FLIGHT ENVELOPE EXPANSION DURING PROTOTYPE DEVELOPMENT

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Abstract

Certification configuration loads are discussed. Flying commitments for unstable fighter aircraft deploying stability augmentation are brought out. Some aspects related to data generation through wind tunnel testing and flight simulation are highlighted. Flight test points for the flight envelope expansion and related criterion are explained. Fault tolerant flight control system testing is covered. The aerodynamic considerations are largely dealt herein for the purpose of flight envelope expansion for the prototype fighter programs.

Key words: Loads, Flying Qualities, Flight Envelope, Flight Testing, Flight Envelope Clearance

Introduction

The flight envelope expansion for the prototype programme of new fighter aircraft is multidisciplinary critical. Each corner points of the previously cleared envelope must be flight evaluated for the available margins to clear the next envelope. Symmetric and asymmetric flight conditions constitute the air loads and inertia loads. The aeroelasticity affects get compounded. Flight operation load spectrum is explained herein. Critical loads needs to be determined by way of accurate strain gauging. Validation of data and reliability of measurements are of prime importance. The load path traced from measurements and that theoretically worked out must be compared during the flight envelope expansion. The manoeuvre definition needs explicit description including reduction in control law orders since these affect the load patterns as well as the handling qualities. Weapon carriage and firing, undercarriage operations, gust loads, engine thrust and accelerations and the vibration spectrum require accurate addressing including control surface travel rates and accelerations.

Flying quality requirements of statically unstable airframes of current fighter aircraft are governed by several new criterions. Subsequent to the active control technology and high digital quadruplex systems, more and more burden is placed on the controls to get these criteria. Pitch oscillations especially the short period, which have been classically referred to as thumb prints have markedly changed in appearance as a result of new technologies. The pitch attitude response, pitch rate overshoots to inputs and close loop tracking are brought out. The pilot induced oscillations (PIO) are critically related by way of phase delay versus pitch attitude bandwidth. Bandwidth criteria boundaries in terms of PIO are explained. Roll response of aircraft is governed by the roll-mode time constant. Permissible oscillations in roll, rolling vector criteria, roll-sideslip relationship are discussed.

High angles of attack aerodynamics can be established through wind tunnel testing. The rolled models are not equivalent to their counter parts in the conventional test setup at the corresponding pitch and yaw angles. The relationship between the aerodynamics in the two frames of references should be invoked to diagnose the facility interference effects influencing dynamic tests of aircraft. Conning motions and effect of path curvature are explained herein. The basic structure of flight simulation, representation of aerodynamic data and production of motion cue are covered. Ground vibration test for varied locations of center of gravity and inertia needs to be performed and structural frequencies be ascertained vis-a-vis control surface frequencies.

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permissible limits of angles of attack should be established through flight testing. Pitch lateral directional trim stability and control are explained. Criterion for various manoeuvres for testing purpose is brought out. Wing rock oscillations, roll attractor phenomenon, wing drop, heavy wing, stall, spin and flutter are covered from practical experiences. Criteria for flight envelope expansion are explained. Tracking the structural dynamics, flutter mode assessments, parametric identification and fault tolerant testing of flight control system are described. Typical windup lateral departure phenomena, stop-go-criteria for rapid roll, change of maximum bank angle, roll reversal versus roll entry normal acceleration, loaded rolls and peak roll rates are explained. Spin resistant certification issues are highlighted.

Certification Configuration Loads

Symmetric and asymmetric flight conditions constitute the air loads and inertia loads. The effect of aeroelasticity are to be considered. The critical load cases need to be ascertained. Flight operation loads can not be accurately assessed through theory or by wind tunnel experimentation alone. The in-flight load measurements by way of strain gauging is essential. The loading conditions are governed as below [1]:

- Maximum linear loads
- Maximum angular acceleration loads
- Maximum control surface loads
- Combinations of above

Symmetric flight conditions encompass of : (a) steady pitching, and (b) pitching with acceleration. Asymmetric flight condition involves, (a) rolling manoeuvre and (b) yawing manoeuvre. The rolling manoeuvre could be a roll around stability axis (wind axis) or around body axis. The roll pull out is a windup manoeuvre which could be performed for varied + ‘g’ conditions. The roll push over produces - ‘g’ values. The gust and wind shear form additional loads [2]. All possible flight envelopes are put for certification clearance. In addition the vibration and liquid slosh loads are taken into consideration. Loads arising due to aerial delivery pullouts, emergency store release, and asymmetric thrust with zero sideslip, low and high speed rudder displacements, various spin conditions and spin recovery conditions are to account for total of load spectrum. There are several conditions of spin i.e., steep or flat, erect or inverted. Rolling and yawing velocities are specified in standards / specifications for which spins are tested. The details of chordwise and spanwise loading are to be established in the entire range of flight envelopes. Such estimates can be addressed using computational fluid dynamics. The wind tunnel verification of loads is essential especially where flow nonlinearities are larger. The characteristics of flows could be marked by the presence of extremely complex conditions.

