Control Considerations for V/STOL Aircraft

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Abstract

The nature of the flight path control (guidance and maneuvering) problem and the attitude control (stability augmentation) problem for V/STOL aircraft was described. The minimum level of control power needed for stabilization is strongly dependent on the open-loop aircraft dynamics, aircraft size, the type and amount of stability augmentation provided, and the turbulence environment. An analytical approach and design methodology, based on the state variable methods of modern control theory, was developed which structures the stability augmentation system required for satisfactory handling qualities, while simultaneously yielding minimum required values of stabilization control power.

Introduction

The growth of the sprawling megalopolitan areas and the choking ground congestion around present metropolitan airports make it mandatory for the airline industry to find a far better method of transporting short-haul traffic (less than 500 miles). As a solution to this problem, many air transportation authorities in industry and government agree that short take off and landing (STOL) and vertical take off and landing (VTOL) aircraft will be important modes of transportation in the 1980's.

The United States Civil Aeronautics Board has concluded that V/STOL service from appropriate landing sites between Boston, Mass.; Hartford, Conn.; New York, N.Y.-Newark, N.J.; Trenton, N.J.; Philadelphia, Pa.; Wilmington, Del.; and Washington, D.C., is technically and economically feasible and that the public convenience and necessity require the institution of this service to reduce congestion and delay and improve the quality of air transportation in these markets (12). The United States Federal Aviation Administration has also recognized the importance of V/STOL transportation by preparing airworthiness standards for such aircraft (16).

In view of these and other developments, it is apparent to this writer that commercial and general aviation V/STOL operations will be a considerable percentage of the total domestic air traffic within the continental United States in the not too distant future. Although the design criteria and methods for V/STOL aircraft are in many ways the same as for conventional take off and landing (CTOL) aircraft, they are considerably different in other areas—most evident of which is the flight control system design (both airborne and ground based elements) for the low speed regions of operation unique to the V/STOL mode.

A considerable number of prototype VTOL airplanes have crashed due to deficiencies in their control systems. Many of these were due to inadequate appreciation and consideration of the effects of atmospheric turbulence on the control system design. This paper is directed to this problem and discusses some of the work which has been done toward accounting for turbulence effects on control system design.

An airplane has six rigid-body degrees of freedom—vertical, forward, and sideways translation of the center of gravity and yaw, pitch, and roll rotations. These are usually referenced to an orthogonal axis system fixed at the center of gravity. The overall control problem is conveniently divided into the guidance function, concerned with control of linear position and velocity of the airplane to cause it to follow a desired flight path time history, and the attitude control or stability augmentation function. When flying IFR (Instrument Flight Rules), the guidance system obtains position and velocity information from the navigation system and uses this data to generate velocity commands, which in turn are implemented by maneuvering the aircraft through displacement of appropriate aircraft controls (such as ailerons, elevator, rudder, and throttles). For the guidance function to be carried out, the airplane must be stable along its flight path. In other words, it must not exhibit divergent oscillations which would cause it to depart from the desired flight path. All VTOL and most CTOL high performance airplanes require such stability augmentation, provided by either an automatic system, or by the pilot working harder to stabilize by control inputs as well as maneuver (guide) the vehicle with additional inputs from the same controls.

The quality of the attitude stability is referred to as the "handling qualities" or "flying qualities" of the airplane, and there has been much research devoted to determination of what these should be for various classes of airplanes in various flight conditions. The handling qualities specifications for CTOL airplanes are given in (1) and for V/STOL airplanes in (2). Pilot opinion ratings, obtained in simulations or from actual flight test, are nearly always used in assessing whether the airplane, in fact, does have satisfactory handling qualities (3).

Although considerable research has been done on the effects of atmospheric turbulence on V/STOL aircraft handling qualities (most of this has been ground-based simulations), very little usable results have appeared in the form of concrete specifications or design criteria. It is generally true that pilot rating deteriorates as turbulence is added in increasing intensity to a handling qualities simulation. But just how this effect should be reflected in the specification is not clear (8, 9). Also, ratings for a given airplane in turbulence and IFR flight are likely to be worse than the same situation in VFR (Visual Flight Rules) conditions. Designers do not know how to translate this into design specifications either. The type, arrangement, and dynamics of the flight instrument displays are obviously an important factor in IFR handling qualities in turbulence. But the way these factors should be properly accounted for in the design criteria is an elusive question.

For V/STOL aircraft to take full advantage of the new terminal area air traffic control systems based on the scanning beam microwave instrument landing systems (MLS), these airplanes must be capable of precise following of the three-dimensional curved approaches at glide slope angles up to 20 degrees (10). This will require excellent IFR handling qualities in turbulent air. The DOT Air Traffic Control Advisory Committee has recommended rapid implementation of this new system (11).

