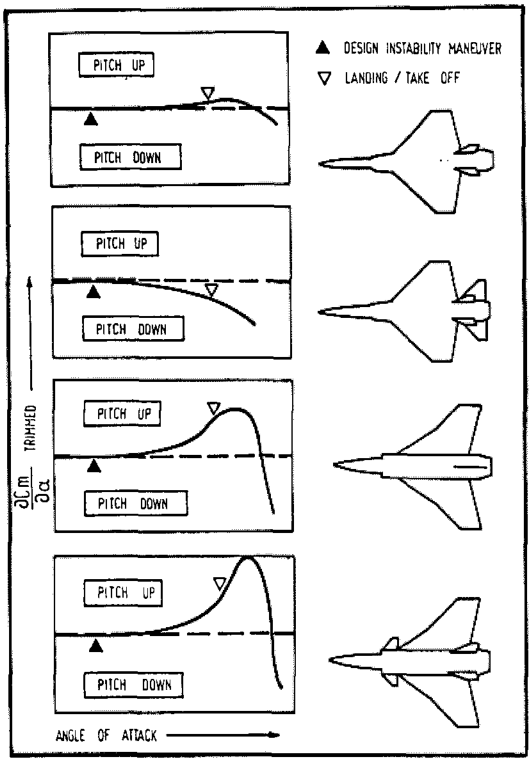

Fig. 20 PITCH UP CHARACTERISTICS OF SEVERAL CONFIGURATIONS

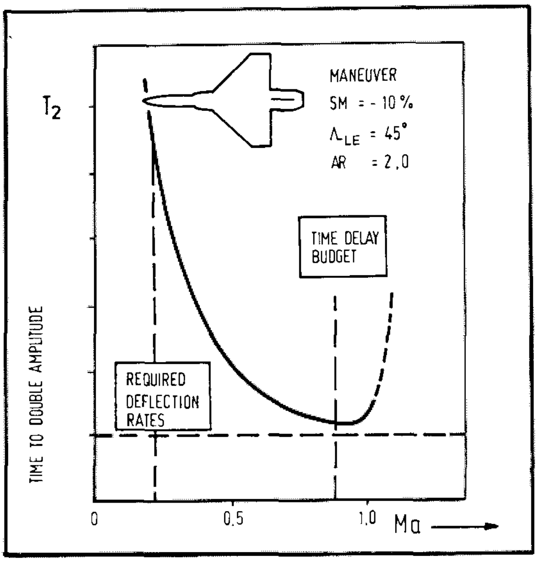

Fig. 22 CRITICAL MACH NUMBERS FOR THE CONTROL SYSTEM

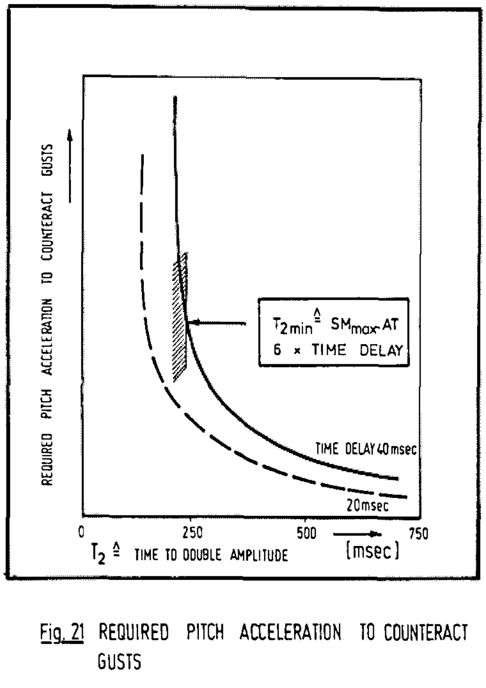

Fig. 21 REQUIRED PITCH ACCELERATION TO COUNTERACT GUSTS

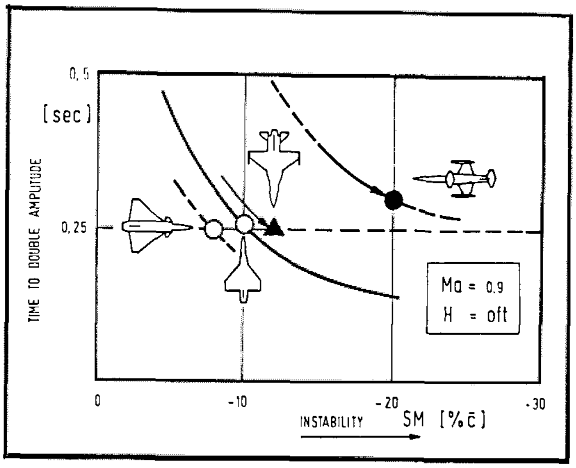

