AIRPLANE DESIGN FOR GUSTS

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I. Structural Design for Gusts

Two basic approaches are generally used for the structural design of aircraft due to gust encounter. One is a discrete gust approach, the other is based on power spectral techniques. Both of these approaches are explained quite thoroughly in References 1 and 2, and thus only a brier coverage is given here. Figure 1 gives the essentials of the discrete gust approach. The incremental load factor An is computed by the equation shown, where K is found from the K_g curve shown on the left. A representative design level for the gust velocity U is 50 fps (equivalent air speed) for altitudes below 20,000 ft. and for cruise airplane speed. The An is added to the 1-g load factor to give the gust load design factor, or n = 1 + An; for design this load factor n

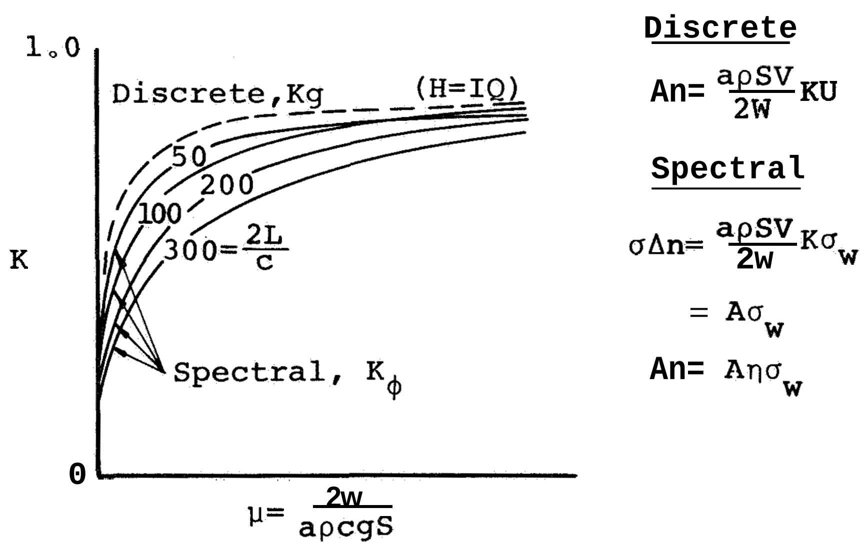


Figure 1 Gust Loads

is treated as though produced by a steady state maneuver load, and is considered to be associated with limit load conditions.

The essentials of the power spectral approach are shown in Figures 2 and 3, and in Figure 1. In reference to

