AERODYNAMICS AIRWORTHINESS ASSESSMENT FOR COMBAT AIRCRAFT

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Abstract

Aircraft require airworthiness certification for the flight testing of prototypes. Airworthiness specifications and standards for various classes of aircraft are therefore laid down. Such specifications provide guide lines for designing the flying machines with adequate safety, acceptable flying qualities and handling characteristics. Advancements in technological concepts and increasing complexity in system design has placed a challenging demand on the description of specifications. Some aerodynamics airworthiness related aspects in relation to the state-of-the-art technology are discussed in this paper. Combat arena, manoeuvrability, load envelopes and handling characteristics of fighter planes are brought out.

Introduction

Combat role requirements are growing due to the increasing complexity of the war field sineriao. Combat environment is getting more and more hazardous and complex. Mission effectiveness lies in aircraft manoeuvrability, flight performance, flying qualities, weapon systems, avionics and electronic capability. Combat arena is dominated by the fighter role criterion, which are listed below :

airsuperiority	:	close-in dogfights
interception	:	stand-off target acquisition and kill capability
close air support	:	attack on columns of troops
interdiction	:	attack on troop bases
defence suppression	:	attack on battlefield defence systems
anti-armour	:	attack on columns of tanks
maritime	:	anti-ship

Airsuperiority dogfighter should possess agility and manoeuvrability at low-medium altitudes at transonic and low supersonic speeds. Turning rate Vs speed characteristics and Specific Excess Power (SEP) at transonic speeds dominate the performance of these aircraft[1,2,3]. High speed and larger climb rates are required for interception. Attack aircraft requires low speed tracking ability,terrian following capability and good speed for the evasion. Sometimes, the air-staff requirements call for a single aircraft which can meet the role of airsuperiority, interception and interdiction. Such aircraft are commonly refered to as Multi-Role Combat Aircraft (MRCA). Such aircraft are designed to provide best possible performance in each of the roles. Combat arena with various types of aircraft is brought out herein.

Manoeuvre capability is influenced by the values of achievable maximum lift coefficient, maximum attainable lift, trimmable lift, trimmable lift/drag values, longitudinal static stability margins, directional stability levels, angular rates, angular accelerations and transonic SEP. Variations in stability derivatives, angular rates and angular accelerations w.r.t angle of attack (alpha) and Mach number (M) are crucial. Design aspects in relation to manoeuvrability are herein discussed[2-6]. Three configurations namely:- aft-tail, tailless and canard are considered for comparative studies. Sizing, location and management of control surfaces is dealt. Flight and load envelopes, trade-offs due to structural and control surfaces limitation, etc., are discussed. Control surfaces schedules and deflection rates are discussed. Static margin of tailless configuration being crucial, the change in this margin due to Mach number and alpha, and margin management through flap schedules are described. Boundaries of angular rates and accelerations envelopes are signified. Influence of alpha and Mach number on stability derivatives, and allied problems (wing rock and nose slice, etc) are highlighted.

Aircraft configurational design characteristics and Flight Control System (FCS) aim at deriving maximum benefits of performance and manoeuvrability. In addition, aircraft are required to possess desirable flying qualities[7-11]. Military specifications towards such issues have drawn a greater attraction especially in context to unstable fighter planes. Unstable aircraft essentially require Active Control Technology (ACT) for manoeuvre and stabilization. Impact of ACT predomination is so high that the aircraft are configured towards ACT and such design concepts are referred to as control configured vehicle (CCV). Flying qualities specifications for military aircraft are described in MIL-F-8785C. There has been a great deal of proposals for exclusively specifying such qualities for unstable[8-11] aircraft. This paper brings out certain recent criterion for pitch, yaw and roll handling qualities. Stability and damping derivatives characterise the flying qualities[12]. Substantial burden of providing ride quality can be vested within the FCS[13-15]. Current FCS aim at synthesizing the artificial stabilisation and assist the damping of oscillations to the required values; even the

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levels of stability can be arranged. Trim management, stick dynamics, lateral-directional control in crosswind and Gust Load Alleviation (GLA), etc., are discussed in this paper. Favourable stick dynamics aim at relieving the pilot's work load. Several control laws are required to be followed for generating good flying qualities and comfortable stick dynamics[14-17]. Certain aspects in this regards are briefly discussed.

Combat Arena

Much of the combat success comes from the mission planning in a hostile terrian. Loittering with low trim drag at low-medium speeds at low altitudes is required for target acquisition. Jamming the ground borne defence systems, use of electronic counter measures, analysis of electro-magnetic spectrum, evading hostile defences, maintaining electro-magnetic silence and lo-lo-lo mission profiles are some of the foremost combat effectiveness measures. Figure-1 generically shows the combat arena for different types of aircraft with their weights at combat. Larger degradation in envelopes results when weights are higher. Therefore, a lone standard of weight, i.e., weight at combat (normally referred to as the weight with 50% internal fuel and two/four close combat missiles) is considered in this study of aerodynamic airworthiness assessment. For the designated role of the aircraft, airworthiness specifications provide guide lines to the designers to ensure that their designs are adequate for mission performance and flight safety.

Tracking capability at medium speeds for ground attack and larger firing opportunity envelope for air-to-air combat are needed. Tracking capability is dominated by Direct Lift Control (DLC) and Direct Side Force Control (DSFC) characteristics. In cases, sudden requirement of air-to-air combat arises, aircraft pull-up capability (to act as airsuperiority force multiplier) becomes imparative. Wing loading is crucial; to pull from a nose down attitude, a high wing loaded aircraft will have to be pulled to higher alphas than a low wing loaded aircraft. Air combat potential is characterized by the turning rate, load factor, SEP, flight envelope size, angular rates and angular accelerations. Low wing loading is advantageous for roll and pitch initiation[1,2,3]. In addition, sustained and instantaneous turns at low speeds are better. However, these advantages get degraded at higher speeds because of the wave drag of larger wing volume of a lowly wing loaded aircraft. In the air-to-air performance, shorter turning is possible by increasing the pitching moment at a constant load factor. This requires an additional flight mode capability. Advantages of DLC and DSFC also lie in air-to-air combat mode for drifting the aircraft flight path without altering the turn rate.

Figure-2 shows various limitations of the load factor envelopes[2,3]. Lift coefficient limitations, thrust limits, structural load limitations, aeroelastic phenomenon and gust loads decide the envelope boundaries. Boundary of the maximum lift gets affected by the aerodynamic phenomenons like wing rock, nose slice, spin departures and buffet. The negative 'g' supersonic boundary gets influenced by the V_H (maximum continuous level speed) definition. If the V_H is considered with reheat engagement, the gust loads largely influence the negative 'g' boundary. The V_H definition for shaping the negative 'g' boundary is crucial from the structural considerations.

Turning rate Vs speed characteristics are typically shown in Figure-3. Increasing the turning rate at lower speeds demands larger thrust. Turning rate gets limited by the maximum lift boundaries. Decoupling of turn rate from turn radius results in added manoeuvre capability, however, this requires an additional flight control mode. Larger number of flight control modes[11] burden the FCS. Power-energy management tactics are useful for building up of the instantaneous turn rates.

The use of ACT in fighter planes has become indespensable. ACT provides several benefits which enhance the air combat potential. Some of these merits are as following :

(a) drag modulated flight
(b) new and useful flight modes - independent six degrees of freedom flight
(c) load alleviation, manoeuvre load control (MLC), turbulence response modulation and GLA
(d) carefree manoeuvring and honesty to aerodynamically disgranted design concepts
(e) synthesis of artifical stability
(f) effective handling of control laws complexity and system integration for overall improvement
(g) reduction in pilot's work load, flight automation, improved flight handling characteristics, good flying qualities and ride comfort
(h) structural mode stability (eg. flexibility suppression, active flutter control etc.)
(i) reduction in control system sensitivity.