Fig. 23 ESTIMATED TIME TO DOUBLE AMPLITUDE VERSUS NEGATIVE STATIC MARGIN OF SOME EXISTING AND PROJECTED AIRCRAFT

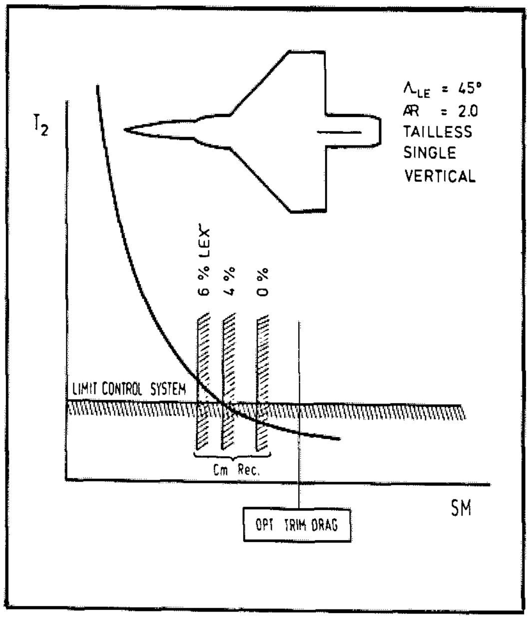

Fig. 24 LIMITS FOR NEGATIVE STATIC MARGIN

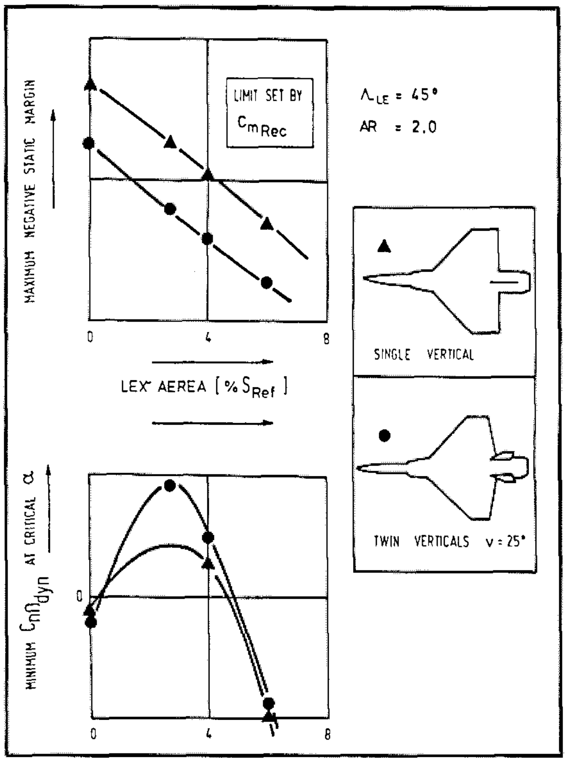

Fig. 25 EFFECT OF LEX SIZE ON LONGITUDINAL AND LATERAL LIMITS AND CHARACTERISTICS