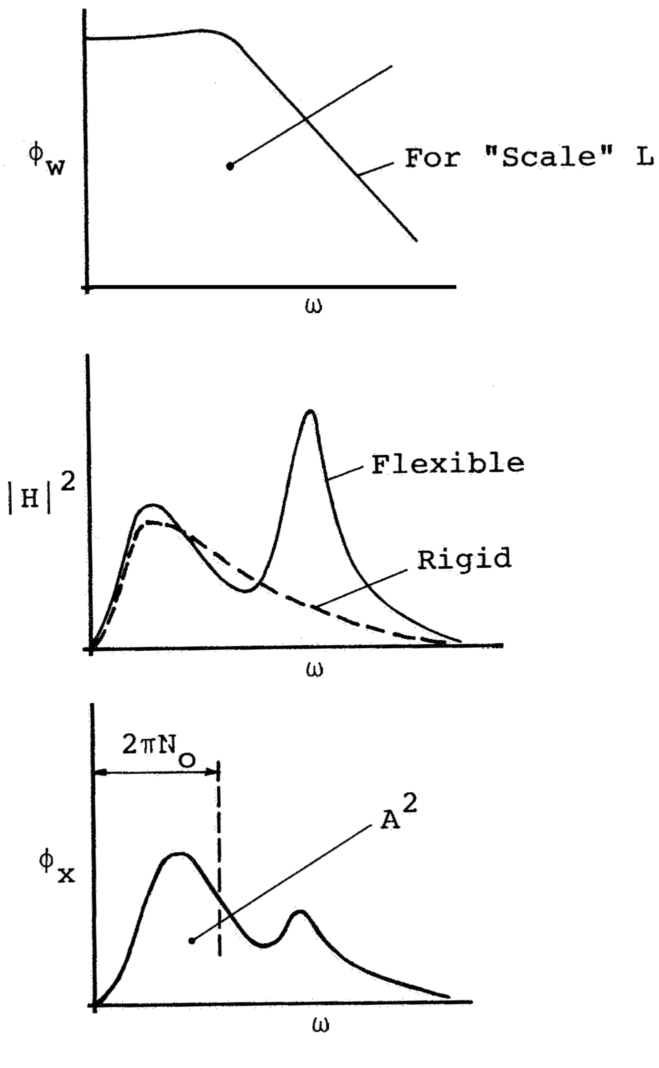


Figure 2 Elements of Power-Spectral Approach

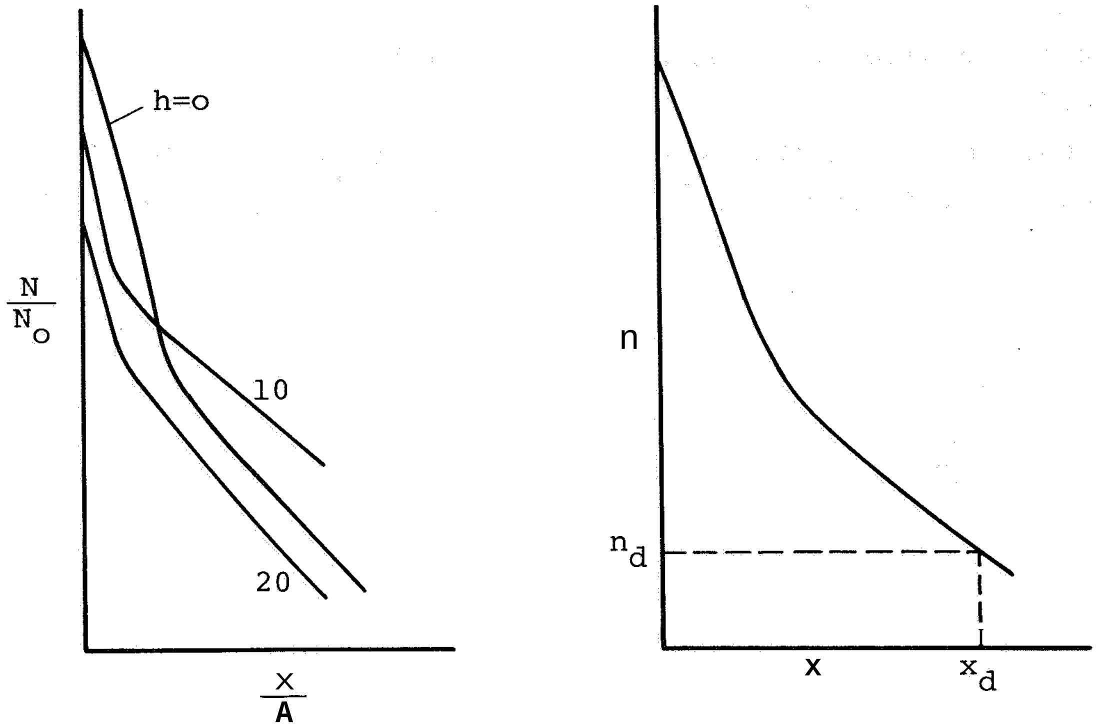


Figure 3 Exceedance Curves for Gust Loads

Figure 2, the input spectrum, as associated with the atmospheric turbulence encountered, is multiplied by the airplane transfer function $|H|^2$ to yield the output response spectrum Φ_x. Two basic parameters are deduced from the output spectrum; one is A which relates σ_x to σ_w according to the relation