Fighter Aircraft Manoeuvrability

Air combat effectiveness is strongly influenced by the fighter aircraft manoeuvrability[3,4,5]. For a given thrust (engine), the manoeuvre performance depends upon the lift/drag (*L/D*) ratio, maximum lift, stability and control characteristics. Lift/drag ratio and lift can be significantly enhanced through the use of Leading Edge Flaps (LEFs) and Trailing Edge Flaps (TEFs) at subsonic speeds. These flaps at supersonic speeds result in larger wave drag and therefore, their utility is limited to subsonic speeds. Figs. 4a & 4b show the typical flaps

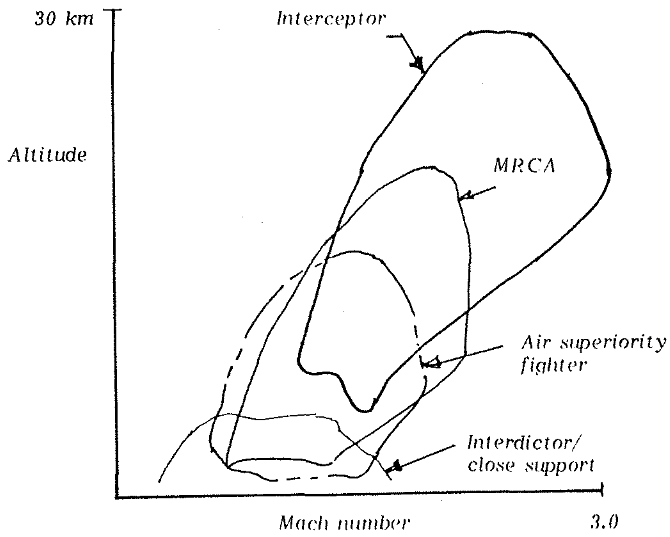


Fig.1 Typical combat envelopes

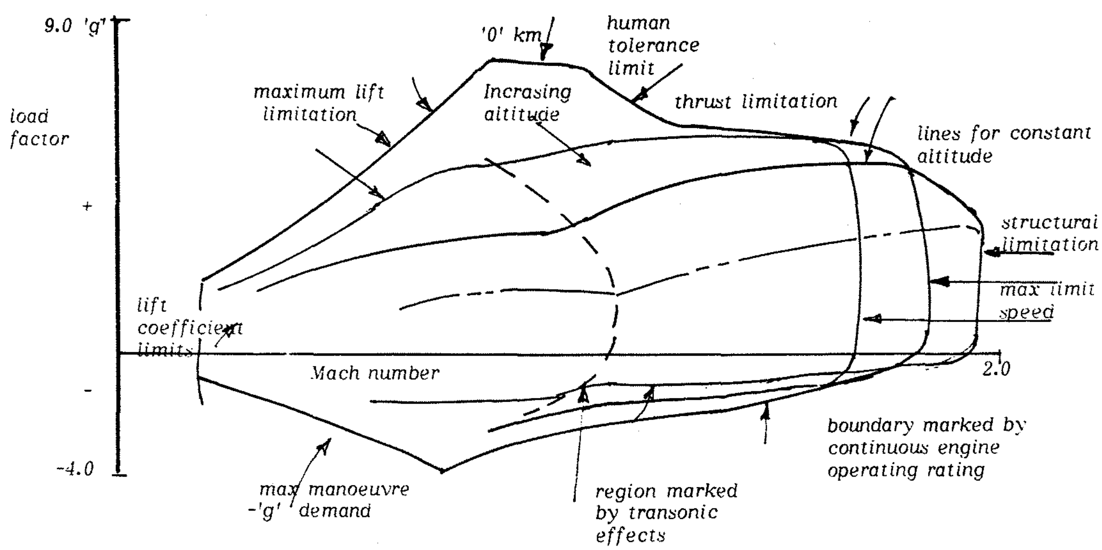


Fig.2 Typical load factor plots

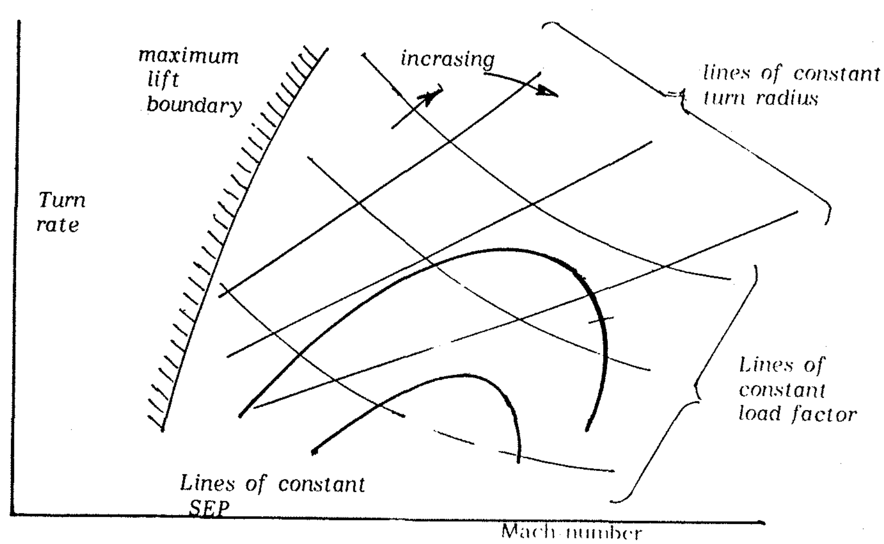


Fig.3 Turning performance criterion

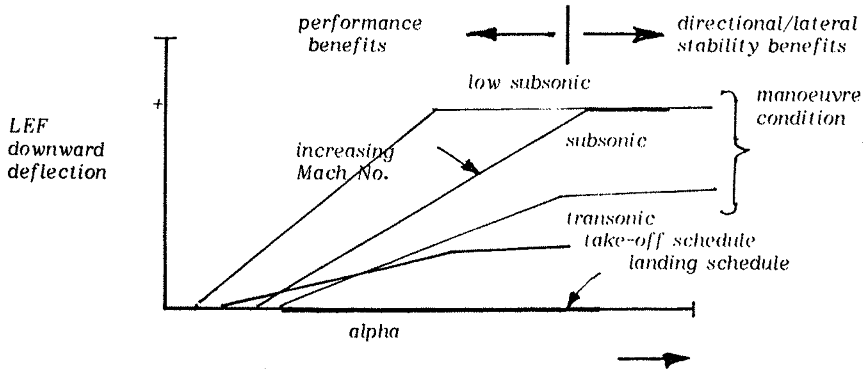
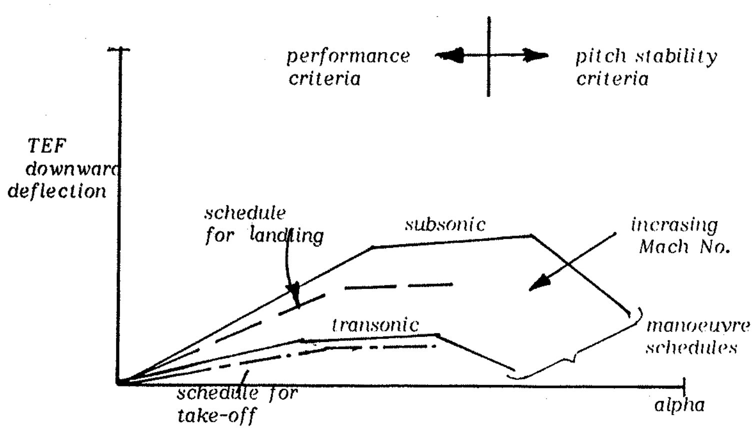


