(5) If necessary for the assessment of loads on aeroplanes with significant non-linearities, it must be assumed that the turbulence field has a root-mean-square velocity equal to 40 percent of the U_σ values specified in subparagraph (3). The value of limit load is that load with the same probability of exceedance in the turbulence field as $\bar{A}U\sigma$ of the same load quantity in a linear approximated model.

(c) Supplementary gust conditions for wing mounted engines. For aeroplanes equipped with wing mounted engines, the engine mounts, pylons, and wing supporting structure must be designed for the maximum response at the nacelle centre of gravity derived from the following dynamic gust conditions applied to the aeroplane:

(1) A discrete gust determined in accordance with CS 25.341(a) at each angle normal to the flight path, and separately,

(2) A pair of discrete gusts, one vertical and one lateral. The length of each of these gusts must be independently tuned to the maximum response in accordance with CS 25.341(a). The penetration of the aeroplane in the combined gust field and the phasing of the vertical and lateral component gusts must be established to develop the maximum response to the gust pair. In the absence of a more rational analysis, the following formula must be used for each of the maximum engine loads in all six degrees of freedom:

$$P_L = P_{L-1g} \pm 0.85 \sqrt{\left({L_{Vi}}^2 + {L_{Li}}^2\right)}$$

Where:

P_L = limit load;

P_{L-1g} = steady 1-g load for the condition;

L_V = peak incremental response load due to a vertical gust according to CS 25.341(a); and

L_L = peak incremental response load due to a lateral gust according to CS 25.341(a).

[Amdt 25/1]
[Amdt 25/12]

AMC 25.341 Gust and Continuous Turbulence Design Criteria (Acceptable Means of Compliance)

ED Decision 2019/013/R

1. PURPOSE. This AMC sets forth an acceptable means of compliance with the provisions of CS-25 dealing with discrete gust and continuous turbulence dynamic loads.

2. RELATED CERTIFICATION SPECIFICATIONS. The contents of this AMC are considered by the Agency in determining compliance with the discrete gust and continuous turbulence criteria defined in CS 25.341. Related paragraphs are:

CS 25.343	Design fuel and oil loads
CS 25.345	High lift devices
CS 25.349	Rolling conditions
CS 25.371	Gyroscopic loads
CS 25.373	Speed control devices

CS 25.391	Control surface loads
CS 25.427	Unsymmetrical loads
CS 25 445	Auxiliary aerodynamic surfaces
CS 25.571	Damage-tolerance and fatigue evaluation of structure

Reference should also be made to the following CS paragraphs: CS 25.301, CS 25.302, CS 25.303, CS 25.305, CS 25.321, CS 25.335, CS 25.1517.

3. OVERVIEW. This AMC addresses both discrete gust and continuous turbulence (or continuous gust) requirements of CS-25. It provides some of the acceptable methods of modelling aeroplanes, aeroplane components, and configurations, and the validation of those modelling methods for the purpose of determining the response of the aeroplane to encounters with gusts.

How the various aeroplane modelling parameters are treated in the dynamic analysis can have a large influence on design load levels. The basic elements to be modelled in the analysis are the elastic, inertial, aerodynamic and control system characteristics of the complete, coupled aeroplane (Figure 1). The degree of sophistication and detail required in the modelling depends on the complexity of the aeroplane and its systems.