$$\sigma_x = A\sigma_w$$

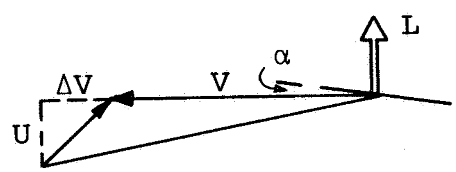
and the other is N_o. Specifically, the area under the spectrum is A^2, while the radius of gyration of this area about the vertical axis establishes N_o. Design can proceed in two ways. One procedure is analogous to the discrete gust design approach. The spectral equation for An shown in Figure 1 is used, where A is found using the solid K curves on the left. The value of the product $\eta\sigma_w$ is taken in the neighborhood of 60-80 fps. Note, Figure 1 applies to a rigid airplane with the degree of freedom of vertical motion only. For this case the type of evaluation shown in Figure 2 can be performed in generalized form, leading to the results given in Figure 1; for this procedure N_o is not used.

The second power spectral approach is shown in Figure 3. A mission profile for the aircraft is specified. Values of A and N_o for each segment of the mission are then evaluated. These values are then used in conjunction with the generalized load exceedance curves shown on the left to establish an expected load exceedance curve as shown on the right. Design is made such that the number of exceedances, n_d, in a specific "lifetime" does not exceed a certain value at the design limit load value x_d. The load exceedance curve established has a second significant use since it represents the expected structural fatigue loading on the airplane due to turbulence encounter.

II. Influence of Horizontal Gusts

Tacit to the discrete and power spectral approaches is the assumption that loading on the airplane arises primarily from vertical gusts. In the study of atmospheric turbulence, measurements have been made of not only the vertical component, but of the longitudinal and transverse gusts components as well. Very little has been done, however, to establish how the gust loads are influenced by the horizontal components; particularly the longitudinal or head-wind component. An analysis was therefore made to establish the loads that develop when explicit consideration is given to both the vertical and head-wind component. A summary of the results of this study is given in this section. (Note, in the measurement of vertical acceleration during gust encounter, some of the vertical loading may be due to the horizontal gusts; subsequent reduction of results to deduce vertical gust velocities assume, however, that only vertical gusts are acting.)

The following evaluation serves to give an indication of the relative influence of the vertical and head-on gusts. Consider an airplane flying at a speed V encountering an inclined gust which has a vertical component U and a horizontal component ΔV, as depicted in the following sketch:



If quasi-steady flow is assumed, the lift is given by

$$L = \frac{a}{2}\rho S(V + \Delta V)^2\left(\alpha + \frac{U}{V + \Delta V}\right)$$

Before the gust encounter the lift was equal to weight, or

$$W = \frac{a}{2}\rho S V^2 \alpha \ .$$

Division of these two equations yields

$$\frac{L}{W} = 1 + \left(2 + \frac{1}{\alpha}\frac{U}{V} + \frac{\Delta V}{V}\right)\frac{\Delta V}{V} + \frac{1}{\alpha}\frac{U}{V}$$

The first term on the right is associated with the 1-g level flight condition. The last term is the increment due to the vertical gust; its value may be in the order of 3. The middle term, which generally has not been considered, represents the magnitude of the loading that is due to the horizontal component, If $\frac{1}{\bar{\alpha}}\frac{U}{V}$ is 3, and for $\frac{\Delta V}{V}$ - 0.2 this term evaluates to 1.04; thus, the horizontal component of a gust may develop a vertical load on the airplane of the same order of magnitude as the airplane weight.

This rough analysis shows that in establishing structural loads, the inclusion of horizontal gusts appears significant. To gain further insight, a more refined analysis was made, wherein nonsteady lift effects and gust penetration effects due to both vertical and horizontal gusts were included. The analysis yielded two primary results, described in schematic form by the aid of Figure 4. One result, curve B, gives the combinations of U and V at which aerodynamic stall of the airplane occurs; the stall region is above the curve. The second result, curve A, gives the combinations of U and V which could develop structural loads of sufficient magnitude to cause structural breakup; the failure side is above. Consideration of both curves, then, defines a failure region, as shown by the shaded region on the figure. The lower edge of this region

