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STABILITY CONSIDERATIONS FOR ENHANCED MANOEUVRABILITY - AN OVERVIEW

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Abstract

Modern fighter aircraft are expected to manoeuvre under adverse conditions. Stability considerations in relation to configurational aspects for enhanced manoeuvrability are bought out in this paper. Static stability derivatives, dynamic stability derivatives, cross-derivatives, aerodynamic and inertia couplings are highlighted.

I. Nomenclature

CL = Lift coefficient
Cl = Rolling moment coefficient
Cm = Pitching moment coefficient
Cn = Yawing moment coefficient
Ix = Roll inertia
Ixy = Cross inertia term
Iy = Pitch inertia
Iz = Yaw inertia
M = Mach number
Mx = Rolling moment
My = Pitching moment
Mz = Yawing moment
p = Angular Velocity in roll
q = Angular Velocity in pitch
r = Angular Velocity in yaw
α = Angle of attack
β = Yaw angle/sideslip
γ = Roll angle
α' = Resultant incidence of air flow

Suffix

max = Maximum
I = Inertia

II. Introduction

In addition to performance considerations, fighter aircraft should possess acceptable handling qualities. Though the modern control systems can augument the stability, aircraft are required to possess certain inherent stability characteristics. It is only then that the control laws for stability augumentation can be described. Effects of compressibility, altitude variations and aeroelasticity further complicate the aerodynamic characteristics of aircraft (1,2).

Current generation of aircraft are required to possess enhanced manoeuvrability (2). At low altitudes, aircraft may operate under stall conditions of flight and yet require manoeuvring (3). At medium altitudes, supersonic manouvrability is expected in dogfight. Stability considerations for enhanced manoeuvrability aim at maintaining a wide envelope of manoeuvre boundaries at all times and also keeping low values of static stability derivatives. Static stability derivatives along with damping, cross and cross-coupled dynamic derivatives decide certain manoeuvre boundaries. Regions of no conflict in manoeuvre performance get narrow down due to several reasons (4). Keeping a larger region of no conflict over a wide range of operational limits requires active configuration design considerations. Configurational changes in flight due to weapon launching, positioning of leading and trailing edge flaps, canard deflections etc., greatly influence the stability behaviour.

This paper brings out the aircraft characteristics towards enhanced manoeuvrability. Design features of aircraft are described from manoeuvring point of view. All the moments and their derivatives are taken about centre of gravity (c.g.).

III. Static Stability

Longitudinal Static Stability : It is governed by the stability derivative Cm_{α} control effort and greater manoeuvrability in pitch. In case the aircraft is stable in pitch i.e., negative Cm_{α} (taking clockwise Cm_{α} as positive), the growing tail-up deflection is required for increasing the load factor. To hold the aircraft in manoeuvre, tail-up position is required to be maintained. In the process of building the load factor, the growing negative tail lift minuses from the growing wing lift, thereby manoeuvrability gets sluggished. Once the load factor is established, the negative tail lift continues to remain and spoils the overall lift system of the aircraft. With higher and higher load factor, larger and larger tail-up movement is required, thereby manoeuvrability gets limited. In case of supersonic flight, aerodynamic center (a.c.) shifts rearwards thereby increasing the static margin. The lift curve slope of the tail plane also drops in this flight regime. Therefore, at high speeds, the supersonic manoeuvrability gets curtailed. As the aircraft approaches high CL, appearance of buffeting may be peculiar to an aircraft. Figure.1 shows typical aircraft characteristics marked by severe buffeting. This figure also shows the control limitation, which results in degradation of manoeuvrability at high speeds. Typical plot of pitch limitation in this figure is for a stable delta configuration that does not have leading edge flap (LEF).