Fig. 4a Typical LEF Schedules



Fib. 4b TEF schedule for performance and stability

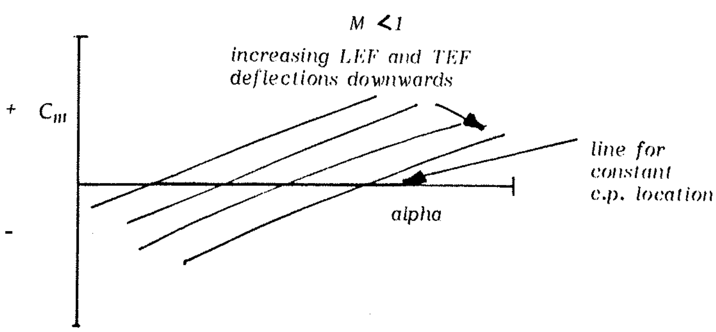


Fig.5 LEF and TEF influence on pitch moment of unstable aircraft

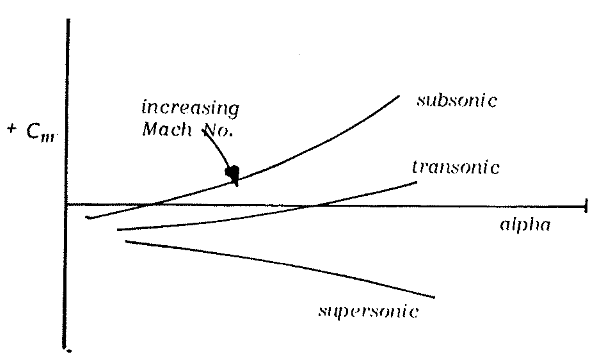


Fig.6 Typical variations in pitch stability

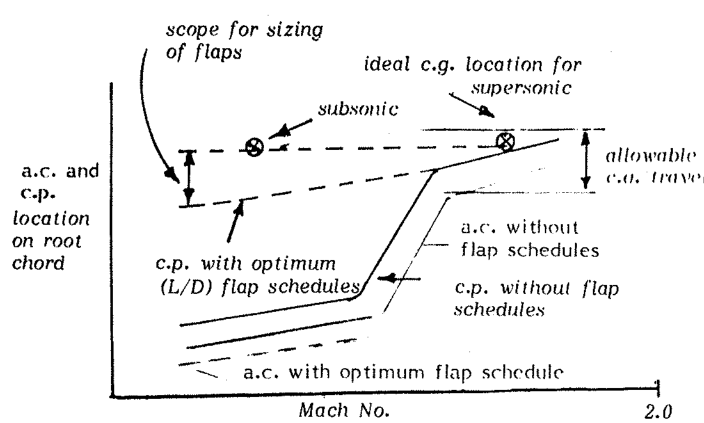


Fig.7 Center of pressure control for cruise flight conditions

schedules for various flight conditions[2,4,5]. At higher alphas, the stability benefits outmerit the performance gains. About 35-40% of (L/D) gain are reported through the use of these flaps[4]. The LEF schedule for take-off aims at higher lift merits of a cambered profile, whereas, undeflected LEF for landing aims at deriving the benefits of vortex lift which is associated with larger drag. Influence of flaps deflections on the pitching moment coefficient (C_m) at subsonic speeds for an unstable configuration is shown in Figure 5. With the downward deflection of these flaps, the location of center of pressure (c.p) can be held constant with increasing variation in alpha. At the transonic and supersonic speeds, the pitching moment variation with alpha gets significantly[15] altered (Figure 6). This is because the c.p. shifts rearwards with the increasing Mach number. Since the flap schedules are meant for subsonic and transonic speeds, larger instability in pitch can be maintained at such speeds. Larger pitch instability, i.e., $\left(+\ C_{m_\alpha}\right)$ results in larger pitch rates (q). At supersonic speeds, low drag profile is possible for cruise conditions alone. This is possible by conciding the c.g. with the supersonic c.p. This results in zero TEF trim–drag. Wing planforms are usually optimised for cruise flight conditions. This results in aerodynamic center (a.c.) which has a finite zero lift pitching moment coefficient $(-\ C_{m_0})$. Conciding of c.p. and c.g. for supersonic conditions results in the location of a.c., slightly ahead of c.g. Thus, at supersonic speeds, marginal instability in pitch is feasible. Larger optimal warp results in loss in transonic horizontal acceleration, thereby, the optimal warp is usually limited. This arrangement of c.p. and c.g. at supersonic speeds reults in larger pitch instabilities at subsonic speeds. Fig.7 shows the modality of maintaining c.p. control over larger Mach number ranges. With the flaps schedules for optimum (L/D) at subsonic cruise, the c.p. shifts rearwards and a.c. shifts forwards. Flaps sizing to maintain the c.p. control is highlighted in this figure.

There are basically three configurations to be considered for fighter role application, namely : (1) aft-tail, (2) tailless and (3) canard. The choice of aft-tail configuration gets limited due to the strong downwash generated by the wing on the tail which results in sluggish pitch response. Thus, the tentative competitors remain tailless and canard configurations. Certain aspects in relation to these two types of configurations are brought out below.

A tailless configuration uses TEF as elevons for roll and pitch control, as a result the TEF in this configuration cannot be used for L/D benefits. Moreover, upward elevon movement generates reflex camber, which is drag penalising and spoils the lift. Figure 8 shows the typical pitching moment characteristics of an unstable tailless configuration at subsonic speeds without the LEF deployments. Larger values of instability in pitch result in larger (L/D)-trim capability. A tailless configuration therefore, depends upon larger levels of relaxed static stability (RSS) for larger manoeuvre margins. However, larger RSS results in larger untrimmable lift region. The lower boundary of C_{m_α} requires shaping with regards to pitch down acceleration $(-\ \dot{q})$ criteria. This is possible by limiting the RSS. Though LEF can be used to generate negative C_m, the LEF failure mode requires due considerations. In such a case, combat effectiveness of the aircraft will have to be quantified. A tailless configuration is marked by the absence of DLC flight characteristics since, the independent control of lift (without effecting the pitching moment) is not feasible with the control surfaces located on the wings alone. Though there are several shortcomings in a tailless configuration, some designers still prefer such configurations in favour of lighter weight criteria and simplicity of controls.

Canard provides larger pitching and trimmable moments. Thus, maximum L/D benefits can be best explored in a canard[1] configuration (Figure 9). Canard pitch criterion is shown for an unstable configuration at subsonic speeds in the absence of flaps deflections (Figure 10). Canard can be aligned with relative air flow direction to provide control even under the stalled wing condition. In addition, DLC is possible through canard surfaces. Canard importance has been much realised, its use is considered essential for agility.

Pitch, roll and yaw rates and angular accelerations, largely influence the ability to acquire the target. MIL-F-8785C lists out the acceptable roll rates (p) for various conditions of flight[7]. Current combat simulation[3] studies have shown the need to have the roll rates of around 5 radians/sec (R/S) at 1 'g' for subsonic conditions. Figure 11 shows roll rates w.r.t normal accelerations (n_z) which are to be committed for good fighter performance. Roll rates get influenced by alpha, altitude of flying and damping. Design of elevons/ailerons are determined to provide required roll performance. Elevon/aileron aeroelastic efficiencies get fast degraded with increasing Mach numbers. Differentially movable LEFs for roll assitance are of negligible merits. Alternatively, spoilers for roll control can be envisaged. Canard has higher aeroelastic efficiencies in comparison to elevons/ailerons. Differentially movable canard aims at roll assistance[1,3]. Typical current standards of pitch and roll angular accelerations are shown in Figure 12. Roll accelerations are limited by the roll control surface deflection rates due to actuator load limitations. Pitch down accelerations at high alphas are limited by C_m Vs alpha values. Aeroelastic ineffeciencies of control surfaces also limit these envelopes. Current designs aim at the use of canards and thrust vectoring techniques to enlarge these envelopes. Yaw rate (r) of 3.5 R/S is considered corresponding to a spin case as per MIL-A-008861. Instances have occurred where spin departure windows have appeared at lower yaw rates at medium alpha conditions[6]. Spin departure characteristics are strongly linked to the directional stability characteristics. Configurational design efforts aim at providing favourable directional stability under the stalled conditions of flight. This is because during spining, the recovery from spin can be made effective through simple forward stick movement. Complexity of controls utility (stick dynamics) under adversities of flight conditions, need to be addressed. Yaw accelerations ($\dot{r}$) of around 8 R/S^2 at the lower values of normal accelerations for subsonic Mach numbers are considered to be adequate for fighters[12]. Values of linear lateral acceleration (n_y) of around 2.0 'g' at subsonic speeds are considered favourable. Figure 13 shows a typical sineriao of yaw angular accelerations[12-15].

Figure 14 shows ideal relationship between the rates/maximum rates Vs angular accelerations/maximum angular accelerations in respect of pitch, roll and yaw. Realistic boundaries are however different because of several limiting factors, e.g. actuator loads and bandwidths, control surface load limitations, torsion, wing root bending moment, etc., which strongly influence the realisable envelopes. Severity of such penality is larger for a tailless configuration, where mixed rates (pitch & roll) demands have to be met through single control surface, i.e., elevons. Torsional effects get enlarged due to change in local chordwise c.p. locations with alpha variations. Current technique of MLC aim at controlling c.p. locations so as to restrict the torsional loads. Substantial load alleviation is realisable through MLC flight mode. Control surfaces deflection rates of current fighter planes are of the orders shown in Table-1[1-3,6,12].

Table 1. Control surfaces deflection standards

	Speed	$M < 1$	$M > 1$
Elevon deflections	rates	$\pm\ 2\ R/S$	$\pm\ 1.5\ R/S$
	accelerations	$\pm\ 35\ R/S^2$	$\pm\ 10\ R/S^2$
Canard deflactions	rates	$\pm\ 1.5\ R/S$	$\pm\ 1.0\ R/S$
	accelerations	$\pm\ 25\ R/S^2$	$\pm\ 5\ R/S^2$
Rudder deflections	rates	$\pm\ 1.0\ R/S$	$\pm\ .75\ R/S$
	accelerations	$\pm\ 15\ R/S^2$	$\pm\ 5\ R/S^2$

Flying Qualities for Statically Stable Aircraft

Aircraft configurational design and control system concepts aim at deriving maximum benefits of performance (*L/D*) and manoeuvrability ($p, \dot{p}, q, \dot{q}, r, \dot{r}$) over larger alpha and Mach number ranges; thereby larger sustained and instantaneous turn rates. In addition, aircraft are required to possess desirable flying qualities[7-15]. These relate to airplane dynamic characteristics. Quantification of these qualities relate to the ease of operation, comfort, good ride and pilot's workload. Flying qualities appraisal process is well describable on a Cooper-Harper Scale. Following are some of the foremost flying qualities.