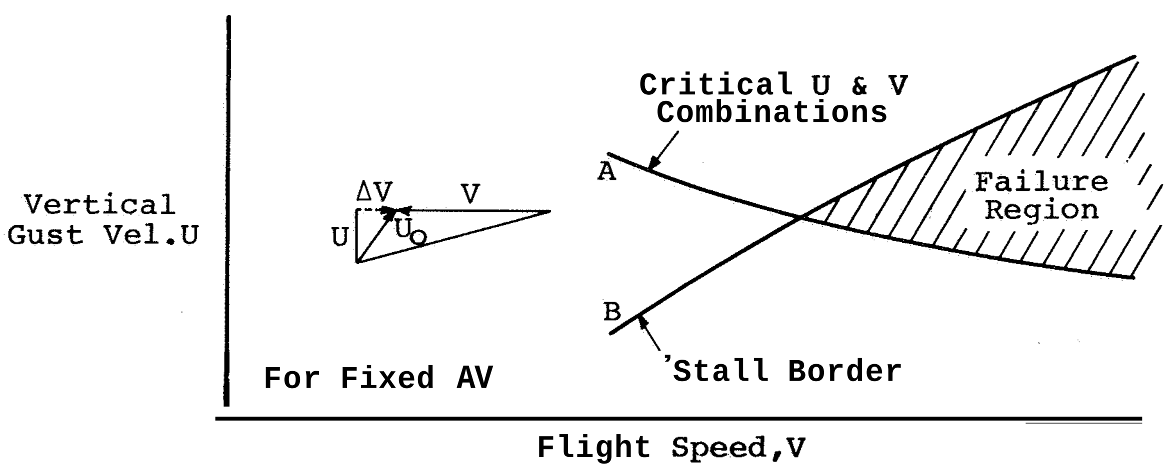


Figure 4

is of prime concern since, for a given V, it indicates the lowest value of U which can cause structural failure, but still not cause stall conditions for the airplane. Note, to the left of the crossing point, failure cannot occur because stall is encountered with increasing U, again for a fixed V, before a failing type load can be reached.. Note also, the results are for a specific choice of AV.

The applications of the analysis to a specific large airplane configuration yielded the results shown in Figure 5. The results apply to the outboard wing section. Part (a), for AV = 0, shows the sensitivity of the results to two parameters of the problem, the slope of the lift curve a, and the effective quasi-steady flight load on the airplane. It must be recognized that in flight through severe turbulence, the pilot is struggling to maintain control of the airplane; in this effort, an effective load factor greater