Advantages of destabilization in pitch are well known. If the a.c. of the wing is made to fall ahead of c.g., then tail-down setting is required for cruise. To generate manoeuvre, tail-up movement is needed and to hold aircraft in menoeuvre, large tail-down movement is required. The increasing tail-down movement with increasing angle of attack (alpha) is necessitated. Again the limitation on tail plane maximum movement will limit the manoeuvre and to come out of manoeuvre further more tail-down movement is required. To overcome this riddle, LEFs are used. In addition to substantial drag reduction, LEF provides increasing pitch down moment with increasing downward deflection, thereby tail plane movement can be conventionally deployed (5). But in this case the movements of tail plane are far lesser compared to that of the stable configuration, Fig.2. LEF also delays buffeting since the point of adverse pressure gradient gets shifted rearwards. Use of LEF in the supersonic flight is prohibited since the shock wave drag associated with a deflected surface is very large. Thus for the control purpose brought out earlier, aircraft configuration must be made stable for supersonic flight conditions. Advantage is taken of the a.c. shift that is associated with the increase in Mach numbers from subsonic to supersonic, to stabilise the configuration in supersonic flight regime. This shift is large on a medium swept back wing and the shift is marginal on a highly swept planform (4). Since the a.c. shifts rearwards from a position ahead of c.g. to a position aft of c.g., low static margin is obtainable. Such an aircraft is far less stable in supersonic flight when compared to a totally stable configuration. The tail plane in fact, can be done away with. Tail plane area can be contained in wing area, giving decrease in wing loading. Lower wing loading results in increased manoeuvrability. Tailless configurations with leading and trailing edge flaps, use such flaps for manoeuvring thereby generating mission adaptive profile (2). Levels of relaxed static stability (RSS) in an unstable configuration (tail or tail-less) are low. Limited RSS levels limit the unsteady part of the manoeuvrability. Though high load factors can be developed on these configurations, the rate of 'g' development is sluggish because of lower RSS levels. High RSS are possible with canard-wing arrangements. There are several other advantages of canard. Canard provides downwash on wing which helps delay stalling, thereby resulting in higher maximum lift coefficient (2). Since the canard is an independent authoritative surface, it can provide pitch control even under the stalled wing conditions. Modern combat situations require taking the aircraft beyond alpha stall and manoeuvring it (3). It is only the canard which can be aligned to relative flow direction to provide pitch control even under stalled conditions of flight. Canard plays a vital role in the longitudinal stability.