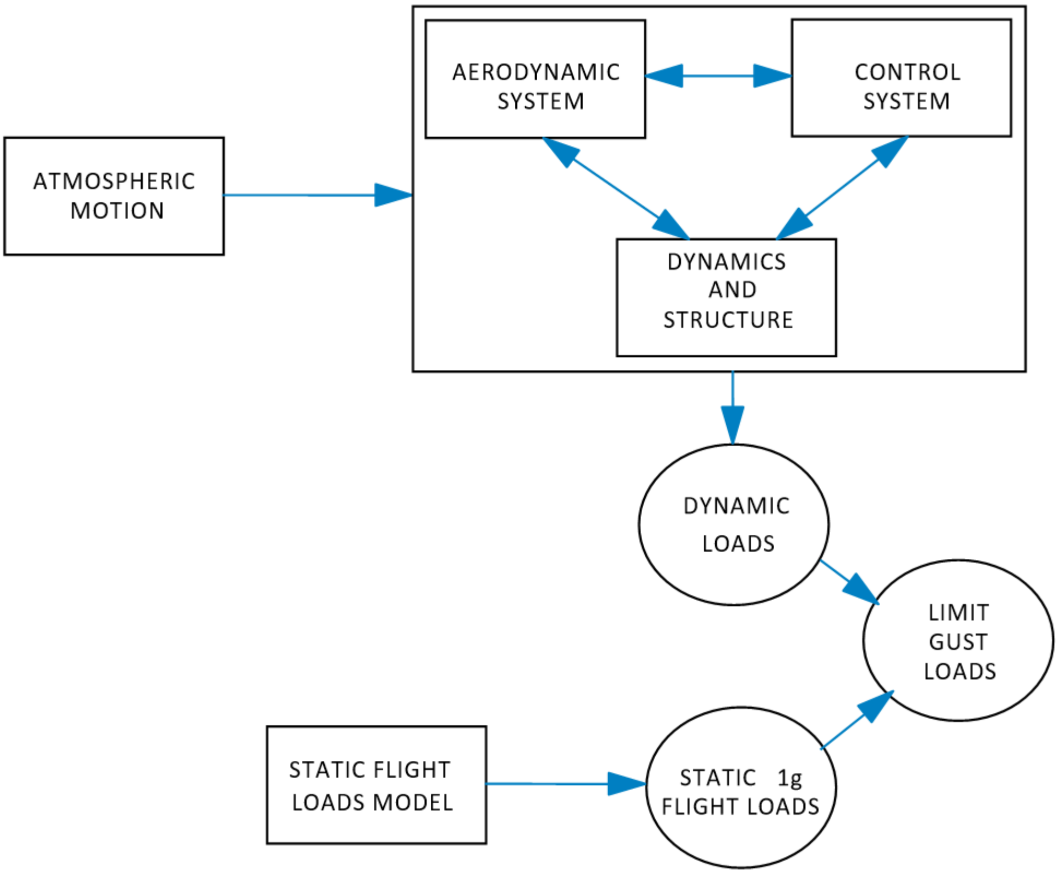

Figure 1 Basic Elements of the Gust Response Analysis

Design loads for encounters with gusts are a combination of the steady level 1-g flight loads, and the gust incremental loads including the dynamic response of the aeroplane. The steady 1-g flight loads can be realistically defined by the basic external parameters such as speed, altitude, weight and fuel load. They can be determined using static aeroelastic methods.

The gust incremental loads result from the interaction of atmospheric turbulence and aeroplane rigid body and elastic motions. They may be calculated using linear analysis methods when the aeroplane and its flight control systems are reasonably or conservatively approximated by linear analysis models.

Non-linear solution methods are necessary for aeroplane and flight control systems that are not reasonably or conservatively represented by linear analysis models. Non-linear features generally raise the level of complexity, particularly for the continuous turbulence analysis, because they often require that the solutions be carried out in the time domain.

The modelling parameters discussed in the following paragraphs include:

— Design conditions and associated steady, level 1-g flight conditions.

— The discrete and continuous gust models of atmospheric turbulence.

— Detailed representation of the aeroplane system including structural dynamics, aerodynamics, and control system modelling.

— Solution of the equations of motion and the extraction of response loads.

— Considerations for non-linear aeroplane systems.

— Analytical model validation techniques.

4. DESIGN CONDITIONS.

a. General. Analyses should be conducted to determine gust response loads for the aeroplane throughout its design envelope, where the design envelope is taken to include, for example, all appropriate combinations of aeroplane configuration, weight, centre of gravity, payload, fuel load, thrust, speed, and altitude.

b. Steady Level 1-g Flight Loads. The total design load is made up of static and dynamic load components. In calculating the static component, the aeroplane is assumed to be in trimmed steady level flight, either as the initial condition for the discrete gust evaluation or as the mean flight condition for the continuous turbulence evaluation. Static aeroelastic effects should be taken into account if significant.