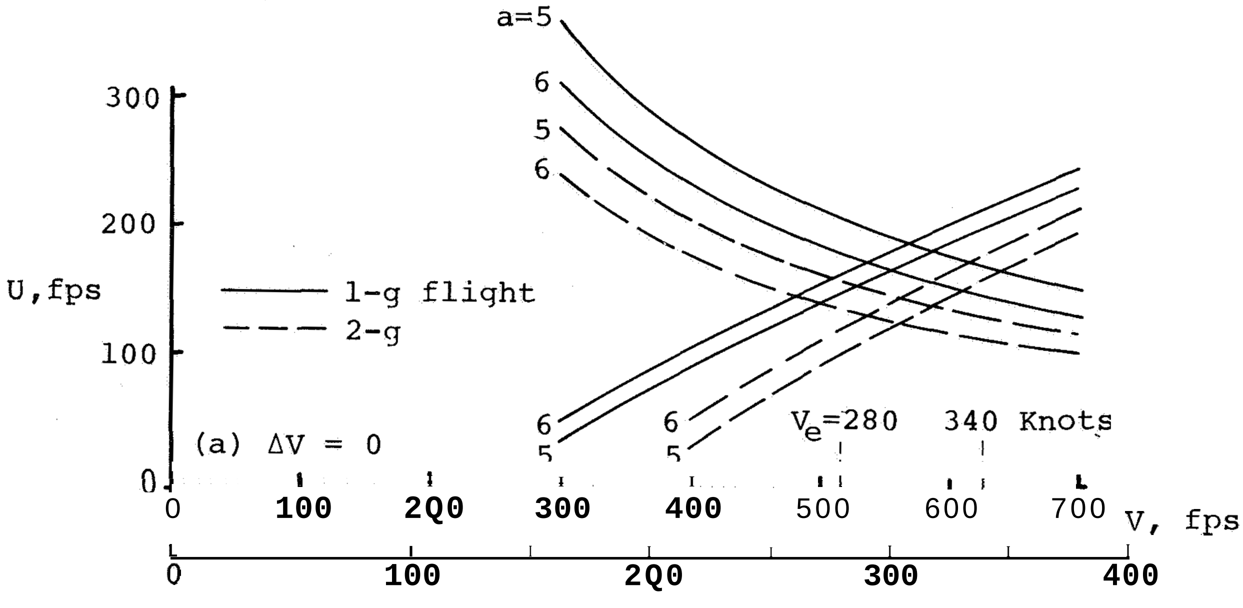


Figure 5

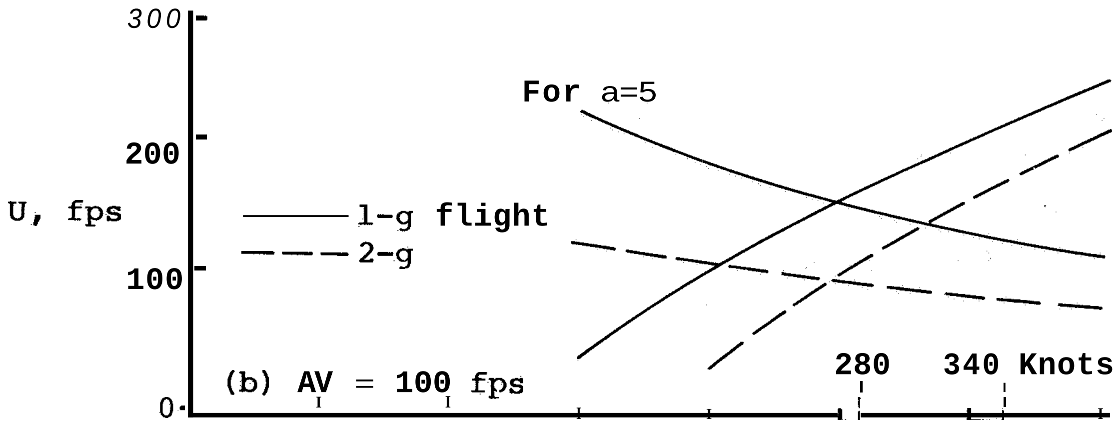


Figure 5, (Cont.)

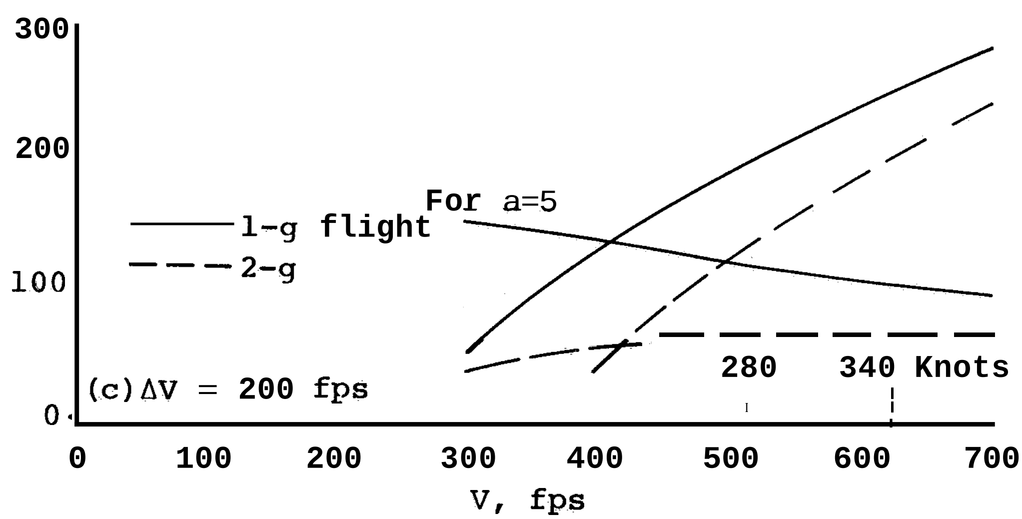


Figure 5, (Cont,)