(a) flight-path stability at low speeds (pitch attitude variations Vs speed changes, i.e., pitch attitude changes in relation to control inputs)
(b) pitch oscillations (phugoid and short-period)
(c) roll rate oscillations, bank angle oscillations, roll spiral characteristics, roll control in sideslip, dutch roll, spiral instability and sideslip excursion
(d) lateral - directional control in crosswind, response to gust and turbulence
(e) trim management (rate of trim operation, trim reversability, trim limits, etc)
(f) control effectiveness during various phases of flight, stall speeds, maximum limit speeds, flight-path departure modes, spin criterion and spin recovery dynamics description
(g) stick dynamics (stick forces during various phases of flight, stick travel, aircraft handlability at manoeuvre boundaries, stick input response, stick snatch, stick force gradient, stick force variation with rapid speed variations, etc).

Flying qualities airworthiness specifications for military aircraft are laid down in MIL-F-8785C. Subject MIL however does not make any specific reference to aircraft with statically unstable airframes. In the recent past, there has been a great deal of effort in quantifying such qualities for the unstable aircraft[8-11]. Configurational design characteristics and control systems are intended to meet such specifications and standards. Stability and control derivatives largely influence the control system design. Though the control systems can be designed to provide aerodynamic honesty and take care of nonlinearities, the nature of stability derivatives play crucial role during manoeuvring at the edges of the flight envelopes. Table-2 lists the important stability derivatives. Manoeuvre boundaries can be best described through a common trade-off between stability, thrust margins, maximum lift and aeroelastic phenomenon. However, stability margins at the edges of the flight envelopes result in carefree manoeuvring without burdening the FCS[17].

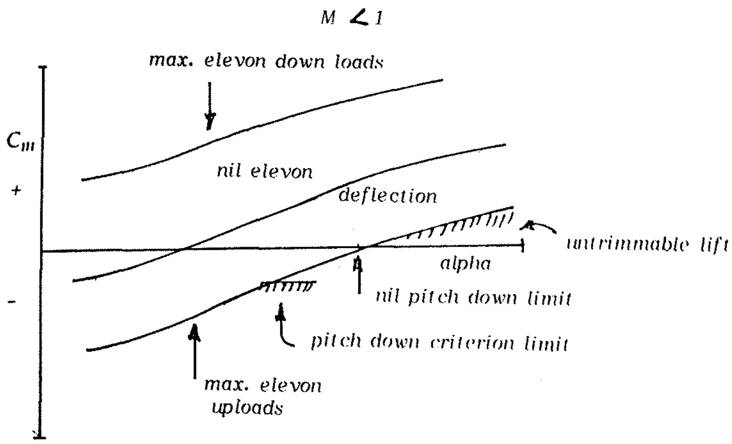


Fig.8 Tailless configuration pitch control

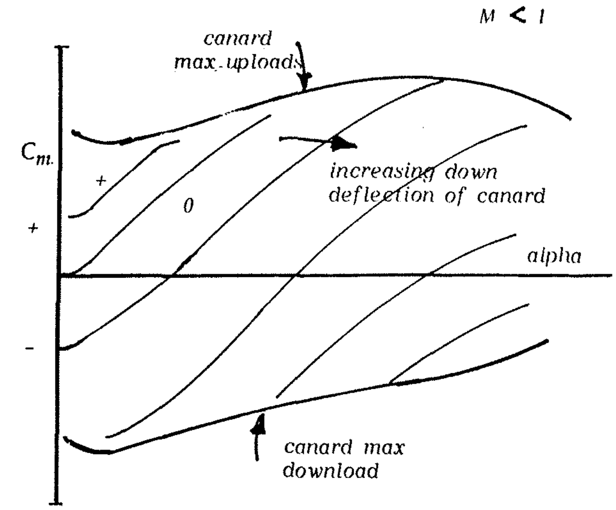


Fig.10 Canard configuration pitch criterion

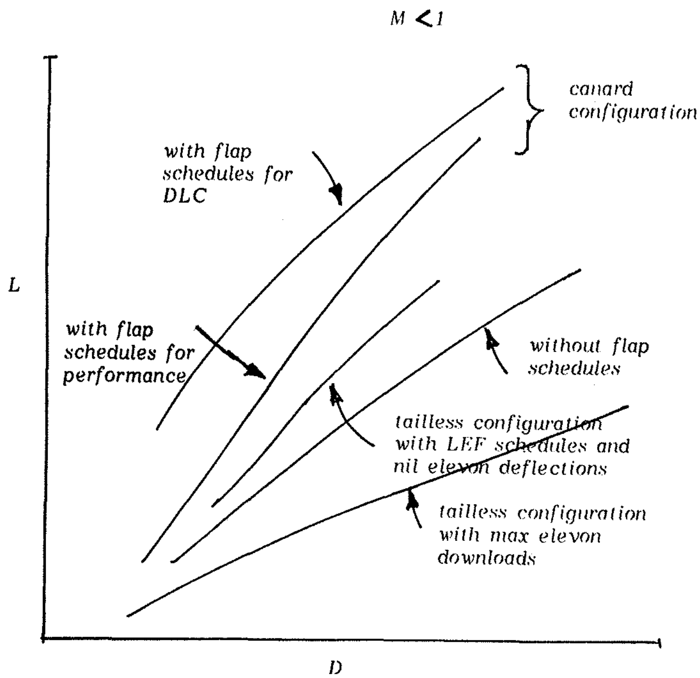


Fig.9 Canard outmerits the tailless configuration

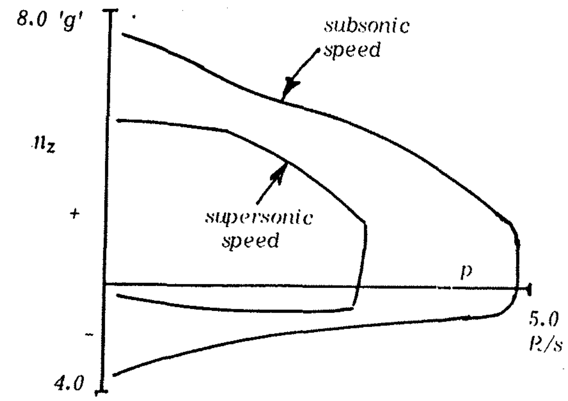


Fig.11 Typical roll rate envelope for weight at combat

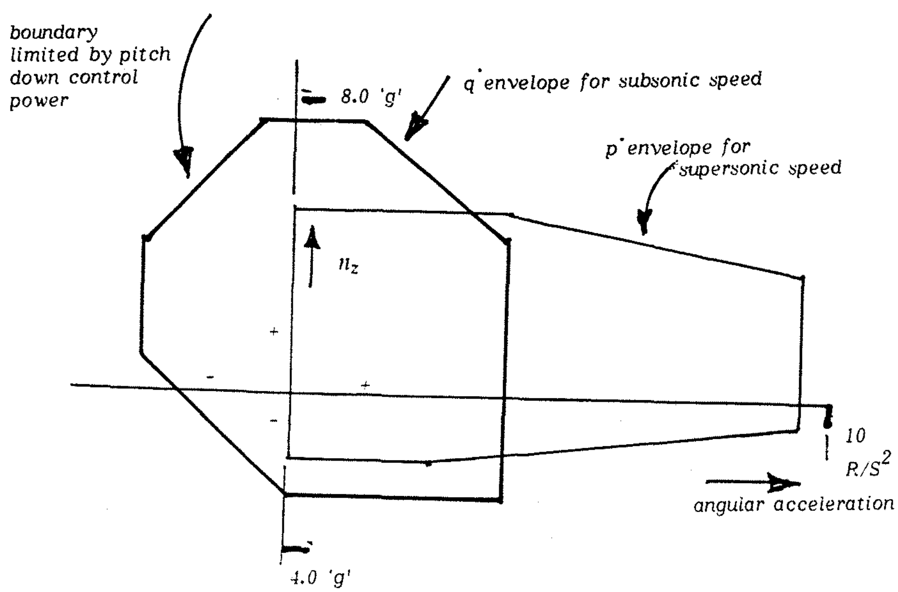


Fig.12 Typical angular acceleration envelope for weight at combat

Table 2. Stability derivatives for motion criterion

Pitch derivatives	Yaw derivatives	Roll derivatives
$-C_{m_\alpha}$	$+C_{n_\beta}$	$-C_{l_\beta}$
$-(C_{m_q}+C_{m_{\dot\alpha}})$	$-C_{n_r}$	$-C_{l_p}$
	$-C_{n_p}$	$+C_{l_r}$

System degraded performance (system component failure/trim control malfunctioning/secondary control surfaces failure, etc) results in degraded flight performances. Therefore, levels of flying qualities are specified (as below) in relation to the ability to complete the mission.