To ensure that the maximum total load on each part of the aeroplane is obtained, the associated steady-state conditions should be chosen in such a way as to reasonably envelope the range of possible steady-state conditions that could be achieved in that flight condition. Typically, this would include consideration of effects such as speed brakes, power settings between zero thrust and the maximum for the flight condition, etc.

c. Dynamic Response Loads. The incremental loads from the dynamic gust solution are superimposed on the associated steady level flight 1-g loads. Load responses in both positive and negative senses should be assumed in calculating total gust response loads. Generally the effects of speed brakes, flaps, or other drag or high lift devices, while they should be included in the steady-state condition, may be neglected in the calculation of incremental loads.

d. Damage Tolerance Conditions. Limit gust loads, treated as ultimate, need to be developed for the structural failure conditions considered under CS 25.571(b). Generally, for redundant structures, significant changes in stiffness or geometry do not occur for the types of damage under consideration. As a result, the limit gust load values obtained for the undamaged aircraft may be used and applied to the failed structure. However, when structural failures of the types considered under CS 25.571(b) cause significant changes in stiffness or geometry, or both, these changes should be taken into account when calculating limit gust loads for the damaged structure.

5. GUST MODEL CONSIDERATIONS.

a. General. The gust criteria presented in CS 25.341 consist of two models of atmospheric turbulence, a discrete model and a continuous turbulence model. It is beyond the scope of this AMC to review the historical development of these models and their associated parameters. This AMC focuses on the application of those gust criteria to establish design limit loads. The discrete gust model is used to represent single discrete extreme turbulence events. The continuous turbulence model represents longer duration turbulence encounters which excite lightly damped modes. Dynamic loads for both atmospheric models must be considered in the structural design of the aeroplane.

b. Discrete Gust Model

(1) Atmosphere. The atmosphere is assumed to be one dimensional with the gust velocity acting normal (either vertically or laterally) to the direction of aeroplane travel. The one-dimensional assumption constrains the instantaneous vertical or lateral gust velocities to be the same at all points in planes normal to the direction of aeroplane travel. Design level discrete gusts are assumed to have 1-cosine velocity profiles. The maximum velocity for a discrete gust is calculated using a reference gust velocity, U_{ref}, a flight profile alleviation factor, Fg, and an expression which modifies the maximum velocity as a function of the gust gradient distance, H. These parameters are discussed further below.

(A) Reference Gust Velocity, U_{ref} - Derived effective gust velocities representing gusts occurring once in 70,000 flight hours are the basis for design gust velocities. These reference velocities are specified as a function of altitude in CS 25.341(a)(5) and are given in terms of feet per second equivalent airspeed for a gust gradient distance, H, of 107 m (350 ft).

(B) Flight Profile Alleviation Factor, F_g - The reference gust velocity, Uref , is a measure of turbulence intensity as a function of altitude. In defining the value of Uref at each altitude, it is assumed that the aircraft is flown 100% of the time at that altitude. The factor F_g is then applied to account for the expected service experience in terms of the probability of the aeroplane flying at any given altitude within its certification altitude range. Fg is a minimum value at sea level, linearly increasing to 1.0 at the certified maximum altitude. The expression for Fg is given in CS 25.341(a)(6).

(C) Gust Gradient Distance, H - The gust gradient distance is that distance over which the gust velocity increases to a maximum value. Its value is specified as ranging from 9.1 to 107 m (30 to 350 ft). (It should be noted that if 12.5 times the mean geometric chord of the aeroplane’s wing exceeds 350 ft, consideration should be given to covering increased maximum gust gradient distances.)

(D) Design Gust Velocity, U_{ds} - Maximum velocities for design gusts are proportional to the sixth root of the gust gradient distance, H. The maximum gust velocity for a given gust is then defined as:

$$U_{ds} = U_{ref}\ F_g\ (H/350)^{(1/6)}$$

The maximum design gust velocity envelope, Uds, and example design gust velocity profiles are illustrated in Figure 2.