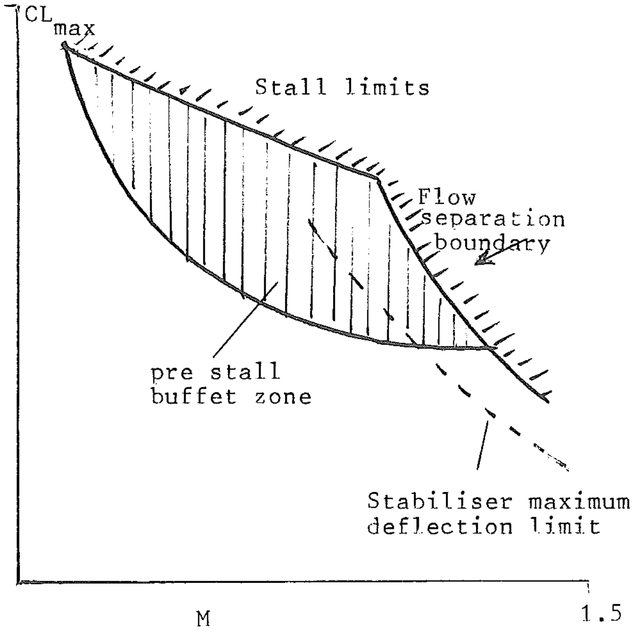

Fig. 1 Typical plot of pitch limitation

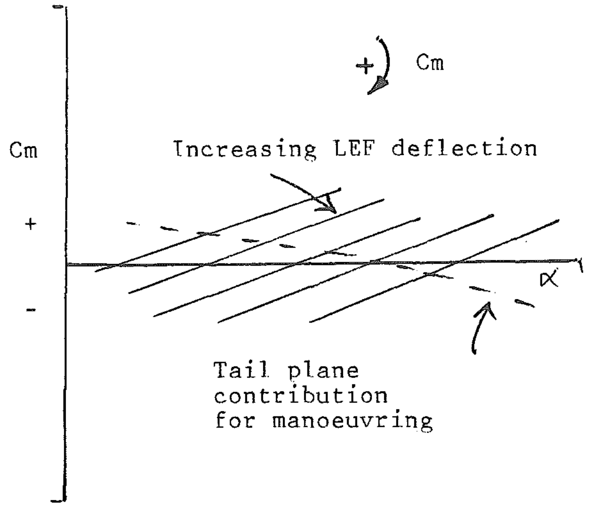

Fig. 2 Plots for unstable configuration

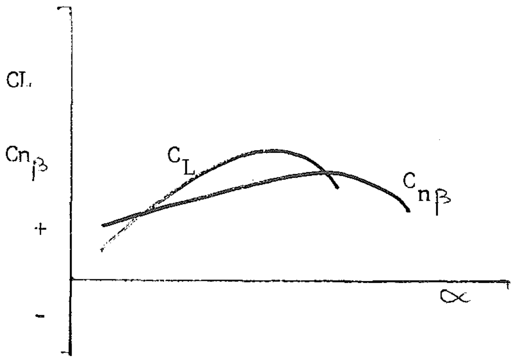

Fig. 3 Post stall manoeuvrability

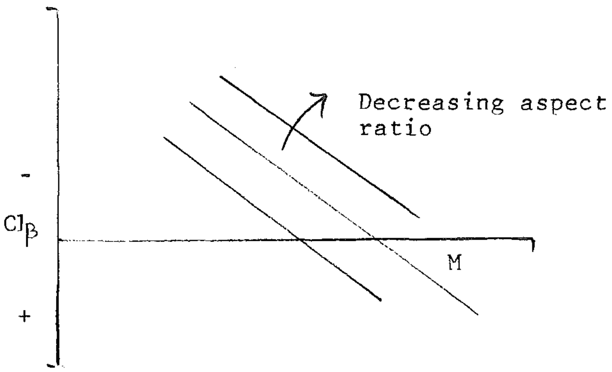

Fig. 4 Dihedral effect of low aspect ratio

Directional and Lateral Static Stability : Directional static stability is measured in terms of Cn_β . Low and positive (stable) Cn_β is desirable for reasons of keeping low control effort and greater manoeubrability. This is required over larger ranges of alphas and Mach numbers. Low levels of directional static stability are possible with twin vertical fin arrangements. Loss of directional stability at increased alpha conditions is inevitable since the vertical fin gets into the wake generated by body and wings. Body shedding vorticity, vortical flow, single/twin tail arrangements, sweeping fin backward/forward, fin canting etc., greatly influence the directional stability. Canard and LEF delay the loss of directional stability due to high alpha (6). Post-stall directional stability is important in current type of combat situations, Fig.3. To some extent, this can be achieved with canard and forward swept fin arrangements (6). Firstly, the wing root itself can be maintained to remain unstalled while the rest of the wing might have stalled. This is because of the favourable canard downwash influence on wing root flow. Secondly the canard streamlined flow while mixing with the stalled wing wake changes the direction of wing wake, downwards. This is possible with a movable canard surface. Increasing supersonic Mach number reduces directional stability (4). This is because of the fall of the lift curve slope of vertical fin with increasing Mach number in this regime of flow. Twin fin arrangement lessens such losses. Component sizing using parametric relationships are useful for first hand information of directional stability, but extensive wind tunnel testing needs be relied upon for determining exact behaviour of aircrat at various attitudes.

Aircraft in yaw produces roll, which is governed by the stability derivative Cl_β . This stability derivative represents the change of rolling moment with side-slip. For the positive lateral stability, side-slip must provide the negative rolling moment i.e., ($-Cl_\beta$). This effect is classically refered to as dihedral. Main contributors to dihedral effect are wing sweep, vertical fins and wing dihedral (4). The effect of compressibility is to reduce the dihedral effect. Under certain Mach number conditions, this derivative may reverse its sign and become positive, Fig.4. This is because of the decrease of lift curve slope of vertical fin at increasing Mach numbers. However, this derivative increases with increasing alpha, Fig.5. This is because of increased lift coefficient at increased alpha values.

Aircraft tendency towards Dutch roll and spiral instability is governed by the relative power of Cl_β and Cn_β i.e., the roll/yaw ratio. Aircraft with large directional stability and lesser lateral stability has the tendency towards spiral instability. Whereas aircraft with lesser directional stability and large lateral stability has the tendency towards Dutch roll, Fig.6. Effect of the increasing altitude is to rotate the Dutch roll boundary clockwise, thereby narrowing down the region of no conflict. Increasing lift coefficient further narrows down the region of no conflict from both the boundaries (4). Dutch roll is very undesirable feature of the flying. Aircraft are usually allowed to possess spiral departure modes which are early predictable and controlable. These motions further get complicated by the aerodynamic damping and cross-derivatives. Additionally, the values of these derivatives get influenced by flight altitude and speed. These issues are brought out later on.