Level I Essential for mission effectiveness

Level II Adequate for mission, but pilot's workload is increased/mission effectiveness is affected.

Level III Inadequate mission effectiveness/larger pilot's workload.

Levels of flying qualities are linked to the categories of flight. Following are the three categories of flight.

Category 'A' (Non-terminal flight phase)

Flight requiring rapid manoeuvring (e.g. combat), precision tracking (e.g. ground attack) and precise flight-path control (e.g. close formation flying).

Category 'B' (Non-terminal flight phase)

Flight requiring gradual manoeuvring, lesser precision tracking ; although accurate flight-path control may be required (e.g. climb/decent, etc.)

Category 'C' (terminal flight phase)

Flight requiring gradual manoeuvring and precise flight-path control (e.g. landing).

Aspects related to flying qualities, mainly in respect of statically stable aircraft, are brought out herein. Pitch, roll and yaw handling are described.

Pitch handling

Flight-path stability, phugoid and short-period oscillations characterise the pitch handling qualities (hqs). Flight-path stability at low speeds degrades because of reduction in inertia in the forward flight. Change in pitch attitude with change in forward speed is crucial. The levels of this gradient signify the pitching accelerations due to pitch control application.

The input-output pitch response can be studied on a Laplace (s) plane. Equation for pitch response can be written using Laplace transforms of input and output equations, as shown in equation (1). The numerator terms in this equation $\left(T_{\theta_1}^{-1} \;\&\; T_{\theta_2}^{-1}\right)$ are called the 'zeros' and the denominator terms are called 'poles' of the transfer function. For a pulse input, the initial response of motion is that of the short-period oscillations which may gradually decay into long period oscillations (phugoid). The values of natural frequencies (ω_n) and those of the dampings (ζ) decide the characteristics of these motions. Roots of the s-algebriac equations can be written as equations (2) - (4).

$$\frac{\text{Pitch attitude }(\theta)}{\text{pitch control force input }(F_s)} \approx \frac{(s+T_{\theta_1}^{-1})\;(s+T_{\theta_2}^{-1})}{(s^2+2\,\zeta_{SP}\;\omega_{n_{SP}}\,s+\omega_{n_{SP}}^2)\;(s^2+2\,\zeta_p\;\omega_{n_p}\,s+\omega_{n_p}^2)} \quad \ldots (1)$$

$$s_{1,2} = -\zeta\,\omega_n \pm i\,\omega_n\sqrt{1-\zeta^2} \quad \ldots (2)$$

or

$$s_{1,2} = -\sigma \pm i\,\omega \quad \ldots (3)$$

or

$$s_{1,2} = -T_R^{-1} \pm i\,\omega \quad \ldots (4)$$

Where

σ = the real part, an index of relative damping, it is reciprocal of response time constant (T_R)

ω = damped natural frequency of the system

Figure 15 shows how the pitch oscillations get influenced by the aerodynamic characteristics of the aircraft. Phugoid are smaller frequency oscillations which are affected by the lift and drag characteristics, i.e., C_{L_α} & C_{d_α}. Aircraft are generally poorly damped in phugoid. A nil value of ζ_p (damping in phugoid) corresponds to level II of flying qualities. Frequency of short-period oscillations ω_{SP} depends upon the value of natural frequency ($\omega_{n_{SP}}$) and damping (ζ_{SP}) in the short-period mode. Static stability increases the natural frequency, and the pitch damping derivative, i.e., $-(C_{m_q}+C_{m_{\dot\alpha}})$ provides damping. The value of $\zeta_{SP} < 1$ is considered adequate to provide oscillations in pitch which are comfortable. Exact specification of damping depends upon the system natural frequency[7]. Natural frequency in relation to load factor and aircraft incidence is described for various levels of flying qualities in ref.7. Values of natural frequency are also found specified in the following way[7-12].