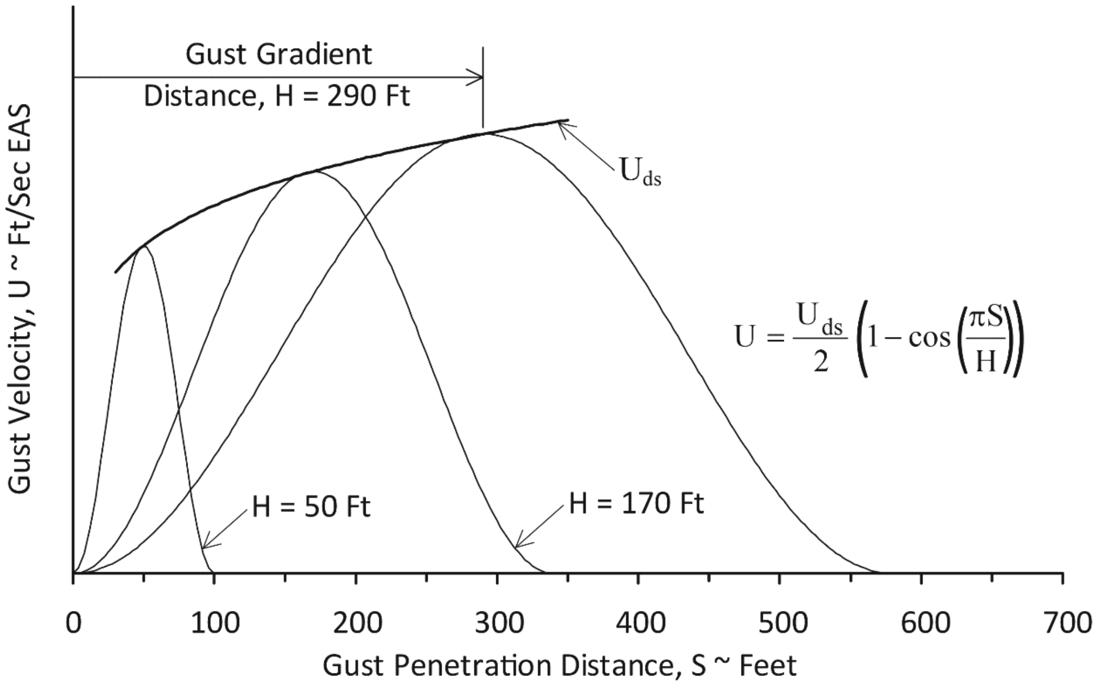

Figure-2 Typical (1-cosine) Design Gust Velocity Profiles

(2) Discrete Gust Response. The solution for discrete gust response time histories can be achieved by a number of techniques. These include the explicit integration of the aeroplane equations of motion in the time domain, and frequency domain solutions utilising Fourier transform techniques. These are discussed further in Paragraph 7.0 of this AMC.

Maximum incremental loads, P_{Ii}, are identified by the peak values selected from time histories arising from a series of separate, 1-cosine shaped gusts having gradient distances ranging from 9.1 to 107 m (30 to 350 ft). Input gust profiles should cover this gradient distance range in sufficiently small increments to determine peak loads and responses. Historically 10 to 20 gradient distances have been found to be acceptable. Both positive and negative gust velocities should be assumed in calculating total gust response loads. It should be noted that in some cases, the peak incremental loads can occur well after the prescribed gust velocity has returned to zero. In such cases, the gust response calculation should be run for sufficient additional time to ensure that the critical incremental loads are achieved.

The design limit load, P_{Li} , corresponding to the maximum incremental load, P_{Ii} for a given load quantity is then defined as:

$$P_{Li} = P_{(1-g)i} \pm P_{Ii}$$

Where $P_{(1-g)i}$ is the 1-g steady load for the load quantity under consideration. The set of time correlated design loads, P_{Lj} , corresponding to the peak value of the load quantity, P_{Li}, are calculated for the same instant in time using the expression:

$$P_{Lj} = P_{(1-g)j} \pm P_{Ij}$$

Note that in the case of a non-linear aircraft, maximum positive incremental loads may differ from maximum negative incremental loads.

When calculating stresses which depend on a combination of external loads it may be necessary to consider time correlated load sets at time instants other than those which result in peaks for individual external load quantities.