Certain levels of lateral static stability are required to be maintained over larger alpha and Mach number ranges. Fighter aircraft wings are highly swept back. This results in large lateral static stability. Vertical fin contributes positively to this stability. Therefore, to reduce the levels of lateral stability, wing anhedral or canard anhedral is given. However the increasing Mach number has the effect of fast degradation of lateral stability. This is mainly because of the loss of lift curve slope of fin. To overcome this, twin fins resulting in reduced lateral stability are useful without having the need to anhedral the wing or canard. Additionally, the loss of lateral stability with increasing Mach number is reduced because of reduced vertical fin size. Figure.7 shows such a choice of design.

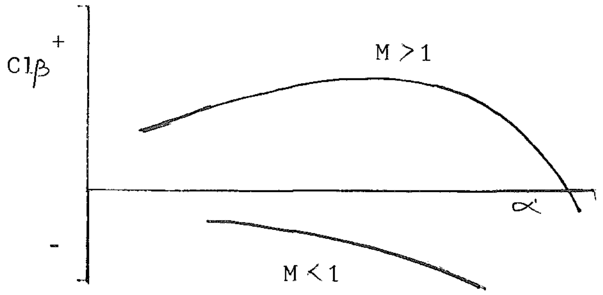

Fig. 5 Typical lateral stability Characteristics

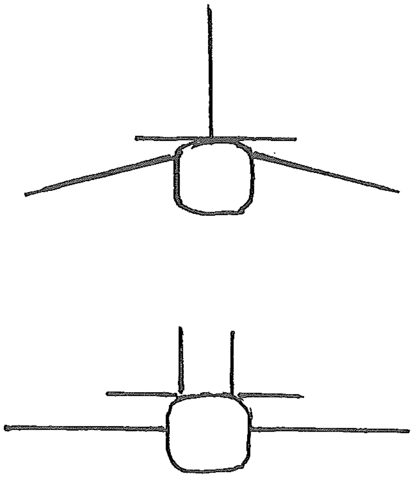

Fig. 7 Choice of design

Fighter aircraft are required to roll at fast rates. This aspect of lateral static stability is measured by the derivative Cl_{γ} . Positive derivative is a stabilising one. Fighter aircraft are mildly stabilized in roll, hence these aircraft have very high roll rates. Wing and canard are the main contributors towards this stability. Loss of

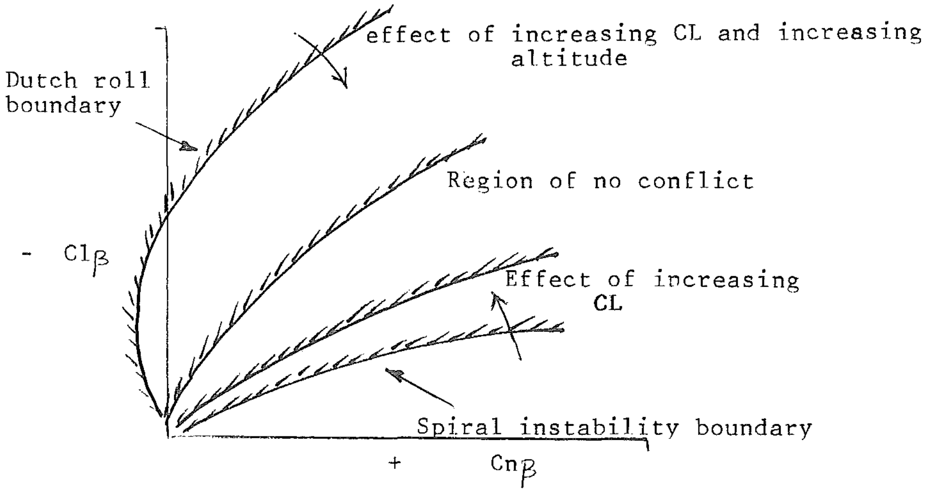

Fig. 6 Typical criteria of instabilities

contribution to lateral static stability from wing at high alphas is inevitable under stalled wing conditions. Lateral stability under such conditions need be provisioned for certain combat situations. Again it is the canard which can be depended upon to play this role (2,6). Canard with differential incidence control is very purposeful for generating roll rates even in the presence of stalled wing conditions. Roll generates yawing, the governing derivative is given by $Cn\gamma'$. The nature of this derivative is very similar to Cn_{β} . Motion in roll is more governed by the damping terms, cross derivatives, aerodynamic and inertia couplings. These aspects are brought out later on.