Weapon (store) carriage and release design / limit loads need to be predicted. Relevant MILs are referred for general design criteria for airborne stores, suspension equipment and aircraft-store interface (carriage phase). Aerodynamic loads for a particular flight condition are combined with inertia loads. The aerodynamic loading can be considered as quasi-static when the inertia loading is applied. Aircraft angles-of-attack and sideslip at specific load envelope points for wing and fuselage mounted stores are to be considered separately. The yaw and pitch attitudes are specified. Inertia loads are determined from the aircraft performance capabilities for given loading of store on aircraft. The performance capabilities of the aircraft get affected by the store type and its location. Intended and unintended asymmetries further restrict the aircraft performance parameters. Loads due to undercarriage operations, landing, turbulence, gunfire vibration, structural vibrations and control surface operation are taken into account. In the event of redundancy in control surface travel, the failure cases should consider extreme rate values of travels.

Flying Qualities Commitment

Levels of acceptability of flying qualities are specified in relation to the ability to complete the mission. Three such levels are namely: level-I corresponding to essential for mission effectiveness, level-II corresponding to adequate for mission with increased work load and level-III corresponding to inadequate mission effectiveness/larger pilot’s work load. Levels of flying qualities are linked to three categories of flight (A, B and C). Category ‘A’ (non-terminal flight phase) corresponds to flight requiring rapid manoeuvring (e.g., combat), precision tracking (e.g., ground attack), and precision flight-path control (e.g., close formation). Category ‘B’ (non-terminal flight phase) corresponds to gradual manoeuvring and lesser precision tracking. Category ‘C’ (terminal flight phase) corresponds to flight requiring gradual manoeuvring and precise flight-path control [3]. Flight-path stability, phugoid and short period oscillations characterize the pitch handling qualities. Short period frequency requirements are governed by [3] MIL-F-8785C. Equivalent systems allow the
use of time-delay terms which are similar to the aircraft cockpit controls for step inputs. Using equivalent time delay [4], high frequency effects of short-period oscillations can be represented as below in a linearized input-output response in Laplace(s) plane. Subscript SP in equation (1) refers to short period.

\[
\frac{q}{F_s} = \frac{(s + T^{-1}) e^{-\tau\theta s}}{(s^2 + 2\zeta_{SP} \omega_{nSP} s + \omega_{nSP}^2)}
\]

where

\[q = \text{pitch-rate}\]

\[F_s = \text{stick force input}\]

\[\zeta, \omega_n = \text{damping and short-period natural frequency respectively}\]

\[\tau\theta = \text{time-delay term}\]

Zeros of the transfer function \(T^{-1}\) are independent of FCS. Airframe-FCS dynamics have poles \((\zeta_{SP}, \omega_{nSP})\) that correlate with pilot’s opinion of flying qualities. Flying qualities specifications thus involve in the pole-placement. Pilot’s rating (1-9) corresponds to three levels of flying qualities specifications thus involve in the pole-placement that correlate with pilot’s opinion of flying qualities. Flyings emerged in the recent past [5,6], please refer Fig.1 (which is symbolically depicted for a fixed reference of procuring agency.

Some new thumb prints on short-period criteria have emerged in the recent past [5,6], please refer Fig.1 (which is symbolically depicted for a fixed reference of procuring agency. The importance from their characteristics that these remain invariant in location to \(T_{\theta_2}\) variations. Line of constant pitch-rate peak time \((T_{\theta 2})\) can also be plotted through Fig.1. These lines vary with \(T_{\theta 2}\) variations. Lower \(T_{\theta 2}\) values are favourable, which is possible through higher \(\omega_{nSP} \times T_{\theta 2}\) values. Thus, larger \(\omega_{nSP}\) are in favor of lower \(T_{\theta 2}\) values. These lines can be excited by a doublet input or through a pulse input or a gentle pull up. The ‘g’ pull up method results in large amplitude input for short period motion with heavy damping.

Another important characteristic which can be linked to short-period oscillations is the Control Anticipation Parameter (CAP) which is governed by equation (4). CAP is alternative to \(\omega_{nSP}/\alpha\) term. Subject time-domain parameter is intended to limit abrupt or sluggish attitude response. MIL-STD-1797A brings out CAP versus \(\zeta_{SP}\) which are acceptable for various levels and flight phase categories. The level-1 CAP corresponds to less than 1.5 and higher than 0.25 value.

\[\text{CAP} = \frac{g T_{\theta 2} \omega_{nSP}^2}{V_c}\]

where \(V_c\) is the steady-state velocity of aircraft.