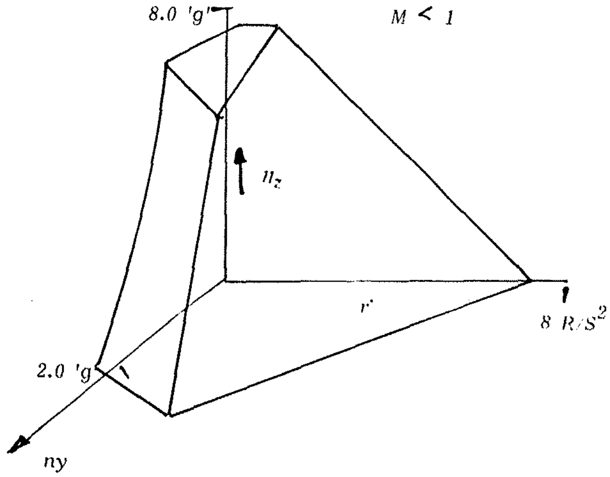


Fig.13 Typical yaw acceleration plots for weight at combat

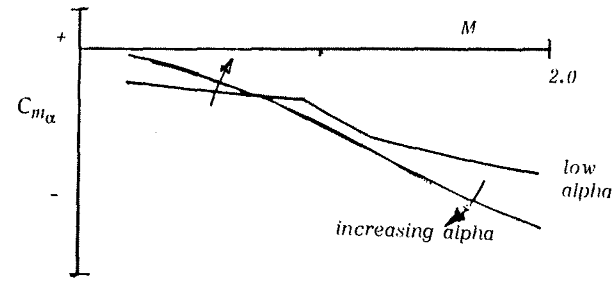


Fig.16(a) Typical static stability variations

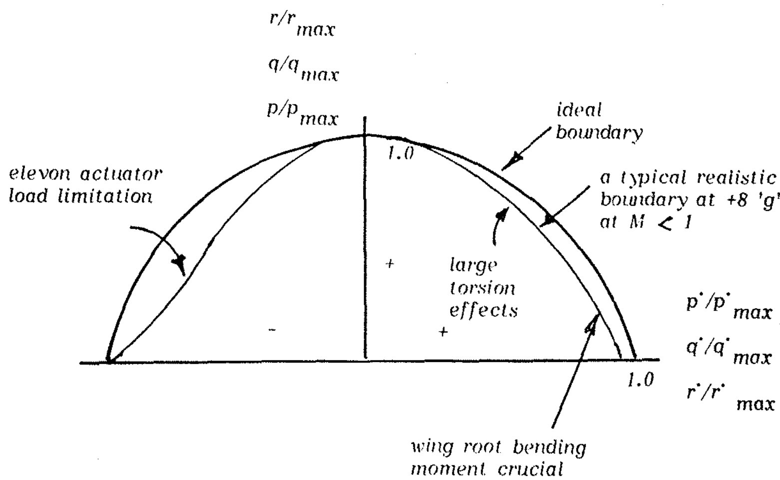


Fig.14 Angular rates and accelerations

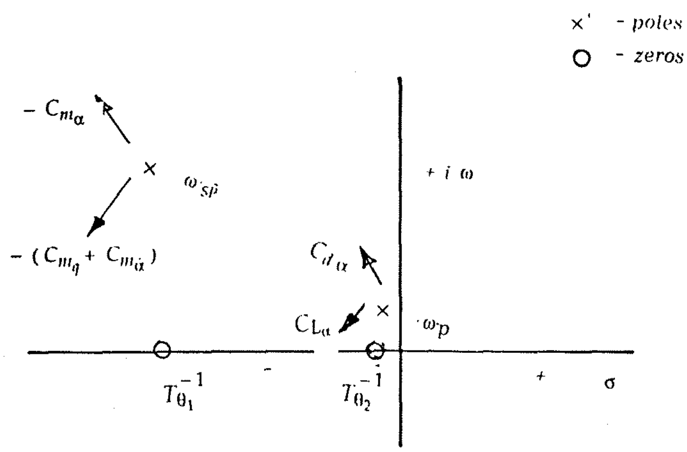


Fig.15 Short period and phugoid oscillations

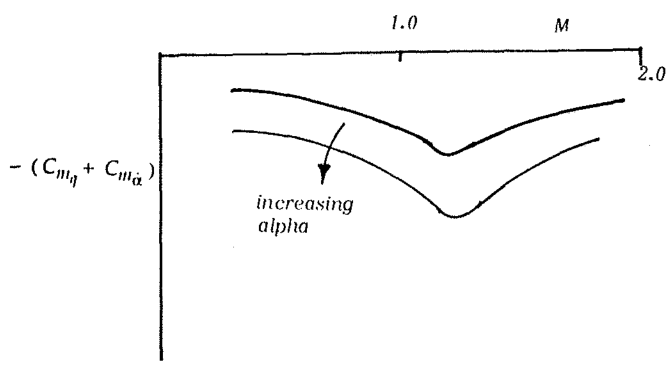


Fig.16(b) Damping derivative variations

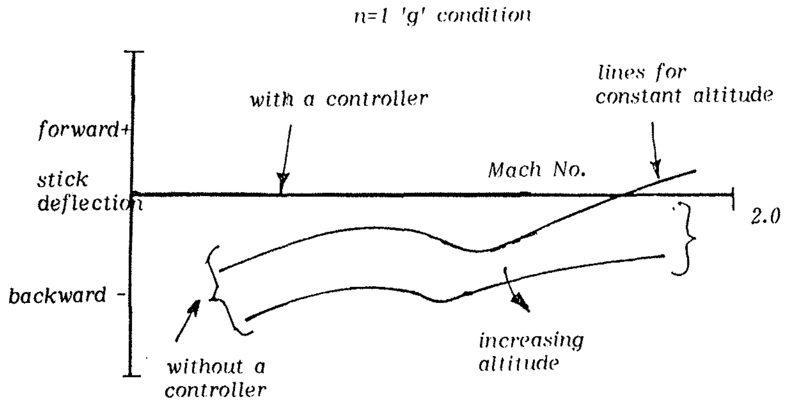


Fig.17 Stick motion criteria for a stable aircraft

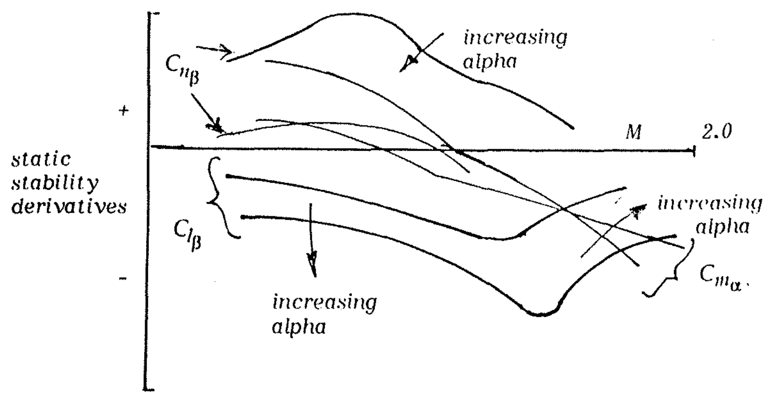


Fig.18 A typical static stability derivative variations

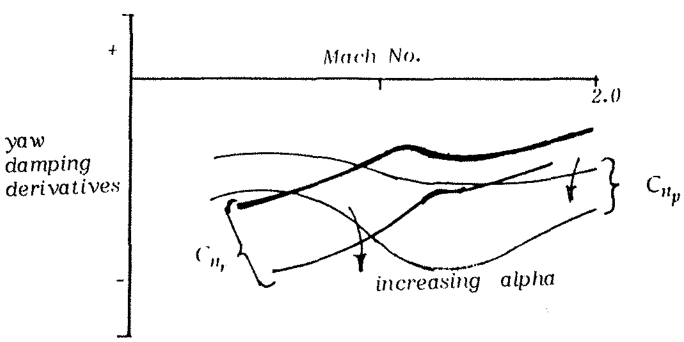


Fig.19(a) Yaw damping variations

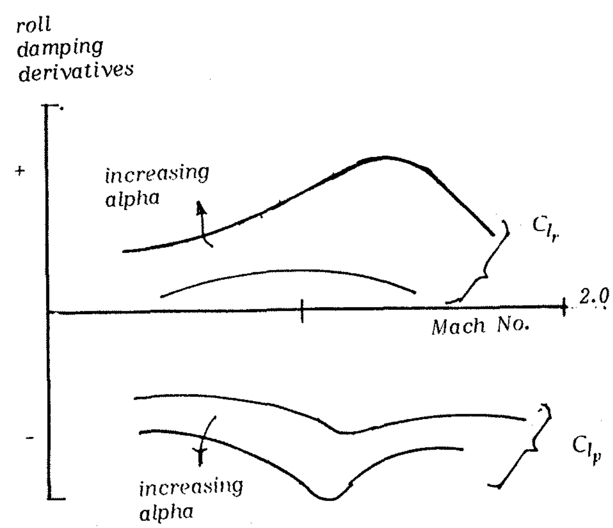


Fig.19(b) Roll damping variations

$\omega_{n_{SP}} \geq K1 \; T_{\theta_1}^{-1}$ for landing, take–off and cruise .. (5)

where $K1 < 1$

$$\omega_{n_{SP}} \approx K2 \sqrt{\frac{n}{\alpha}} + K3 \quad ...(6)$$

manoeuvre

where K2 & K3 are

specfied values and n is the load factor

Damping can also be synthesized by moving the pitch control surface in a phase lag relation to the aircraft motion. Current FCS aim at meeting the specified levels of damping in pitch. This is essential for an unstable aircraft where natural frequency of configuration does not exist. However, during certain flight modes, unfavourable coupling of control inputs and control surface activity can contaminate an intended purified response e.g. excessive tracking in the presence of turbulence can fall within certain bandwidths which could threaten the stability of aircraft. Such bandwidths have to be identified.

Pitch stability derivatives get influenced by the alpha and Mach number variations[12-15]. Figures 16 (a & b) show the pitch derivatives variations for a stable configuration. Since the stability derivatives and inertia in forward flight vary with flight conditions, the input-output flight characteristics become largely nonlinear. Pilot's workload on stick handling can be relieved through the benefits of ACT. Mechanically, the stick force is dependent upon the load factor, alpha and the altitude of flying. If the stick inputs are linked to the load factor demands alone, the resulting stick response will be independent of the attitude of flying, altitude and Mach number (Figure 17). However in this case, aircraft attitude are required to be known as a motion cue. This is because of the delinking of the stick motion from the aircraft attitude condition.

Control laws aiming at acceptable hqs need to be envisaged; these require crucial airworthiness assessment. System failure transients and degraded modes need to be addressed in terms of response characteristics. Actuating systems rate and acceleration limitations in the critical load cases and its impact on pitch oscillations needs evaluation. The MIL-A-00861 brings out the flight load criticalities.

Roll handling

Roll performance has been emphasized in the recent past; 360 deg/sec roll rates are required at 1 'g' condition at subsonic speeds and rapid rolls at higher 'g' values are of importance to combat. Lateral control sensitivity in relation to roll time constant is important. Roll acceleration and roll damping determine the bank angle response characteristics. Initial roll accelerations which are linearly varying with command are favourable. Rate shaping is possible through forward loop integration. Such gains are useful for quickening the motion in the regions of characteristically sluggish response. Cancellation of high levels of initial roll acceleration by feedback and forward-path integration aim at good rolling characteristics. Roll stability derivatives vary with flight conditions. Provisioning of constant roll rate to stick aims at favourable stick dynamics and reduces the pilot's work load.

Rolling the aircraft about the wind axis results in oscillatory pitch rate (pitch rate excursion), but the load factor remains constant. In contrast, rolling about body axis produces zero pitch rate, but the normal acceleration is oscillatory (load factor excursion). Conical motion of rolling around the wind axis reduces the sideslip, but produces large amount of pitching moment at high angles of attack. This pitch moment is proportional to the square of the roll rate and is sine of twice the alpha. Advantage of blending pitch rate with normal acceleration can be taken to provide specified roll characteristics[16]. It is possible to compliment the wind axis roll if the error signal were of load factor, and the body axis roll can be complimented if the error signal were of the pitch rate. Load factor excursion and pitch rate excursions during 360 deg roll can be substantially improved by using the mix of the adjusted relative gains of these two components. However, higher 'g' rolls necessitate the rolling of aircraft around wind axis so as to avoid sideslip. Control laws are aimed to derive such benefits from the aileron-rudder interconnects. At higher alphas, such gains need to be varied to avoid pitch overshoots. These gains are also required to be linked to the roll rates, since roll rates result in the inertial pitch accelerations.

During the roll pull-outs, initial roll load factor will be at values between 0.8 times the symmetric limit load factor[7] and 1.0. In the case of a tailless configuration, the pitch and roll demands require crucial sharing for a roll pull-out. Control laws are envisaged for such purposes. Aerial delivery roll rates are specified upto certain bank angles. Take-off and landing approach roll rates are specified upto 90 degree angle of bank. Roll response to aileron input during aerial delivery or during take-off/landing is specified much slower compared to the roll requirements for combat engagements[7].