In what follows, discussion will center on some of the ways turbulence is considered in the analysis of V/STOL aircraft dynamic response and stability augmentation system design, which are fundamental considerations in providing good handling qualities.

Dynamic Response

The design of control systems for V/STOL aircraft is still very much an art rather than a well defined and documented procedure. Attempts to apply analytical methods which were developed for CTOL airplanes have had only limited success in many cases. One such area of limited success is in analytically modeling and analyzing the dynamic response to atmospheric turbulence during hover and transition flight. A fundamental difficulty in this case involves providing a valid analytical representation of the turbulence-generated disturbance forces and moments acting on the vehicle.

The sources of aerodynamic forces and moments are the three components of wind relative velocity U, V, and W referenced to an orthogonal body axes coordinate system fixed in the airplane, where, in general, each can contain a mean component U_0, V_0, and W_0 and turbulence or gust components u_g, v_g, and w_g. The coordinate is usually chosen so that the vertical component W_0 is zero. The magnitudes of u_g, v_g, and w_g vary with time and spatial position and create forces and moments on the airplane by primarily two mechanisms: 1) circulation lift due to Bernoulli's theorem and the Kutta-Joukowsky law of circulation, and 2) momentum transfer between the gust components and the airframe.

For aircraft in conventional flight, circulation lift is predominant. However, as a VTOL aircraft transitions to hovering flight, the contribution due to circulation decreases to the point where it may well be of the same order of magnitude as that due to momentum transfer, when turbulence is severe. Therefore, a valid aerodynamic theory in the hovering mode must account for both types of inputs.

Circulation lift theories are well-developed for conventional flight and express the results in Taylor series expansions involving coefficients and stability derivatives. Such theories are not nearly as accurate for VTOL hover due to violation of the small angle assumption on gust inputs; that is, inputs in the nonlinear range of the lift curve slope. There are no good aerodynamic theories which adequately describe the gust input forces and moments due to either circulation or momentum transfer, let alone both simultaneously, for VTOL vehicles in or near hover. Consequently, VTOL designers continue to use the stability derivative approach for describing vehicle gust input forces in hover, even though the applicability is questionable in many cases. It should be pointed out, however, that it is still probably accurate enough to use a Taylor series expansion of the aerodynamic forces and moments resulting from the motions of the aircraft. These motions are likely to be within the small perturbation assumption on the dependent variables such as pitch angle θ, angle of attack α, etc.—particularly where the VTOL aircraft has a stability augmentation system (as most do), which tends to maintain small angle responses to gusts and other disturbances.

There are two classes of atmospheric turbulence which act to disturb the flight of V/STOL aircraft: *homogeneous* and what I choose to call *heterogeneous*. Homogeneous turbulence refers to that which can be described in a statistical sense through use of power spectral density techniques. Heterogeneous refers to discrete turbulence such as vortex patterns and shears generated by obstacles, trees, hills, buildings, etc. Methods of analysis of the dynamic response of aircraft subjected to homogeneous turbulence are fairly well established (4, 5, 7, 13, 14). However, very little has been done in the way of dynamic response analysis under heterogeneous turbulence inputs.

Reference (6) is the only work of which this writer is aware that analyzes the response of V/STOL aircraft to such discrete turbulence. The XC-142A airplane was analytically subjected to vortex turbulence in the hover flight mode. The velocity discontinuity at the center of the vortex causes a rapid reversal in the moment applied to the airplane as the vortex passes over. The vortex tangential velocity is given by

$$V_T = \frac{A}{B + |r|} \operatorname{sgn}(r) \qquad [1]$$

where A and B are adjustable parameters of the vortex and r the radial distance. The XC-142A was idealized to flat plate planform geometry and momentum transfer theory applied to compute the forces and moments on the aircraft due to vortex patterns traversing over the aircraft from various directions. A nose-to-tail traverse would cause rapid pitch and yaw reversals, depending on the orientation of the vortex axis relative to the airplane. Likewise, a wing tip—to wing tip traverse would result in rapid roll and yaw reversals. Severe disturbances of this type put extreme demands on the pilot and stability augmentation system and quite possibly will represent the critical design conditions for V/STOL aircraft control systems. Much more work is needed to effectively relate vortex and wind shear turbulence to control system design requirements in a quantitative manner.