Figure 1 also shows lines of constant pitch-rate overshoots \(q_m/q_{ss}\), where \(q_m\) is the maximum pitch-rate value and \(q_{ss}\) is steady state pitch-rate. Subject lines draw the importance from their characteristics that these remain invariant in location to \(T_{\theta 2}\) variations. It is known that for fighter aircraft, pitch-rate overshoot is required for gross target acquisition in air combat mode while a deadbeat pitch-rate is preferable for a good fine tracking. Thus, these lines provide good indication of target acquisition and tracking capabilities. Line of constant pitch-rate peak time \((T_{\theta 2})\) can also be plotted through Fig.1. These lines vary with \(T_{\theta 2}\) variations. Lower \(T_{\theta 2}\) values are favourable, which is possible through higher \(\omega_{nSP} \times T_{\theta 2}\) values. Thus, larger \(\omega_{nSP}\) are in favor of lower \(T_{\theta 2}\) values. Short period oscillations can be excited by a doublet input or through a pulse input or a gentle pull up. The ‘g’ pull up method results in large amplitude input for short period motion with heavy damping.
A recent criterion on satisfactory pilot rating is due to Gibson [5]. This Dropback (Drb) criterion applies for a block-input command and is governed by equation (5) below. The \( \text{Drb} / q_{ss} \) can also be written as equation (6). Small positive Drb and low \( T_r \) are considered favourable. Fig.1 typically shows a higher handling quality (hq) boundary.

\[
\text{Drb} = \frac{T \times \omega_{nSP} - 2\gamma_{SP}}{\omega_{nSP}}
\]

where \( t_q \) is the flight-path angle delay.

Lateral-directional dynamics are now discussed to match the response of pitch agile airframes. Roll response of aircraft is governed by roll-mode time-constant (\( \tau_R \)). Minimum value of \( \tau_R \) of 1.0 corresponds to level-1 for all flight phase categories. The time-to-roll through a particular bank angle does not change significantly with the variations in \( \tau_R \). However, the time-to-roll and capture a particular bank angle significantly gets affected by the roll-mode time-constant. Current trends aim at lower \( \tau_R \) values than those specified in MIL-F-8785C to capture a bank angle position in a lesser time. Permissible oscillations in roll are required to be simultaneously met. Rolling the aircraft around stability axis generates pitch-rate excursion however the load factor excursion is minimal. Instead, the rolling around body axis generates load factor excursion and the pitch-rate excursion is minimal. A blend of two excursions based upon angle of attack and speed conditions requires a hq evaluation through simulation since this relation may be peculiar to cockpit location and aircraft configuration.

### Wind Tunnel Testing and Flight Simulation

High angles-of-attack unsteady aerodynamics can be well established through wind tunnel testing. The wind tunnel balances, atmospheric gust generation, tunnel wall interference removal and data reduction are highlighted herein. The equivalence between orientations obtained by a combination of pitching-yawing, and that by a combination of pitching-rolling are different. The rolled models are not equivalent to their counterparts in the conventional test setup at the corresponding pitch and yaw angles. The relationship between the aerodynamics in the two frames of references should be invoked to diagnose the facility interference effects influencing dynamic tests of aircraft. The nature of unsteady interference is strongly dependent on the test configuration and installation geometry. Substantial design data can be generated through theoretical computations. However, under the complicated flow conditions, the accuracy can be relied upon experimentation. Static and dynamic balances provide means for accurate measurements of forces and moments on models. Highly Nonlinear aerodynamics with strong coupling between lateral and longitudinal degrees of freedom can be determined. This requires generation of conning motion [7,8]. Conning characteristics by the use of rotary rig provide very important experimental tools. Rotary balance techniques provide aerodynamic forces and moments on a model undergoing steady rotation at a constant attitude. These data are useful to predict potential steady spin
modes and also for the building up of data base for the spin portion of the flight simulation. However, the rotary balance data can not be used to predict oscillatory spins. This is because the forces and moments are constant in rotary rig test for a given set of conditions. Dynamically scaled free-spinning models can predict the oscillatory nature of spin. Measurements of the effect of the path curvature is possible through a swirling arm [9] arrangement. Swirl is essentially the movement of air around the annular shaped test passage. Centrifugal effects influence the way models are mounted. Data reduction and analysis needs to be established and is a difficult exercise in a swirling arm device.

As the aircraft become more complex, more dependency is sought on ground simulation. When the ground simulation results are erroneous, in-flight simulation is resorted too. In-flight simulation uses hybrid technology. It is the ground simulator that flies and a test bed aircraft that makes believe. The object of flight simulation is to reproduce on ground the aircraft flight patterns. Flight simulators are used for developmental programs as well as for training. These provide vital tools for exercising different design options. These provide means of evaluating the consequences arising from failure conditions of systems [10]. Production of motion cues depend upon motion sensing and perception. Some angular velocities generated due to these parameters are highlighted. In-flight simulation is more practical in nature. In case the flight envelope of aircraft to be simulated lies within the flight envelope of aircraft in which simulation is made, then it is possible to do in-flight simulation of the aircraft which is to be modeled.