IV. Dynamic Stability

Dynamic motion is governed by the levels of static stability, damping derivatives and cross derivatives. Aerodynamic and inertia couplings further complicate the behaviour of motion. Aspects related to these effects for enhanced fighter manoeuvrability are studied herein. Tale-I shows the various stability derivatives.

TABLE - 1

STABILITY DERIVATIVES

STATIC STABILITY DERIVATIVES		
Pitching	Yawing	Rolling
Cm_{α}	Cn_{β} Cnr	Clr Cl_{β}
DYNAMIC STABILITY DERIVATIVES		
Damping Derivatives		
$Cmq + Cm_{\dot{\alpha}}$	$Cnr + Cn_{\dot{\beta}}$	Clp
Cross Derivatives		
	Cnp	$Clr + Cl_{\dot{\beta}}$
Cross-Coupled Derivatives		
$Cmr + Cm_{\dot{\beta}}$ Cmp	$Cnq + Cn_{\dot{\alpha}}$	$Clq + Cl_{\dot{\alpha}}$

Damping Derivatives : Oscillations in pitch, yaw and roll are required to be damped. Positive damping effect is governed by the negative value of the damping derivatives. Motion in pitch is governed by the derivative pair (Cm_{α} , $Cmq + Cm_{\dot{\alpha}}$). The derivatives Cm_{α} represents the levels of static stability. The derivatives Cmq represents the snaking motion and $Cm_{\dot{\alpha}}$ is the motion in plunge. Damping-in-pitch is the rate of change of pitching moment due to rate of pitch. Associated derivative is usually a negative one for aft-tail or canard alone configuration. Damping ratio (ζ) is given by the eqn. 1. In this equation negative sign indicates damping. Damping of response (η) is given by eqn. 2. The short period oscillations are of much concern in flying. The effect of variation of static stability and damping derivatives on short period oscillations is shown in Fig.8. Increasing the static stability increases the frequency of short period mode of motion (4). Increasing the damping derivative increases the damping and lowers the frequency of motion. A tail-less configuration is poor in pitch damping, canard/tail assists damping. Figure.9 shows trend in damping characeristics of various configurations for fixed control surfaces. Control surface deflections result in the increase or decrease in damping depending upon the phase relationship between aircraft motion and control surface deflections. In addition to damping this aspect is used to provide artificial stability to an unstable configuration (6,7). Aft-tail configuration with RSS requires only the stabilization effort when compared to tail-less configurations with RSS, where a dual responsibility lies on the control system i.e., of stabilization and providing artificial damping. Further the severity of damping requirement through control system is much more for an unstable canard configuration when campared to a unstable tail-less configuration. In fact the canard configuration need not be an unstable one. It is only the unsteady part of pitch manoeuvre, when RSS is needed. During cruise or during steady manouvres, configuration instability is of no use. Moreover greater is the instability, more is the effort required to bring the aircraft out of manoeuvres. Closely coupled canard aims at producing very high RSS levels during manoeuvring of otherwise stable configuration. Under such circumstances, substantial effort of generating artificial stability can be taken off from the control system. Theoretical prediction of exact control software gets complicated by the nature of flow past configurations. Damping effort can be best determined from inflight conditions i.e., the control software synthesis can be automated to get desirable flying characteristics.

$$\zeta = \frac{Cmq + Cm_{\dot{\alpha}}}{2\sqrt{-Cm_{\alpha}}} \tag{1}$$

$$\eta = \zeta \omega_n \tag{2}$$

Where ω_n is the natural frequency.