Control Power

A number of VTOL crashes have been attributed to a lack of sufficient control power to stabilize the aircraft in turbulence. Control power is most often defined as the angular acceleration produced by a control input. For example, instantaneous yaw control power is given by

$$CP(t) = N_{\delta_r} \delta_r(t) \qquad [2]$$

where $\delta_r(t)$ is the yaw control, usually rudder deflection or its equivalent in terms of reaction jet thrusting, and $N\delta_r$ is the control sensitivity (change in yawing moment due to unit δ_r divided by aircraft yaw mass moment of inertia). Similar expressions give control power in roll and pitch. This definition applies to the control power needed for maneuvering and that needed for stability augmentation about a trimmed flight condition.

There is a critical need for better methods of determining the minimum levels of control power necessary to provide adequate stabilization and maneuverability for VTOL aircraft. An insufficient amount is unsafe and an excess reduces the available lift engine thrust, as control power is obtained by bleeding air or modulating thrust from the propulsion system. The amount needed for maneuvering is generally independent of aircraft size and dynamic characteristics. However, that needed for stabilization is strongly dependent on aircraft size, open-loop dynamics, the type and amount of stability augmentation provided, and the turbulence environment. Analytical design methods are needed which structure the stability augmentation system required for satisfactory aircraft handling qualities, while simultaneously yielding the minimum required values of stabilization control power. One such approach (15) is described next.

Stability Augmentation

The published research literature and the VTOL aircraft built to date give no indication that designers have recognized the importance of the type of feedback control system used on the resulting control power requirements. Most three-axis stability augmentation systems have employed conventional attitude and rate feedback loops with no regard for what this control law structure means in terms of stabilization control power levels. For example, most vehicles in a hovering mode have nonminimum phase transfer functions and require unnecessarily high control power levels when stabilized by conventional servoanalysis design techniques. It has been shown that modern linear state variable control synthesis methods can be used for direct synthesis of stability augmentation systems yielding prescribed handling qualities and minimum stabilization control power (15). These methods are applied to the task of synthesizing a lateral-directional stability augmentation system for the Doak VZ-4 tilt-duct VTOL aircraft. The chosen flight condition was hover at 100 feet over a fixed ground point in turbulent air with a 35 knot mean headwind. The equations of motion were put in the so-called "phase variable canonical form" of [3], where d_0, d_1, d_2, and d_3 are the coefficients of the open-loop characteristic equation.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -d_0 & -d_1 & -d_2 & -d_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \delta_r \end{bmatrix} \qquad [3]$$

It is well known in modern linear control theory that a single control input variable (rudder control in this case) can achieve any desired set of closed-loop poles if all state variables are fed back, and the resulting closed-loop characteristic equation will be the same order as that for the open-loop (fourth-order in this case). Furthermore, the control law is of the form in [4] and is optimal in that the weighted time integral of δ_r^2 is a minimum, which means minimum control power.

$$\delta_r = -k_1x_1-k_2x_2-k_3x_3-k_4x_4 \qquad [4]$$

Combining [3] and [4] gives [5]

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -(d_0+k_1) & -(d_1+k_2) & -(d_2+k_3) & -(d_3+k_4) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \qquad [5]$$

The last row elements in [5] are now the coefficients of the closed-loop characteristic equation, and the k values can be chosen to give desired handling qualities in terms of closed-loop roots.

The next question is what does the control law of [4] mean in terms of control power requirements? Disregarding gust velocity spatial distribution effects, which are important when making an accurate analysis (13, 14) only the lateral component of gust velocity v_g excites lateral-directional responses. The closed-loop transfer function G(s) relating δ_r to v_g can easily be obtained and gives

$$\delta_r(s) = G(s)v_g(s) \qquad [6]$$

where s is the Laplace complex variable. The power spectral density of δ_r (assuming homogeneous turbulence) is

$$\Phi_{\delta_r}(s) = |G(s)|^2 \, \Phi_{v_g}(s) \qquad [7]$$

where $\Phi_{v_g}(s)$ is the PSD of v_g, frequently represented in the form of [8] and [9].

$$\Phi_{v_g}(s) = 2\sigma_{v_g}^2 \frac{L}{U_o} \frac{1}{1-\left(\frac{Ls}{U_o}\right)^2} \qquad [8]$$

$$\sigma_{v_g}^2 = \frac{1}{2\pi j}\int_{-j\infty}^{j\infty} \Phi_{v_g}(s)ds \qquad [9]$$

σ_{v_g} is the rms value of v_g, L the integral scale of low altitude turbulence, and U_o the mean wind speed.