Stability derivatives, forces and moments coefficients form the data for the small perturbation equation. These coefficients and derivatives can be expressed as function of angle of attack, control surface deflections, speed, Mach number, rotation rates, altitude, aircraft c.g. and geometry (e.g., flap positions, wing sweep etc). Polynomial fit to data or look up tables are some means of presentation of aerodynamic data. Detail models encompassing complexity may be used in practice. Visual and inertial cues combined provide a better stimulus. It is imperative that the motion platform should not generate motion cues that are uncharacteristic of aircraft. The system must perform to lowest structural resonances and these should be out of frequency bands of interest. Cross-coupling effects and unaccounted nonlinearities directly decrease the useable range of motion platform. Spurious accelerations must be minimized as far as possible. The ‘g’-seat is an effective device for producing some of the cues of aircraft motion by supplementing or replacing those by a motion platform. The requirement of producing the inertial cues of motion in a manned flight simulator depends upon the type of simulator’s requirement. The sensitivities of the body’s sensors of inertial motion peak in the range of 0.1 - 1.5 Hz. Typical pitch and roll simulations responses are shown in Figs. 2 and 3 for a agile fighter aircraft.

Flight path angle tracking consists of flight path angle acquire and hold. The manoeuvre explores n’g’ lag ‘q’, i.e., the way the longitudinal attitude begins to change immediately after longitudinal control input. The flight path angle will change after longitudinal attitude changes. The lag between n’g’ and ‘q’ is proportional to the flight path to attitude lag time constant. The manoeuvre requires velocity display. At low velocities the interchange between angle of attack and speed takes place at nearly constant load factor values, unless power is added. Attitude tracking involves in capturing and holding attitude angles (longitudinal and including that at various lateral bank positions). A variant of this method has been created recently consisting of two types of patterns, ‘sum of sines’, and discrete inputs. The input signal shall have enough energy and bandwidth in order to excite pilot induced oscillations. Modeled turbulence can be stored and activated in the control loop to simulate turbulence. Power spectral density of signal form with high noise variations of small frequencies are alternative input concentrates and more powerful in low frequencies.

The awkward reality for flights mechanics prediction is that much of the post stall manoeuvring envelope which could lie within the domain of unsteadiness and aircraft may have chaotic nature of aerodynamic response. Much of the dynamic data generated in the nonlinear domain is restricted and do not provide information on the basic hysteretic behavior. The key focus in simulation of aircraft dynamics is on appropriate test conditions rather than on the volume of data that could be generated. Maneouvre data quality could be considered satisfactorily only if the flow physics relative to flight is captured. A threshold coning rate exits that indicates the onset of unsteadiness leading to bifurcation. Identification of this condition, including the definition of the steady-state hysteresis, is necessary for the implementation of the nonlinear rotary data. The modeling of the nonlinear responses should be traceable in the deterministic range and in the unsteady domain; careful modeling of the viscous fluid/motion coupling is required.
Manoeuvring longitudinal stability and load factor capability can be established through windup turns and symmetric push-overs/pull-ups. The engine power and aircraft speeds need to be maintained constant. The demonstration of limits of flight and manoeuvre envelopes requires exhibiting safe handling characteristics till envelope corner points. Tail plane efficiency versus effective lift coefficient needs to be established over the wider Mach number range. Flying qualities under degraded flight control system conditions, defining the relight envelopes, working out the no spin recovery zone, establishing c.g. travel limits allowable in complete flight envelope including resulting any emergencies needs to be type recorded. Lateral and directional trim stability and controls are required to be demonstrated for safe handling. Rapid rolling and roll pullouts upto permitted stressing levels to be explicitly written in type records. Any limitations towards rapid roll should be worked out for asymmetric store configuration cases. The side skid can be worked through a slow down in a hard turn. Slow down in a hard turn to the high angles of attack conditions for varied configurations needs to be demonstrated for the permissible shift of ball width of turn and slip indicator. The skid should be of permissible tolerance for 1/3rd shift of ball width. These manoeuvres are performed at safe heights.

Stall, spin, flutter and heavy asymmetric store carriage test flying is larger risk involving. Stall/post-stall/spin flight test demonstration requirements for airplane are governed by MIL-S-83691A. Maximum allowable asymmetry shall be demonstrated and Flight Control System (FCS) failure order during manoeuvre adequately addressed. Wing rock oscillations, bucking un-commanded pitching oscillations, nose slice i.e. un-commanded lateral/directional motion can occur during experimental flights. Roll attractor and wing rock around roll attractor are some more possible oscillations which can be present during high angles of attack testing. The stall and normal acceleration during recovery are recorded. Uneven stall of wings leads to stick snatch. Use of boundary layer fence helps in uniformity of both wing stalls. If the rolling and yawing are occurring during recovery, these should be opposed by control application. The potential problem of the wing drop/roll-off is due to the differences in contour (shape) of the right and left wing. Wing leading edge shapes are extremely detrimental to wing drop, especially where leading edge skin are formed of dies. Deep stall lock-in may occur where excessive down loads occur on elevators due to shed vortices resulting in reduction in elevator pitch down capability to reduce angle of attack for stall recovery. The stalls are demonstrated at specified deceleration rates prior to stall.