Lateral-directional flying qualities

Dutch roll, spiral mode, roll rate oscillations, bank angle oscillations, sideslip excursion are some of the foremost lateral-directional flying characteristics. Dutch roll mode can be excited using a pulse input to the rudder (δ_r). Directional stability and damping derivatives play a crucial role in the occurance of modes, (Table 2). Yawing moment coefficient C_n due to sideslip (β), i.e., $C_{n\beta}$ is prospin. In contrast, rolling moment coefficient (C_l) due to sideslip, i.e., C_{l_β}, is antispin. Dutch roll may turn into spiral mode if the product of prospin terms is higher than that of antispin terms, equation (7). However, this may not happen unless certain amount of bank angle (ϕ) is developed. Damping in dutch roll comes from C_{n_p} and damping in spiral mode is provided by C_{l_p}. These damping terms affect the rapidness of mode occurance.

Dutch roll oscillations are uncomfortable motions which require adequate damping. In contrast, spiral mode is predictable and correctable. Thus, the natural frequency (ω_{n_d}) and damping (ζ_d) in dutch roll are curical. Directional stability derivative influences this natural frequency, and yaw damping derivatives influence the dutch roll. Values of ω_{n_d} and ζ_d in relation to product of $\omega_{n_d}^2$ with ratio of bank angle ϕ to β, i.e., $\omega_{n_d}^2 \mid \phi/\beta \mid$, are crucial and are specified[7]. Aircraft configurational designs aim at meeting with such specifications[12-15]. In addition, FCS can be dedicated to meet any discrepencies. The stability derivatives largely vary with alpha and Mach number; Figures 18, 19 (a & b) show the typical variations. Positive C_{l_r} (Figure 19 b) is in favour of cancellation of negative signs of C_{l_β} & C_{n_r} in the presence of positive C_{n_β} in equation (7). Nonlinear variations in these derivatives result in the rudder and aileron control forces nonlinearities. Current control system designs aim at providing control force linearities and smoothen the motion for good ride through pole-zero assignment techniques[16].

$$\left\{\begin{array}{c} (-C_{n_r})\,(-C_{l_\beta}) > (+C_{n_\beta})\,(+C_{l_r}) \\ \text{dutch roll criteria} \\ (+C_{n_\beta}\,(+C_{l_r}) > (-C_{n_r})\,(-C_{l_\beta}) \\ \text{spiral mode criteria} \end{array}\right. \quad \ldots(7)$$

Roll rate oscillations, bank angle oscillations and sideslip excursion can be generated through a step aileron input. Values of these parameters are laid towards airworthiness aspects. Transfer function for a roll-sideslip coupling for a step aileron input (δa) can be written in the form of equation (8). Figure 20 shows the poles and zeros for this equation. The bank angle oscillations are considered as aileron inputs, thereby, the zeros shift to the frequency domain. There could be several ways in which the bank angle could vary. This depends upon the values of the roll stability and damping derivatives, thereby resulting in several roll-sideslip coupling motions[7]. A left top zero corresponds to the dutch occuring in a larger sideslip motion. A left lower zero indicates dutch in a slower sideslip. A zero towards right top signifies the presence of dutch without sideslip and a zero towards lower right corresponds to a dutch with sideslip in a direction opposite to the bank. Poles of dutch roll oscillation (ζ_d, ω_d), the poles of sideslip (l_β) and the poles of the roll mode (l_p) are shown in the figure.

$$\frac{\phi}{\delta a} \approx \frac{s^2 + 2\,\zeta_\phi\,\omega_{n_\phi}\,s + \omega_{n_\phi}^2}{(s - l_p)\,(s - l_\beta)\,(s^2 + 2\,\zeta_d\,\omega_{n_d}\,s + \omega_{n_d}^2)} \quad .(8)$$

Spin

Advance fighter aircraft are prohibited towards spin departures, however prototypes during developmental stages can exhibit spin. Therefore, such a manoeuvre requires ellaborations. Moreover, advance fighter trainer aircraft are especially given larger spin considerations, since such manoeuvres are intentionally performed by relatively inexperienced crews. Spin entry speeds and associated critical parameters are specified for the load assessment.

Spin departure yaw velocities depend upon the engine locations. Spin condition (whether steep or flat, whether erect or inverted) and the maximum allowable angular velocities and load factor combinations are laid for the purpose of estimation of limit loads. For example, a flat erect or inverted spin is considered with $q = 0$ and $n \pm 1$ with some specified values of p & r.

Aircraft Control in Gust

Cross-winds, gusts, wind shears and turbulence levels are specified for the purpose of designing aircraft for reasons such as response, ride comfort, controlability, etc. Head winds or tail winds and wind shears in the proximity of the runways are crucial for take-off and landing. Figure 21 shows, take-off and unstick speeds variations with variations in temperatures, pressures and static margins. These envelopes are largely influenced by the horizontal gust velocities and wind shears, and thus require crucial assessments. MLC are some recent measures which aim at enhancing the performance capabilities under the adversities of the flight conditions. Wind shears are crucial to phugoid stability[18], Figure 22.

Lateral-directional control in the crosswind is influenced by the stability derivatives (C_{n_β}, C_{l_β}) and the control derivatives ($C_{n_{\delta r}}$, $C_{l_{\delta a}}$). The yawing and rolling control moments play crucial role in determining the aircraft handling characteristics in the presence of crosswinds. As per MIL-A-008861, a 90 deg crosswind of 50 ft/sec is required to be handled during landing and take-off. Figure 23 shows the sideslip control under a constant crosswind. Increasing altitude has the effect of increasing gust impact. Larger rudder control provides larger sideslip handling thereby lower landing speeds are possible in the gust presence. After allowing a certain margin for yaw authority, the take-off/landing speeds can be described. Configuration with elevons alone authority (pitch and roll) are crucial for the lateral

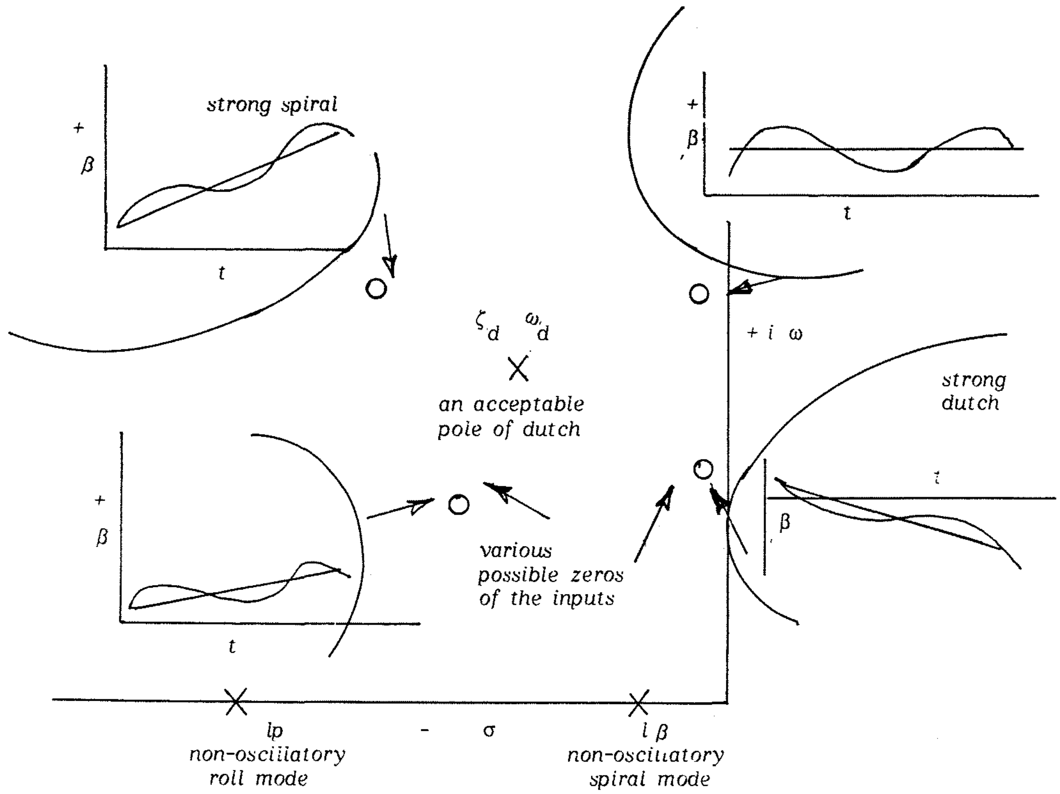


Fig. 20 Aileron input-output response characteristics (positive sign of β signifies sideslip in direction of roll)