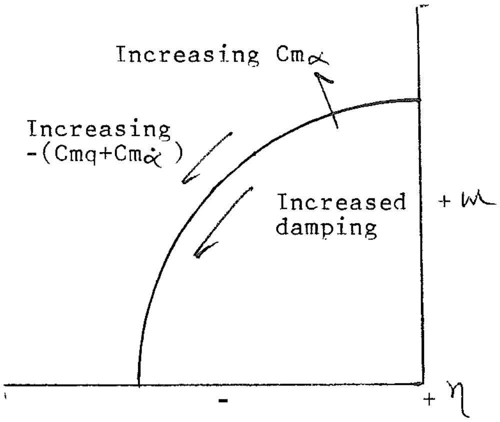

Fig. 8 Damping of short period oscillation

Damping-in-yaw is the rate of change of yawing moment with rate of yaw. Damping-in-yaw is governed by the derivatives pair (Cn_β , $Cnr + Cn_{\dot{\beta}}$). The derivative Cnr represents the snaking motion, and side way motion is governed by $Cn_{\dot{\beta}}$. All contributions to Cnr are negative ones. Vertical fin, vental fin, fuselage and wing contribute negatively. The motion is usually a damped one over large alpha and Mach number ranges. Due to large inertia in forward direction the yaw rates are usually low. Therefore, the motion in yaw is governed by eqn. 3. Figure.10 shows typical yaw characteristics of an aircraft (8). Loss in damping followed by loss of directional stability is inevitable since it is the vertical fin which has a major damping contribution. There is need to provide directional static stability and hence also the damping under the stalled wing conditios. As brought out earlier, canard influences the delaying of loss of directional static stability at increased alpha values and so is the loss of damping-in-yaw gets delayed.

$$I_z \ddot{\beta} \propto \left| Cn_\beta \beta \right| - \left| Cnr \quad r \right| \tag{3}$$

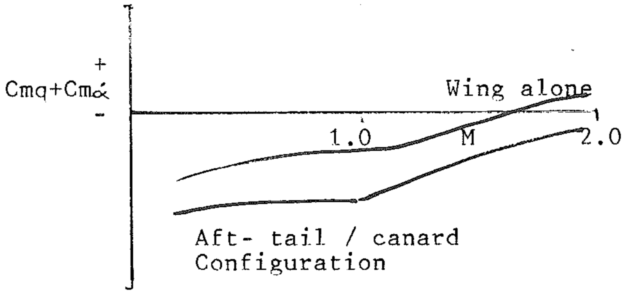

Fig. 9 Typical damping Characteristics

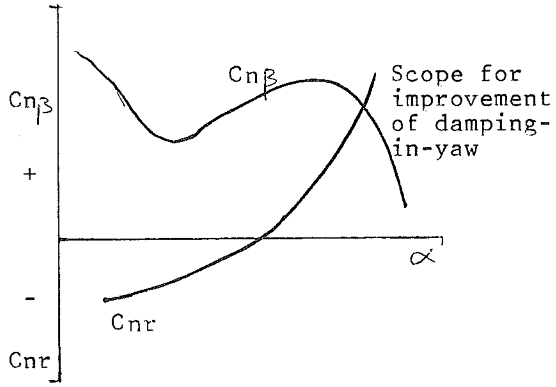

Fig. 10 Typical yaw characteristics of an aircraft

Damping-in-roll is governed by the derivative Clp. It is the rate of change of rolling moment due to rate of roll. The resulting motion is decided by eqn. 4.

Vertical fin and wing are the main contributors to damping-in-roll. Motion in roll is usually a damped one. The problem of wing rock developes at some alpha conditions if the damping becomes unfavourable, Fig.11. The down going wing whose motion is assisted by unfavourable damping-in-roll, developes greater lift than its counterpart. The down going wing having developed larger lift creates roll to the other side and so on. The phenomenon well known as wing rock occurs primarily because of loss of damping-in-roll (6). Autostabilization systems aim at providing artificial damping-in-roll by a phase lag arrangement of aileron movement in relation to aircraft roll. Some combat situations demand high roll rates in the vicinity of high alpha conditions which are close to stall. Phenomenon of autorotation developes under such conditions of flight. In roll, down going wing developes greater alpha due to relative change of flow direction compared to up going wing where alpha gets reduced. If the conditions are close the stall, the down going wing gets into stall while the up going wing continues to provide lift. Due to the loss of lift on a side, the aircraft continues to roll. Roll results in yaw, thus a continuous roll-yaw follwed by loss in altitude due to loss of lift results in motion of autorotation. Autorotation is more prone at low forward speeds because of greater change in flow incidence during roll at such speeds (6). Though certain advantage from aeroelastic tailoring can be arranged to prevent autorotation, but this does not serve as the sole means to an end. It is the variable incidence wing that can be relied upon to do this job. Such an effort is weight penalising, therefore an alternative is to use LEF differentially. LEF on down going wing can be moved into flow direction to reduce effective alpha. This task can be automated through control software.