Spinning of some fighter class of planes is required to be demonstrated. Spin tests to be done at the most permissible c.g. and weight conditions. Number of possible turns in the spin and spin recovery action should be worked out from safe prescribed heights. Spin when fully developed is either upright/erect or inverted. In the later case the yawing and rolling motions are in opposite direction. Rotary motion of spin may have oscillations in pitch, roll and yaw superimposed upon them. Incipient spin is the initial, transitory phase of motion during which it is not possible to identify spin mode. Fully developed spin is attained when the trajectory has become vertical and no significant change is noted in the spin characteristics from turn to turn. Post-stall gyration i.e., uncontrolled motion about one or more aircraft axes following departure at high angles of attack can be also be present. The c.g. envelope for spin testing and the control action for spin recovery should be established. In the aerobatic category, the recovery from spin in a fully developed spin should be possible in one and one half additional turns by the normal use of controls, without exceeding airspeed or load factor. In case of flap down spin test, if required it should be permissible to retract the flap during recovery. Spin characteristics requirements are specified for fighter aircraft design. The recovery is worked out and demonstrated. Spin recovery parachutes are installed on aircraft during prototype testing. The spin test matrix must be adequately specified for flight test programme. An ideal spin recovery should be possible by off loading the angle of attack. The use of rudder generates unfavorable rolling moments which are in fact prospin. The need for out spin aileron action along with pitch control for spin recovery vis-à-vis the c.g. envelope and cases of store asymmetries should be established for varied altitude conditions. Autorotation can occur if one of the wings is under stalled conditions while the other is not. It is a vertical gyration motion, if not controlled in time, can dangerously develop into uncontrollable attitude.

Wing rock can occur on swept back wings at high angles of attack. Wing rock is a limit cycle roll oscillation experienced by aircraft where amplitude and frequency of wing rock is a nonlinear function of many parameters such as angle of attack, sideslip etc. Several theories have been put forward over the years to explain the wing rock phenomenon. Some of the factors, which emerge out of these are as follows:
• wing rock initiated because of vortex asymmetry,
• vortex bursting does not initiate wing rock, but plays an active part in limiting the amplitude of the limit cycle,
• there is negative roll damping at small angles of bank and positive roll damping at higher angles of bank,
• wing rock is caused by the relative time lag between the static and dynamic position of vortex normal to the wing surface.

These studies indicate that the vortex formation plays important role during wing rock, hence manipulation of these vortices help in wing rock suppression. Wing rock around roll attractor is structurally overloading and unsafe condition since it is not normally accounted for in the detailed structural design. Flight test condition should be able to see from parametric estimation the likely presence of such phenomenon to account in design work. Certain manoeuvre conditions are load critical which otherwise might not be foreseen during design and development. The rudder doublet action during a velocity axis roll generates loads which are more severe than rapid roll case.

Flutter flight test are done to determine V-n envelope free of flutter. The coupling of resonant frequencies of various modes create flutter. The most common approach to flight flutter testing is to track estimated modal damping ratios of the aircraft over a number of flight conditions. These damping trends are then extrapolated to predict whether it is safe to move to the next test point and also to determine the flutter speed. During the design stage of the aircraft the aeroelastic behavior is estimated by producing detailed mathematical and aeroelastic wind tunnel models. Subcritical damping data can not always be safely extrapolated to obtain on accurate prediction for flutter velocity. The aeroelastic stability can change from positive to negative with little increase in value of airspeed. There are several flutter prediction methods. The most common method is to analyze damping levels that vary with flight condition and extrapolate the resulting trend. The flutterometer is an on-line tool that indicates a measure of distance to flutter in terms of a flight condition during a flight test. The flutter margin that is computed by the flutterometer is the robust flutter margin for analytical model with respect to uncertainty. This margin is mathematically valid based on the aeroelastic dynamics as indicated by the model. The flutterometer is a tool designed to predict the onset of flutter with more confidence than traditional approaches. The validity of flutterometer must be extensively tested to ensure its usefulness. The quality of the structural model can be evident by comparing transfer functions from the model and the test data.

Parametric identification (PID) involves in estimation of stability and control derivatives. Parametric identification aims at minimizing the error between input and output data in a least square way. The demand of improved performance characteristics and high maneuverability of fighter aircraft has led to statically unstable airframes. The flight determination of aerodynamic derivatives of basic unstable aircraft i.e., of the open loop with control closure is of application interest in flight mechanics. Estimation of aerodynamic derivatives from flight data of an unstable aircraft poses several difficulties. While the frequency domain system identification method can be readily used, these methods are limited to the linear equations of motion. This constitutes a major disadvantage since the aircraft fly in extreme flight regimes exhibiting non-linear aerodynamic characteristics. Time domain methods are more useful for the parametric estimation of unstable aircraft. Time domain methods are applicable for both linear and non-linear systems [11].