(3) Round-The-Clock Gust. When the effect of combined vertical and lateral gusts on aeroplane components is significant, then round-the-clock analysis should be conducted on these components and supporting structures. The vertical and lateral components of the gust are assumed to have the same gust gradient distance, H and to start at the same time. Components that should be considered include horizontal tail surfaces having appreciable dihedral or anhedral (i.e., greater than 10º), or components supported by other lifting surfaces, for example T-tails, outboard fins and winglets. Whilst the round-the-clock load assessment may be limited to just the components under consideration, the loads themselves should be calculated from a whole aeroplane dynamic analysis.

The round-the-clock gust model assumes that discrete gusts may act at any angle normal to the flight path of the aeroplane. Lateral and vertical gust components are correlated since the round-the-clock gust is a single discrete event. For a linear aeroplane system, the loads due to a gust applied from a direction intermediate to the vertical and lateral directions - the round-the-clock gust loads - can be obtained using a linear combination of the load time histories induced from pure vertical and pure lateral gusts. The resultant incremental design value for a particular load of interest is obtained by determining the round-the-clock gust angle and gust length giving the largest (tuned) response value for that load. The design limit load is then obtained using the expression for P_L given above in paragraph 5(b)(2).

(4) Supplementary Gust Conditions for Wing Mounted Engines.

(A) Atmosphere - For aircraft equipped with wing mounted engines, CS 25.341(c) requires that engine mounts, pylons and wing supporting structure be designed to meet a round-the-clock discrete gust requirement and a multi-axis discrete gust requirement.

The model of the atmosphere and the method for calculating response loads for the round-the-clock gust requirement is the same as that described in Paragraph 5(b)(3) of this AMC.

For the multi-axis gust requirement, the model of the atmosphere consists of two independent discrete gust components, one vertical and one lateral, having amplitudes such that the overall probability of the combined gust pair is the same as that of a single discrete gust as defined by CS 25.341(a) as described in Paragraph 5(b)(1) of this AMC. To achieve this equal-probability condition, in addition to the reductions in gust amplitudes that would be applicable if the input were a multi-axis Gaussian process, a further factor of 0.85 is incorporated into the gust amplitudes to account for non-Gaussian properties of severe discrete gusts. This factor was derived from severe gust data obtained by a research aircraft specially instrumented to measure vertical and lateral gust components. This information is contained in Stirling Dynamics Laboratories Report No SDL –571-TR-2 dated May 1999.

(B) Multi-Axis Gust Response - For a particular aircraft flight condition, the calculation of a specific response load requires that the amplitudes, and the time phasing, of the two gust components be chosen, subject to the condition on overall probability specified in (A) above, such that the resulting combined load is maximised. For loads calculated using a linear aircraft model, the response load may be based upon the separately tuned vertical and lateral discrete gust responses for that load, each calculated as described in Paragraph 5(b)(2) of this AMC. In general, the vertical and lateral tuned gust lengths and the times to maximum response (measured from the onset of each gust) will not be the same.

Denote the independently tuned vertical and lateral incremental responses for a particular aircraft flight condition and load quantity i by L_{Vi} and L_{Li}, respectively. The associated multi-axis gust input is obtained by multiplying the amplitudes of the independently-tuned vertical and lateral discrete gusts, obtained as described in the previous paragraph, by $0.85*L_{Vi}/\surd(L_{Vi}^2+L_{Li}^2)$ and $0.85*L_{Li}/\surd(L_{Vi}^2+L_{Li}^2)$ respectively. The time-phasing of the two scaled gust components is such that their associated peak loads occur at the same instant.

The combined incremental response load is given by:

$$P_{li} = 0.85\sqrt{\left({L_{Vi}}^2 + {L_{Li}}^2\right)}$$

and the design limit load, P_{Li}, corresponding to the maximum incremental load, P_{li}, for the given load quantity is then given by:

$$P_{Li} = P_{(1-g)i} \pm P_{li}$$

where $P_{(1-g)i}$ is the 1-g steady load for the load quantity under consideration.