$$Ix\ \ddot{\gamma} \propto \left| Cl_{\gamma} . \gamma \right| - \left| Clp .\ p \right| \qquad (4)$$

Cross-derivatives : Table-1 gives the various corss-derivatives. Rate of change of rolling moment due to snaking in yaw is governed by Clr and rate of change of rolling moment due to side way motion is governed by $Cl_{\dot{\beta}}$. Due to the large inertia in forward directions, the second derivative is usually a negligible one. Damping-in-roll due to yaw angular velocity (Clr) along with damping-in-yaw (Cnr) influence the Dutch roll and spiral modes. The condition of spiral stability is expressed as eqn. 5 i.e., the product of anti-turn derivatives (Cnr x Cl_{β}) must be greater than product of pro-turn derivatives (Cn_{β} x Clr), for the aircraft to possess spiral stability. For fixed values of Cnr and Clr, a typical spiral boundary on the (Cl_{β} - Cn_{β}) diagram is drawn, Fig.6. The values of Cnr and Clr vary with speed (i.e., CL) (4,6). Increasing CL increases Clr thereby turning the spiral boundary anti-clockwise. Turning of the spiral boundary is required to be prevented for maintaining larger region of no conflict. This is possible if with increasing alpha, appropriate increase in negative Cl_{β} is managed. Further at high alphas, drop in Cn_{β} and loss of negative Cnr can be equally arranged. A great deal in preventing the turning of boundaries is possible through component sizing. Under the stalled wing conditions, contribution to lateral static stability from wing is lost. To maintain this part of stability, mainly to limit the ratoration of spiral boundary, canard surface needs be depended upon.

$$\left| Cl_{\beta} \times Cnr \right| - \left| Cn_{\beta} \times Clr \right| > 0$$

$$\text{or} \quad \left(\frac{-\,Cl_{\beta}}{Cn_{\beta}} > \frac{Clr}{-\,Cnr} \right) \qquad (5)$$

Since Cl_{β} & Cnr are usually negative.

Yawing moment is also generated due to rate of roll. It is governed by Cnp. Contribution to directional stability due to this part is high because of vertical fin size. While deciding the Dutch roll and spiral instabilities, this term needs be taken care off.

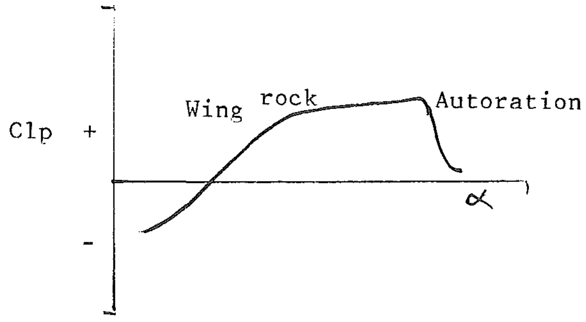

Fig. 11 Typical problems of damping-in-roll

Cross-coupled derivatives : Longitudinal and lateral-directional motions can be separately treated to some extent. Current generation of slenderical wing aircraft are expected to develope complicated manoeuvres. Under such conditions, motion in pitch ($q, \dot\alpha$) produces yawing and rolling moments (9). Also the motions in roll (p) or yaw ($r, \dot\beta$) produce pitching moments. For example the total pitching moment may be governed by eqn. 6. Such cross-coupling is referred to as aerodynamic coupling and is governed by the cross-coupled derivatives. Table-1 shows the various cross-coupled stability derivatives. Peculiar to a configuration, these effects may be very predominent thereby requiring component sizing. Motions leading to aerodynamic coupling are complex, therefore, theoretical or wind tunnel predictions are not a viable proposition. Extensive flight testing needs be relied upon to generate such datas (10).

$$\sum Cm = Cmq \times q + Cmp \times p + Cmr \times r + Cm_{\dot\beta} \times \dot\beta + Cm_{\alpha} \times \alpha \qquad (6)$$