Among the various methods, the ‘regression startup method’ has the advantage that the initial values of unknown parameters are not required. The optimization procedure can be started with zero values of all the parameters, at least for the case of stable system. Another technique known as the ‘equivalent de-coupling method’ in which the independent state measurements result forulates the state model in such a way that each differential equation can be integrated independently. This method is a variation of the regression method commonly incorporated as a start up procedure for the ‘output error method’, which is the most commonly used method for the stable systems. This method needs artificial stabilization since the solution of an unstable system is sensitive to the errors in the initial conditions and system parameters which are unknown or/are inaccurately known initial conditions and are likely to result in diverging integrated solution. This artificial stabilization is analogous to the ‘filter error method’, which possess stabilization properties and is most generally used. By introducing a non-linear filter, numerical approximation of sensitivity coefficients enables development of programming modifications each time the nonlinear model structure is affected. Another technique ‘multiple shooting method’ is commonly applied to solve estimation problem by fitting unknown parameters in an iterative procedure by solution of the initial values problem. A direct solution to this problem is
provided by constrained optimization. A more efficient approach is to recognize the special structure and to apply the Gauss-Newton method in combination with a condensation algorithm. The advantage of multiple shooting methods is that by defining additional grid points, the computed solution remains closed to the observed data. Exponential growth of the parasitic components in the solution of unstable differential equation can be restricted. The approach to subdividing the integration interval into several segments is different than evaluating simultaneous multiple time records.

Fault Tolerant FCS Testing

Current research activities are towards restructurable fault tolerant scheme based on failure accommodation phase. For example formulation of on-line to regain control of the aircraft at the nonlinear dynamic conditions is one phase. Second phase is the once back stable and linear conditions, a linear restructurable control law is formulated for designing of control laws. Accurate post-failure aerodynamic models are needed for the simulation purposes. The aerodynamic characteristics of a surface are to be expressed in terms of normal force, axial force and moment around control point. The longitudinal failure is more important than the aileron and rudder failures because of the unavoidable coupling between the longitudinal and lateral - directional dynamics. On-line time-domain PID techniques mainly include variations of the least square regression method, such as recursive least square. Potential problem with the time domain PID techniques may be the lack of a reliable parameter for an on-line estimates in the presence of un-modeled noise. To overcome these problems, the frequency-based PID techniques using Fourier transforms are useful. Aircraft dynamics is modeled using the conventional continuous-time state variable model.

In a multiple redundant FCS, characterization of failure transients are required to contain failure transients under failure conditions. Detailed modeling and analysis to allow in-depth investigations to predict aircraft transients due to failures and to evolve subsequent system reversions is not only tough to do with perfection but the whole process is generally not adequate to provide enough confidence for clearance. Hence the design is based on quasi-static calculations of failure transients and compliance with the requirements is validated by testing on real-time simulators. During which the failures are injected into real systems by inputs of several types like step, pulse, ramp and cyclic variations to stimulate the system in open loop. Failure transients of control surfaces under simulated failure conditions are thus characterized and final evaluation is done through pilot in closed loop. Hardware-in-loop simulation facility is the only ultimate platform in clearance process. Fighters aim at carefree manoeuvring for relieving pilots work load. Envelope protection for carefree manoeuvring is governed by limit detection & avoidance, and aircraft constrained by structural, power and control margins etc. Limit avoidance if left to pilot results in pilots increased work load and simplified operational limits results in sub-optimal performance. Possible benefits with a limit avoidance system are following.

- Improved agility and manoeuvrability by expanding the usable flight envelope
- Improved handling qualities by providing carefree handling
- Reduced maintenance costs by avoiding excessive limit violation
- Improved flight safety by warning the pilot when limits are approached

The key to limit avoidance is a timely prediction of the limit margins and its translation to control/command margins.

Flight Envelope Clearance

Envelope Definition

Flight-testing is done to define safe envelopes for aerodynamics, control, structural and propulsion considerations. Flying limitations are recorded in the aircrew and operating data manuals. The basis of principal flying limitations are as below. Fig.4 shows typical test points.

V-n diagram: Velocity (V) and load factor (n) in clean and gusty conditions. Limitations during take-off and landing. The V-n envelopes are defined in all stores configurations. Asymmetry in stores is taken care-off.

Stiffness of: Limitations in speed and normal acceleration to avoid structure aeroelastic effects.

Handling: Combined rolling and pitching manoeuvres, rapid rolling qualities, limitations due to stall, spin characteristics, climb, rudder angle etc., cross wind conditions taken into account for rudder power versus landing/takeoff speeds.
Armament: Carriage and release envelopes, jettisoning limitations, stores safe store attitudes.