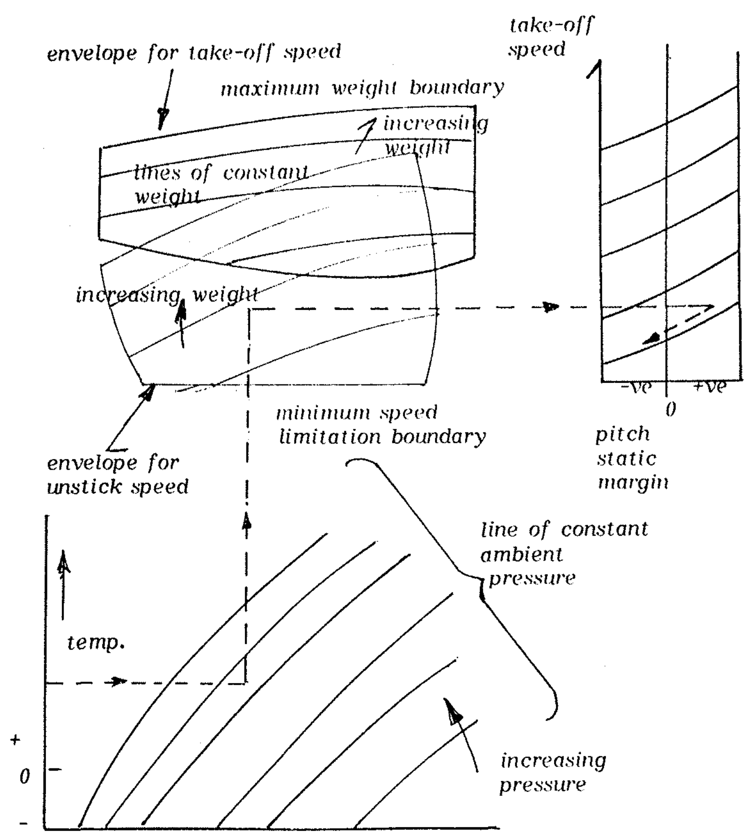


Fig.21 Typical take-off/unstick speed plots

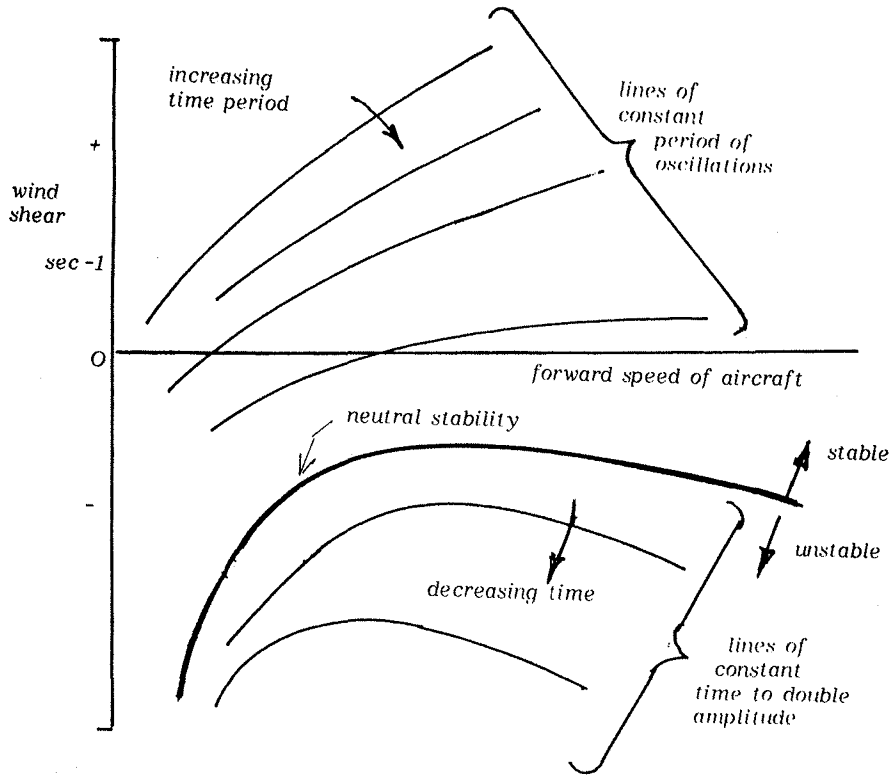


Fig.22 A typical effect of shear layer on fighter aircraft phugoid stability

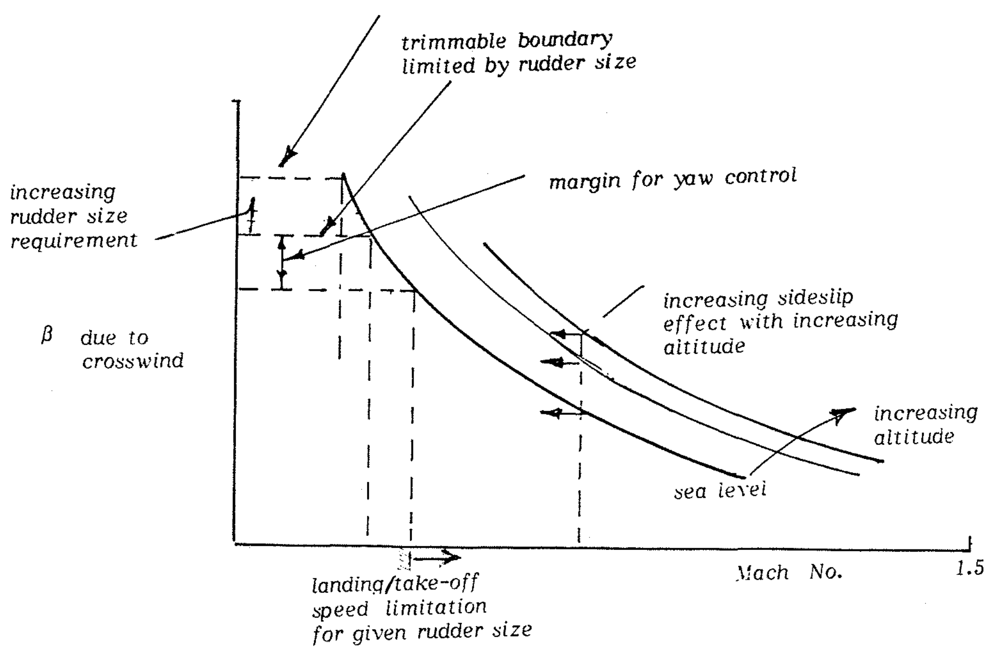


Fig. 23 Sideslip control under a constant crosswind condition

control in the presence of crosswinds. The GLA capabilities through ACT aim at better control managements in the presence of crosswinds. Open-loop GLA system does not interfere with the basic flying characteristics of the aircraft. Hence, these are attractive, but these systems require measurements of gust velocities ahead of the aircraft. Accuracy of such measurements are limited, therefore, these systems do not provide accurate load alleviations. In contrast, close-loop systems do not require measurement of gust field, thus, these are accurate. However, the flying qualities get affected by the close-loop systems.

Several mathematical models aim at representing atmospheric turbulence. Continuous turbulence analysis uses spectral methods to characterize the atmospheric turbulence which is considered as a continuous random process. There are atleast two air turbulence models which need consideration, namely : 1) Von Karman model, and 2) Dryden model. For example, spectra for turbulence velocities in three directions (i.e., ϕ_{u_g}, ϕ_{v_g} and ϕ_{w_g}) in respect of Von Karman form is given as below.

$$\phi_{u_g}(\Omega) = \sigma_u^2 \frac{2L_u}{\pi\left[1 + (1.339\, L_u\, \Omega)^2\right]^{5/6}}$$

$$\phi_{v_g}(\Omega) = \sigma_v^2 \frac{L_v}{\pi} \frac{1 + \frac{8}{3}(1.339\, L_v\, \Omega)^2}{\left[1 + (1.339\, L_v\, \Omega)^2\right]^{11/6}}$$

$$\phi_{w_g}(\Omega) = \sigma_w^2 \frac{L_w}{\pi} \frac{1 + \frac{8}{3}(1.339\, L_w\, \Omega)^2}{\left[1 + (1.339\, L_w\, \Omega)^2\right]^{11/6}} \qquad \ldots(9)$$

where

σ_u = root-mean-square intensity of disturbance velocity along longitudinal exis

σ_v = root-mean-square intensity of disturbance velocity along lateral exis

σ_w = root-mean-square intensity of disturbance velocity along vertical exis

L_u, L_v and L_w = scale factors in respect of three components of velocities (i.e., u_g, v_g and w_g) due to turbulence.

Optimal control laws aim at minimum control surface activity and result in minimum input power spectrum. In addition, ride quality improves and wing root bending moment variations get minimised.

FCS which are designed for rapid response to step or pulse input could result in excessive accelaration loads on airframe in the presence of turbulence. Atmospheric turbulence, terrian following feedback or radar noise forms a random input which can not be exactly modeled. FCS performance prediction for turbulence and radar noise needs analytical prediction before some simulation in flight could be attempted.

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