than the level flight 1-g condition may be induced at a given wing station either by a pullup type maneuver or by a rolling motion on the airplane. Both the lift curve slope and the effective maneuver factor are seen to have a very significant influence on the critical combinations U and V. By contrast with Figure 5(a), results for AV of 100 and 200 fps are shown in parts (b) and (c), but only for a = 5. (The vertical ticks at 280 and *340* knots define an estimated range in speed for the particular airplane under consideration at the time of turbulence encounter.) The primary result brought out by Figure 5 is that the inclusion of the horizontal gust component AV can have a very significant effect on the combinations of U and V which can produce failure type loading conditions.

A cross plot of the results shown in Figure 5 is shown in Figure 6. This plot emphasizes the importance of knowing various flight conditions in inferring what gust velocities are needed to lead to failure type structural loads. As an example, if we consider the airplane in 1-g flight and travelling at 600 fps, and take AV = 0, then we see that a U of around 180 fps is necessary to cause failure. If U and AV are taken about equal, which is more likely, then the U causing failing loads is about 130 fps. If the wing is experiencing a 2-g loading, then U and AV need only be around 100 fps to produce failure type loading; this observation is seen to apply even for a flight speed of 500 fps. It should be remarked that the results shown in Figures 5 and 6 are conservative in a sense, since certain load aggravating effects were not included. The analysis is based on a rigid airplane encountering a single discrete gust that is uniform in the spanwise direction. The following three load amplifying effects are thus not taken into account: (1) the continuous nature of turbulence or the possibility that a

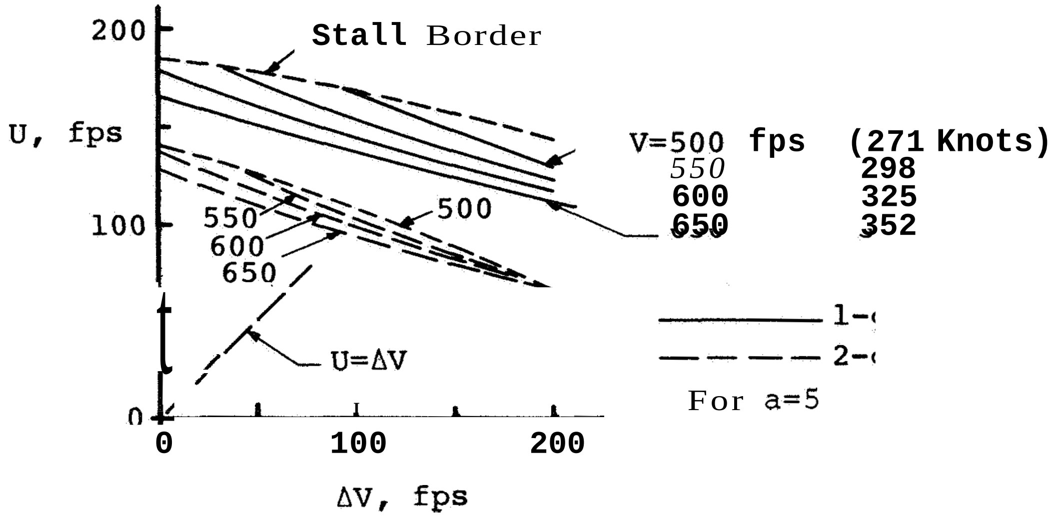


Figure 6

down gust may follow an up gust, (2) dynamic amplification effects due to aircraft flexibility, and (3) the nonuniformity of the turbulence in the spanwise direction. The inclusion of these effects would probably indicate smaller values of U and ΔV to produce failure.