Specific Tests: Testing which are specific in nature.

During spin testing or high angles of attack manoeuvres or weapon firing cases, engine flame out could occur. In flight relight envelope in a single engine aircraft with augmented flight control system where engine starting has no provision for assisted start in flight is crucial to establish. In the event of unsuccessful starts, flame out landing is to be executed otherwise the aircraft is lost. In the event of engine flame out all driven accessories make the control operations difficult or restricted. Choice of airfield and aircraft configuration must be planned for minimizing the risk. The hot relight is for the case where sufficient residual rotational speed is available, and the cold relight is for the case of compressor wind milling. The handling qualities of the aircraft in this case of power loss (engine flame out condition) can degrade to level III and pilots workload may be very excessive.

Tracking the structural dynamics is imperative for safe flight envelope expansion. The issues involved are airframe elastic modes (aeroelasticity) and flight control - elastic mode interaction (aeroservoelasticity). Most critical structural dynamics modes need to be accurately identified and monitored. Atmospheric turbulence, stick jerks or control mounted excitation system can be used to excite the structural modes. Flutter testing is done if theoretical calculations indicate insufficient margins of safety against flutter. Flutter is a self-excited phenomenon, even though if aircraft has been flown through its speed range without occurrence of flutter, it does not prove freedom from flutter unless adequate vibration excitation has been used to start vibration in critical components. A rotary mass excitation system on a control surface provides a frequency sweep vibration input to predict torsion flutter mode at high speeds. The rate of decay of vibration after the structure has been deflected by either gust in rapid deflection of control surface or by other means as a function of airspeed. As the critical flutter speed is approached, the rate of decay approaches zero. Aircraft is flown to sub-critical speeds and rate of decay of vibrations of critical part determined. Change in rate of decay with speed is extrapolated to result in critical flutter speed. The rotary mass excitation system on a control surface provides a frequency - sweep vibration input to predict control torsion flutter mode at high speeds.

Envelope Clearance

The envelope expansion programme essentially involves in identifying accurate test points and the requisite parameters to be obtained from in-flight measurements. Flight test encompasses of test conditions for the test points. Measuring of the manoeuvring longitudinal stability of aircraft is possible by way of windup turns and symmetric push-overs/pull ups. The build up of normal acceleration is done at specified increased value of g/sec until either of the following is reached.

- Limiting lift conditions, buffet, pitch up tendency, wing rock or yaw departure
- Control limits
- Limit governed by spin tendency
- Maximum normal acceleration

Demonstration of limits of flight and manoeuvring envelopes are made at all forward and most aft e.g. conditions. Maximum weight conditions are covered. The expansion of static margin forms the part of envelope expansion programme. Prior to carrying out of longitudinal handling assessment, slow down should be carried out. This is to check the aircraft behavior at the limiting angle-of-attack under normal ‘g’ conditions. Simultaneous airbrake extension and reheat cancellation have pitching affects. At specified speed and altitude, this assessment is made for varied static margin, weight and inertia combinations. Windup turns at high incidences exhibit lateral phenomena of wing rock or yaw off. Plots of the static margin variations for fuel consumption is taken into consideration. The lateral departure phenomenon are examined during windup turns. Fig.5 typically shows occurrence of wing rock and yaw-off at certain points within the structural envelopes, thereby restricting the never exceed limits due to aerodynamic considerations.

Directional and lateral stability test should address control system behavior, static stability, dynamic stability, ability to trim and effect of turbulence. Intended asymmetry needs explicit release to service documentation action. Unintended asymmetry like hang fire of store should cover restrictions in flight envelope thereby placing operational limitations. The directional and lateral aspects upto about 10° of incidence can be determined by way of dutch rolls. The flight data recorder are decoded to determine the stability derivatives with respect to angle-of-attack and Mach number for given altitude conditions. Lateral- direc-
Roll response to yaw control should be assessed as per any laid down specifications. In a gentle bank with a light yaw control, a tendency to gentle roll is considered as favourable. Safety of flight considerations should include instructions for pilot to put a gentle rudder input and make assessment of dutch roll behavior, before doing a doublet. Higher incidence directional stability can be assessed through sideslip control. Rapid rolling criteria must be defined. Under heavier weight conditions or due to unintended asymmetry, the rolling might have to be GRMO (gentle roll to maneuver only) due to structural considerations. Where the rudder-elevon interconnects is used, static decoupling is must. Failure of static decoupling is catastrophic. The assessment of rolling performance of aircraft is to see aircraft behavior in rolling manoeuvres and autorotation tendencies resulting from inertia cross-coupling. The most forward and aft c.g. positions, store configurations, weight, Mach number and altitude combinations are considered. Flight verified models are useful to predict aircraft response and structural loading for standard cases of tolerances. Rolling manoeuvres to include roll outs at $360^\circ$/$720^\circ$ per second of roll rate. Maximum permissible change in bank angle could be restrictive under asymmetric/heavy weight conditions.