The rms value of δ_r is then

$$\sigma^2_{\delta_r} = \frac{1}{2\pi j}\int_{-j\infty}^{j\infty} \Phi_{\delta_r}(s)ds \qquad [10]$$

From [2], the rms value of control power is

$$CP_{rms} = N_{\delta_r}\sigma_{\delta_r} \qquad [11]$$

If one were to specify that the installed available control power be the "three-sigma" value given by [12], this would mean that the probability of the instantaneous required control power exceeding that available is 0.0027. In other words, 99.73% of the time the amount installed would be sufficient for stabilization purposes.

$$CP_{available} = 3N_{\delta_r}\sigma_{\delta_r} \qquad [12]$$

The above outlined approach takes into account the aircraft open-loop dynamics, the stability augmentation which yields desired handling qualities, and the homogeneous turbulence. The amount of control power needed for stabilization in heterogeneous turbulence and that needed for maneuvering capability would be additional requirements. However, the minimum total requirement would be less than the sum of the three components, since the probability of needing instantaneously the maximum of each component is negligibly small.

Concluding Remarks

To provide safe, efficient control for V/STOL aircraft of the future, more research must be done on determining what constitutes desired VFR and IFR handling qualities in turbulence and casting such requirements into a useable design specification.

To make full use of the coming scanning beam microwave instrument landing systems for V/STOL, much better flight control systems will be needed than past aircraft have had. Precise control of the flight path in turbulence will be essential, and this likely means high levels of stability augmentation.

Literature Cited

1. CHALK, C. R., T. P. NEAL, T. M. HARRIS, F. E. PRITCHARD, and R. J. WOODCOCK. 1969. Background information and user guide for MIL-F-8785B (ASG), military specification-flying qualities of piloted airplanes. AFFDL-TR-67-72. Wright-Patterson AFB, Ohio 690 p.

2. CHALK, C. R., D. L. KEY, J. KROLL, JR., R. WASSERMAN, and R. C. RADSFORD. 1971. Background information and user guide for MIL-F-83300, military specification-flying qualities of piloted V/STOL aircraft. AFFDL-TR-70-88. Wright-Patterson AFB, Ohio. 499 p.

3. COOPER, G. E., and R. P. HARPER, JR. 1969. The use of pilot rating in the evaluation of aircraft handling qualities. NASA TN D-5153. Ames Res. Cent. Moffett Field, Calif. 52 p.

4. EGGLESTON, J. M., and W. H. PHILLIPS. 1960. The lateral response of airplanes to random atmospheric turbulence. NASA TR R-74. Langley Res. Cent. Hampton, Va. 59 p.

5. ETKIN, B. 1959. A theory of the response of airplanes to random atmospheric turbulence, J. Aero/Space Sci. 26:409-420.

6. GOGOSHA, O. R., and T. E. MORIARTY. 1967. The response of a hovering V/STOL aircraft to discrete turbulence. GGC/EE/67-7. AF Inst. of Tech. Wright-Patterson AFB, Ohio. 103 p.

7. HOUBOLT, J. C., R. STEINER, and K. G. PRATT. 1964. Dynamic response of airplanes to atmospheric turbulence including flight data on input and response. NASA TR R-199. Langley Res. Cent. Hampton, Va. 115 p.

8. INNIS, R. C., C. A. HOLZHAUSER, and H. C. QUIGLEY. 1970. Airworthiness consideration for STOL aircraft. NASA TN D-5594. Ames Res. Cent. Moffett Field, Calif. 65 p.

9. KROLL, J., JR. 1968. Initial VTOL flight control design criteria development-discussion of selected handling qualities topics. AFFDL-TR-67-151. Wright-Patterson AFB, Ohio. 162 p.

10. Federal Aviation Admin. 1971. National plan for development of the microwave instrument landing system. Wash., D.C. 93 p.

11. Dep. of Transportation 1969. Report of department of transportation air traffic control advisory committee, Vol. 1. Wash., D.C. 105 p.

12. SEAVER, E. R. 1970. Northeast corridor VTOL investigation. Docket 19078. U.S. Civil Aero. Bd. Wash., D.C. 119 p.

13. SKELTON, G. B. 1968. Investigation of the effects of gusts on V/STOL aircraft in transition and hover. AFFDL-TR-68-85. Wright-Patterson AFB, Ohio. 150 p.

14. SWAIM, R. L., and A. L. CONNORS. 1968. Gust velocity spatial distribution effects on lateral-directional response of VTOL aircraft. J. Aircraft. 5:53-59.

15. SWAIM, R. L. 1970. Minimum control power for VTOL aircraft stability augmentation. J. Aircraft. 7:231-235.

16. Federal Aviation Admin. 1970. Tentative airworthiness standards for powered lift transport category aircraft. Wash., D.C. 229 p.