A few comments on the measurement of turbulence are made to end this section. Systematic measurement of the U and ΔV components have been made in clear air turbulence and in cumulus clouds, and some probing has been done near thunderstorms. Unfortunately, systematic measurements in or near thunderstorms of the more severe or extreme combinations of U and ΔV have not been made, The reason is, of course, understandable because any attempt to make such measurements with the type aircraft probes normally used would cause destruction of the aircraft. Systematic measurements of the various components of turbulence in the vicinity of thunderstorms with "rigid" fighter type aircraft are very much in need.

With respect to the use of radar to interpret turbulence severity near or in thunderstorms, much has been done to correlate the various signature patterns with broad levels of turbulence severities. Identification of localized areas of extreme combinations of U and **AV** does not, however, appear possible from the signatures obtained with present equipment. Airplane flight in or near thunderstorms should in general be avoided. But if such flights are to be made for some reason, then for safe flight we need reliable ways to interpret radar signatures, or other measurements, to pinpoint areas of severe combinations of U and AV, *so* that these areas can be avoided.

III. Gust Effects During Landing Approach

Some brief comments of a general nature are made in this section on gust effects during landing. The previous sections dealt mainly with gust loads as influencing aircraft strength. Gust loading is also of concern, however, during takeoff and in the landing approach of an airplane. The concern in these stages of flight is mainly with respect to maintaining control of the attitude, altitude, and power setting of the airplane. During approach, in particular, we need to know not only the variation in turbulence along the flight path, but we need to know its spatial distribution about the airplane. The gusts acting, for example, on the left wing, the right wing, and the vertical tail may all be different, see Figure 7. For approach simulation studies, we need to know these quantities better, not only to be able to apply more realistic values of forces on the airplane, but also to apply realistic values of pitching, yawing, and rolling moments.

For Approach Simulation

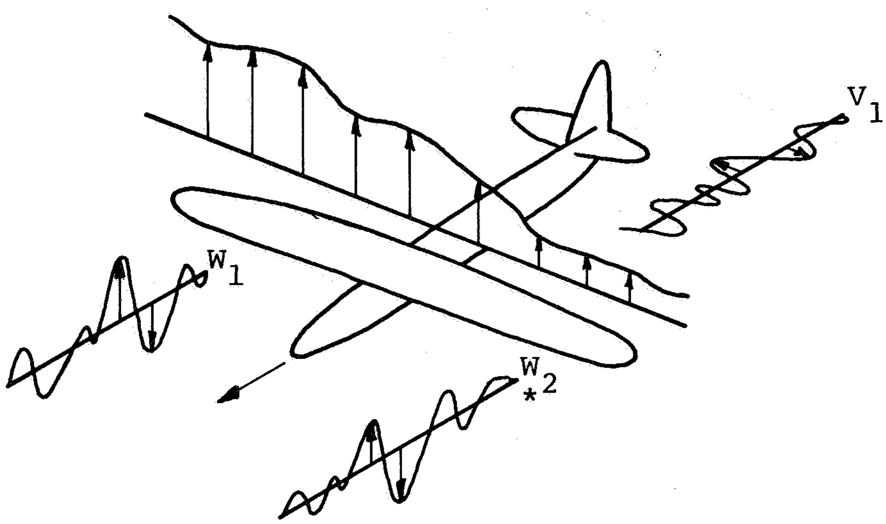


Figure 7

An ideal facility to measure these turbulence velocities would be a track centered along the approach path to a runway, with a cart that could measure the u, v, and w components of turbulence at various spatial points, see Figure 8. The feasibility of constructing such a facility is, of course, not very good; the main point to be made, however, is that measurements of the type that could be made with such a facility are needed.