Input of longitudinal stick during the initiation and during the roll could be restrictive due to structural limits. The roll should be terminated by a sharp centering of the stick with a minimal longitudinal input. If the roll rate continues after the removal of the stick, opposite partial stick is used to overcome the roll rate. The aircraft can be then gently recovered to 1 ‘g’ trim condition. In the unlikely event that the aircraft enters auto-rotation, the stick should be centered laterally and eased back to oppose the negative pitch-rate. Auto-rotation is recognized by pilots as a rolling motion with incidence fluctuating. Safety of flight should include points like the rapid rolling manoeuvre not to be continued if more than specified stick is required to hold aircraft in trim if any auto stabilizer function is failed or if any evidence of lateral departure phenomena (wing rock, yaw-off) or excessive buffet is observed during flying.

The normal rapid rolling trials procedure involves a work up towards the flight envelope corner points. Prior to attempting rapid rolls, dutch rolls be carried out and the stability information known. Rapid rolls are scheduled in the flight trials close to but not at the most critical flight conditions. The ultimate objective of the rapid rolling flight trials is to clear the aircraft for the coarse application of full lateral stick to achieve high rate of roll and large roll attitude changes. The criteria for service clearance to rapid rolling is following.

- Peak roll-rate vs entry normal acceleration
- Peak normal accelerations vs entry normal acceleration
- Peak sideslip vs roll entry normal acceleration

Figures 6, 7 and 8 show some realistic problems faced in these criteria, thereby limiting rapid rolling under certain conditions. The phenomenon of autorotation is undesirable. Autorotation is linked to the inertia cross-coupling, where a nose-down pitch rate is superimposed on rate of roll on an inertially slenderical aircraft. Details of static margin and roll inertia variations during flight are important.

Buffet maneuvers need be explicitly defined. Current flight test programs have shown the presence of intense vibrations associated with buffet manoeuvres. The buffet manoeuvre envelope is generally bounded by speeds of 0.8 to 0.9 Mach and altitudes of 3-10 kms. Aircraft stores may experience about 1/2 minute of manoeuvre buffet vibration for one hour of captive-carriage flight. Large energy levels are at lower frequencies 20-100 Hzs. The manoeuvre buffet and aerodynamic vibration tests may be combined or performed separately if necessary to duplicate both rigid body and bending modes.

**Spin Resistant Certification Issues**

Spin is the stalled condition of flight with yawing, rolling and pitching motions. It never stops by itself. Relevant design requirements towards spin characteristics of fighter trainer aircraft are governed by DEF STANDS. A trainer aircraft should have spinning characteristics while the fighter aircraft should be capable of recovery from inadvertent spin entry. Flat spin, inverted spinning and spin from turning flight should be possible in a fighter trainer aircraft. Spin entry and recovery should satisfy the varied loading conditions governed by specific military standards.
Spin resistant objective is to have smooth, continuous uninterrupted control of aircraft from its minimum speed to its maximum speed. The aircraft should have tolerance to maintain controllability in all three axes, after sustain stall or minimum flying speed manoeuvres. Current standards of highly maneuverable aircraft require controllability under the stalled conditions of flights. Under the conditions of most aft c.g. loading in extreme i.e., high pitch rate condition, a best design aircraft could be pro-spin. The concept of spin resistant is as followings.

- Protect overshoot stall
- Maintain aileron control and damping-in-roll at and aft of the point at which inspin wing buffeting and nose down pitch occurs.
- Sufficient roll power to obviate yaw rate. This is because anti-yaw through rudder application could only result in pro-spin action and aggravate spin.
- Provide post stall control which has conventional control movements.

The current spin resistant criteria of advance fighters are as followings.

- It must be possible to maintain wing level flight during stall maneuvers by using aileron and rudder, within 15° of bank angle. Also roll to ± 30° be possible.
- At the stall speeds, to promote entry into spin, full rudder applied for a specified period or 360° heading changes occurs, whichever is earlier. The 360° heading change should meet a specified time limit. At the end of turning, aircraft should respond to spin recovery action. The aileron during turning flight should be held in adverse yaw condition.

Uncoordinated flight with full rudder displacement or at least one ball width displacement on a turn and slip indicator needs to be demonstrated.

References

Fig. 1 Short-period New Thumb Print Criteria

Fig. 2 Simulated Pitch Manoeuvre

Fig. 3 Simulated Roll Manoeuvre

Fig. 4 Typical Test Points in Flight Envelope

Fig. 5 Typical Windup Lateral Departure Phenomena

Fig. 6 Some Stop-go-Criteria for Rapid Roll in Relation to Peak Roll Rate
Fig. 7 Typical Stop-go-Criteria for Rapid Roll in Relation to Peak Normal Acceleration

Fig. 8 A Stop-go-Criteria for Rapid Roll in Relation to Sideslip