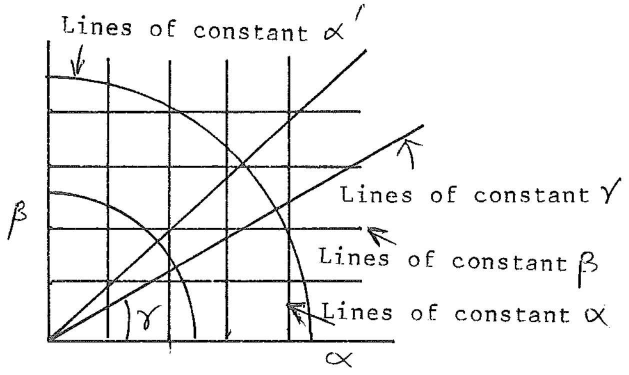

Fig. 12 Relationship between α, β, γ

Phase lagging : Aircraft in roll (without turning) undergoes changes in alpha and yaw angles (6). Aircraft in turning flight developes plane of air at an angle to the lateral plane of the aircraft. There is phase lagging which results in aircraft roll relative to plane of wind direction. Figure-12 shows the influence of roll on various conditions of angles. Phase lagging results in additional terms in Clp, Cnp and Cmp which are $Cl\dot{p}$. Sin α , $Cn\dot\beta$ Cos α and $Cm\dot\beta$ Sin α respectively. The addition of these terms further complicate the equations of motion. The motions governed by these derivatives are extremely complicated and offer substantial difficulty in accurate mathematical modelling. Wind tunnel testing under varied flight conditions is not possible due to the limiting test section of these tunnels. Study on such motions can be best relied upon through flight testing.

V. Inertia Coupling

Complicated motions involve cross-coupling due to inertia which are governed by eqns. 7-9. Modern fighter aircraft wings are slenderical, thereby the value of Ix are very low. In case of rapid roll and rapid yaw, first term in the inertial pitching moment given by eqn. 7 becomes significant and the second term becomes negligible. Thus a fast turning aircraft would develope significant pitch-up divergence that needs prediction and early correction in flight. Certain manoeuvres require fuselage yawing without rolling. In this case the first term in eqn. 7 becomes negligible and the second term becomes significant. Inertial rolling moment given by eqn. 8 shows that pitch and yaw together produce rolling whose value depends upon the related value of Iy and Iz. Since the value of Iy is usually much higher than that of Iz, substantial roll due to yaw and pitch coupling is expected. Inertial yawing moment eqn. 9 shows that pitch and roll together produce yawing, depending upon related values of Ix and Iy. While coupling the control requirements for manoeuvring, inertial terms need be predicted and accounted for. Knowledge based control system needs be relied upon for good manoeuvring (12).

$$\dot q_I = \frac{pr\ (Iz - Ix) + (r2 - p2)\ Ixz}{Iy} \qquad (7)$$

$$\dot p_I = \frac{r\ (Iy = Iz) + (\dot r + qp)\ Ixz}{Ix} \qquad (8)$$

$$\dot r_I = \frac{q\ (Ix = Iy) + (\dot p = qr)\ Ixz}{Iz} \qquad (9)$$

VI. Conclusions

Large manoeuvrability and controllability in pitch is possible through canard and LEF. For pitch and roll control under stalled wing conditions, differentially all moving canard is necessitated. Substantial advantage of regaining directional stability from LEF deflection aims at cutting down the size of vertical fin thereby reducing the lateral static stability levels of highly swept wing fighters. Roll/yaw ratio can be maintained over larger ranges of flight envelope with the arrangement of twin fins and canard wing surfaces without anhedral/dihedral. Loss of directional stability and loss of damping-in-yaw need be related without lagging. Roll/yaw damping ratio plays significant role in deciding the boundaries of Dutch roll and spiral instabilities. Contribution to this damping ratio needs be relied upon from ventral fins.

Inherent stability of the aircraft depends upon the stability derivatives, which affect the frequency and damping of oscillations. Further the stability derivatives can be artificially influenced by phase lag arrangement between aircraft motion and control surface deflections. Control aerodynamic aims at meeting such requirements. Prediction of control aerodynamics in the presence of aerodynamic and inertia couplings for varied manoeuvre requirements, gets complicated. RSS is not important when canard is used, thereby substantial burden of generating artificial stability from control software can be releaved. Control aerodynamic synthesis under complicated motions need be relied upon through the flight testing.

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