The Ideal Facility for Approach Turbulence Studies

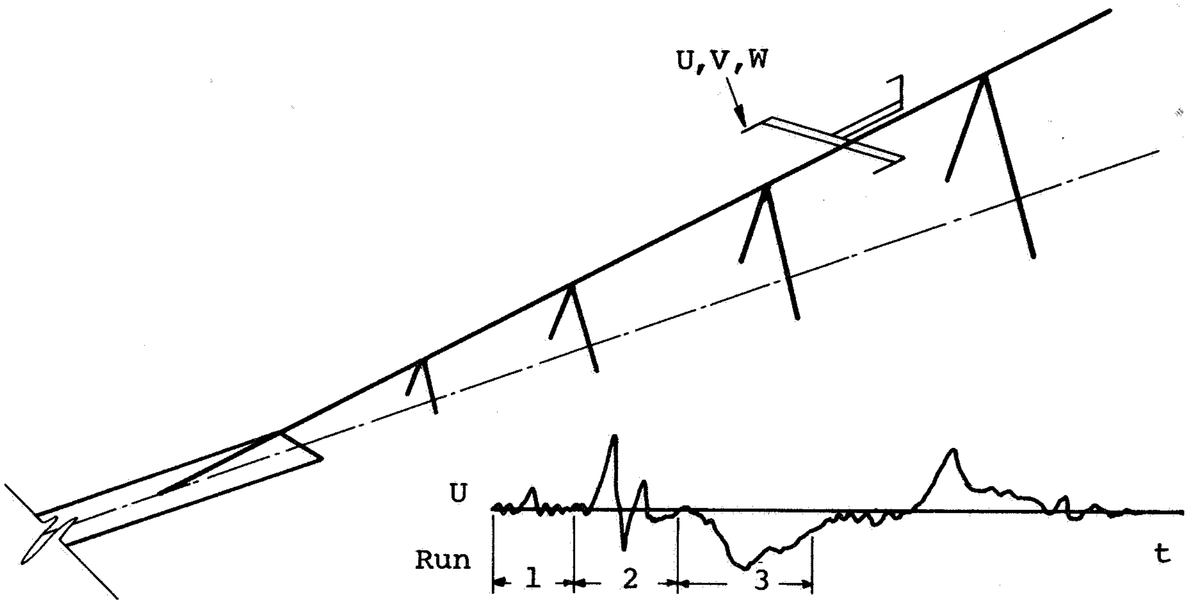
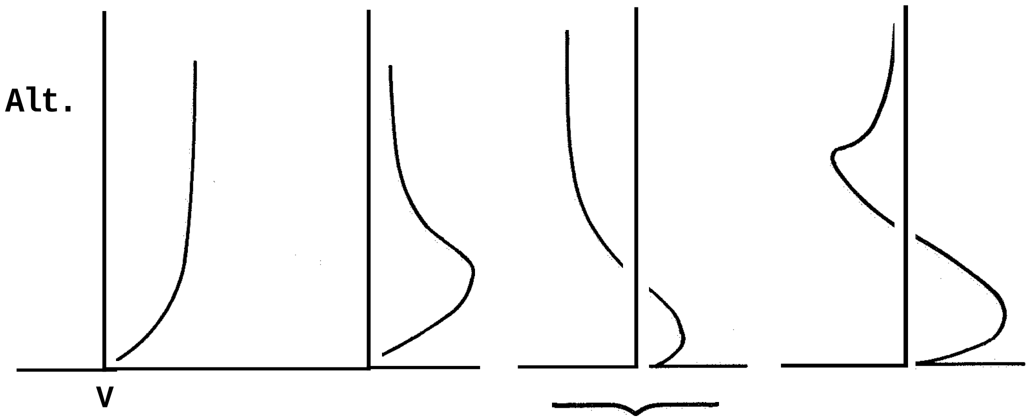


Figure 8

With respect to the wind shear problem, more information on the wind profiles that are encountered during approach is needed. Possibly we need to establish a stable of the types of wind profiles that are encountered, Figure 9. It may be that, out of this stable of profiles, there may be a distinct type that could serve as critical wind shear profile for landing approach studies, just as the discrete-gust profile has been used for years for strength design. Most urgently needed in the wind shear problem is the means €or predicting when a non-negotiable profile may exist.

Need "Stable" of Wind Profiles



The Discrete
"Critical"Profile

Figure 9

References

1. Houbolt, John C. "Dynamic Response of Airplanes to Atmospheric Turbulence Including Flight Data on Input and Response." NASA TR R-199, June 1964.

2. Houbolt, John C. "Design Manual for Vertical Gusts Based on Power Spectral Techniques." AFFDL-TR-70-106, December 1970.