The incremental, time correlated loads corresponding to the specific flight condition under consideration are obtained from the independently-tuned vertical and lateral gust inputs for load quantity i. The vertical and lateral gust amplitudes are factored by $0.85*L_{Vi}/\surd(L_{Vi}^2+L_{Li}^2)$ and $0.85*L_{Li}/\surd(L_{Vi}^2+L_{Li}^2)$ respectively. Loads L_{Vj} and L_{Lj} resulting from these reduced vertical and lateral gust inputs, at the time when the amplitude of load quantity i is at a maximum value, are added to yield the multi-axis incremental time-correlated value P_{lj} for load quantity j.

The set of time correlated design loads, P_{Lj}, corresponding to the peak value of the load quantity, P_{Li}, are obtained using the expression:

$$P_{Lj} = P_{(1-g)j} \pm P_{lj}$$

Note that with significant non-linearities, maximum positive incremental loads may differ from maximum negative incremental loads.

c. Continuous Turbulence Model.

(1) Atmosphere. The atmosphere for the determination of continuous gust responses is assumed to be one dimensional with the gust velocity acting normal (either vertically or laterally) to the direction of aeroplane travel. The one-dimensional assumption constrains the instantaneous vertical or lateral gust velocities to be the same at all points in planes normal to the direction of aeroplane travel.

The random atmosphere is assumed to have a Gaussian distribution of gust velocity intensities and a Von Kármán power spectral density with a scale of turbulence, L, equal to 2500 feet. The expression for the Von Kármán spectrum for unit, root-mean-square (RMS) gust intensity, $\Phi_I(\Omega)$, is given below. In this expression $\Omega = \omega/V$, where ω is the circular frequency in radians per second, and V is the aeroplane velocity in feet per second true airspeed.

$$\Phi(\Omega) = \frac{L}{\pi} \frac{1 + \frac{8}{3}(1.339\Omega L)^2}{\left[1 + (1.339\Omega L)^2\right]^{11/6}}$$

The Von Kármán power spectrum for unit RMS gust intensity is illustrated in Figure 3.

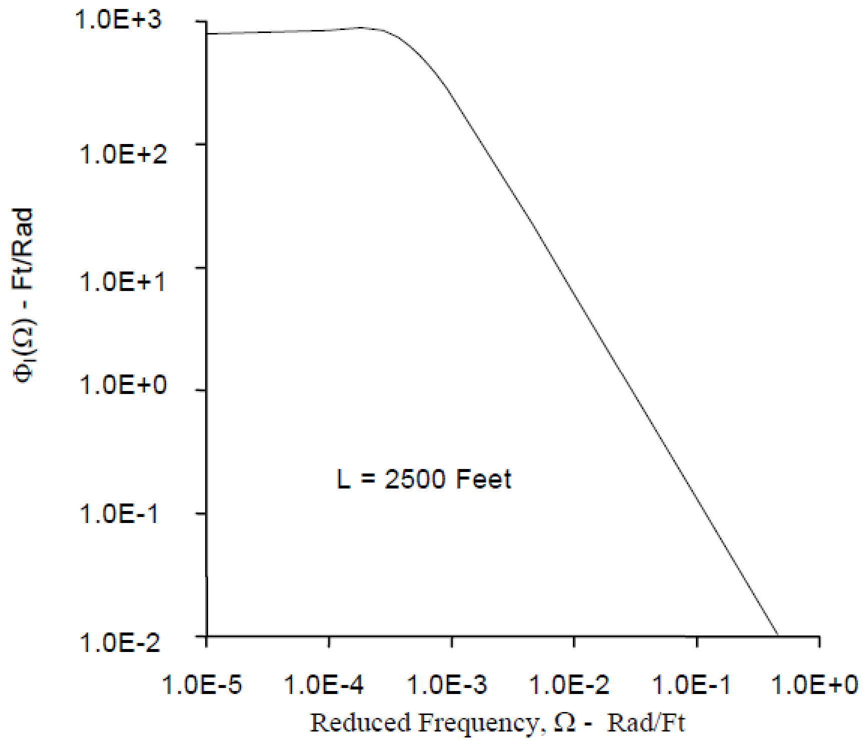

Figure-3 The Von Kármán Power Spectral Density Function, $\Phi_I(\Omega)$

The design gust velocity, U_σ, applied in the analysis is given by the product of the reference gust velocity, $U_{\sigma ref}$, and the profile alleviation factor, Fg, as follows:

$$U_\sigma = U_{ref}\, F_g$$

where values for $U_{\sigma ref}$, are specified in CS 25.341(b)(3) in meters per second (feet per second) true airspeed and Fg is defined in CS 25.341(a)(6). The value of Fg is based on aeroplane design parameters and is a minimum value at sea level, linearly increasing to 1.0 at the certified maximum design altitude. It is identical to that used in the discrete gust analysis.

As for the discrete gust analysis, the reference continuous turbulence gust intensity, Uσref, defines the design value of the associated gust field at each altitude. In defining the value of Uσref at each altitude, it is assumed that the aeroplane is flown 100% of the time at that altitude. The factor Fg is then applied to account for the probability of the aeroplane flying at any given altitude during its service lifetime.

It should be noted that the reference gust velocity is comprised of two components, a root-mean-square (RMS) gust intensity and a peak to RMS ratio. The separation of these components is not defined and is not required for the linear aeroplane analysis. Guidance is provided in Paragraph 8.d. of this AMC for generating a RMS gust intensity for a non-linear simulation.

(2) Continuous Turbulence Response. For linear aeroplane systems, the solution for the response to continuous turbulence may be performed entirely in the frequency domain, using the RMS response. is defined in CS 25.341(b)(2) and is repeated here in modified notation for load quantity i, where:

$$\bar{A}_i = \left[\int_0^\infty |h_i(\Omega)|^2 \ \Phi_I(\Omega) d\Omega \right]^{1/2}$$

or

$$\bar{A}_i = \left[\int_0^\infty \Phi_I(\Omega)\, h_i(i\Omega) h_i^{\,*}(i\Omega) d\Omega \right]^{1/2}$$

In the above expression $\Phi_I(\Omega)$ is the input Von Kármán power spectrum of the turbulence and is defined in Paragraph 5.c.(1) of this AMC, $h_i(i\Omega)$ is the transfer function relating the output load quantity, i, to a unit, harmonically oscillating, one-dimensional gust field, and the asterisk superscript denotes the complex conjugate. When evaluating $\bar{A}_i$, the integration should be continued until a converged value is achieved since, realistically, the integration to infinity may be impractical. The design limit load, P_{Li}, is then defined as:

$$P_{Li} = P_{(1-g)i} \pm P_{li}$$
$$= P_{(1-g)i} \pm U_\sigma \ \overline{A}_i$$

where U_σ is defined in Paragraph 5.c.(1) of this AMC, and $P_{(1\text{-}g)i}$ is the 1-g steady state value for the load quantity, i, under consideration. As indicated by the formula, both positive and negative load responses should be considered when calculating limit loads.

Correlated (or equiprobable) loads can be developed using cross-correlation coefficients, ρ_{ij}, computed as follows:

$$\rho_{ij} = \frac{\int_0^\infty \Phi_I(\Omega) real\left[h_i(i\Omega) h^*{}_j(i\Omega)\right] d\Omega}{\overline{\mathrm{A}}_i \, \overline{\mathrm{A}}_j}$$

where, 'real[...]' denotes the real part of the complex function contained within the brackets. In this equation, the lowercase subscripts, i and j, denote the responses being correlated. A set of design loads, P_{Lj}, correlated to the design limit load P_{Li}, are then calculated as follows:

$$P_{Lj} = P_{(1-g)j} \pm U_{\sigma}\, \rho_{ij}\, \overline{A}_j$$

The correlated load sets calculated in the foregoing manner provide balanced load distributions corresponding to the maximum value of the response for each external load quantity, i, calculated.

When calculating stresses, the foregoing load distributions may not yield critical design values because critical stress values may depend on a combination of external loads. In these cases, a more general application of the correlation coefficient method is required. For example, when the value of stress depends on two externally applied loads, such as torsion and shear, the equiprobable relationship between the two parameters forms an ellipse as illustrated in Figure 4.

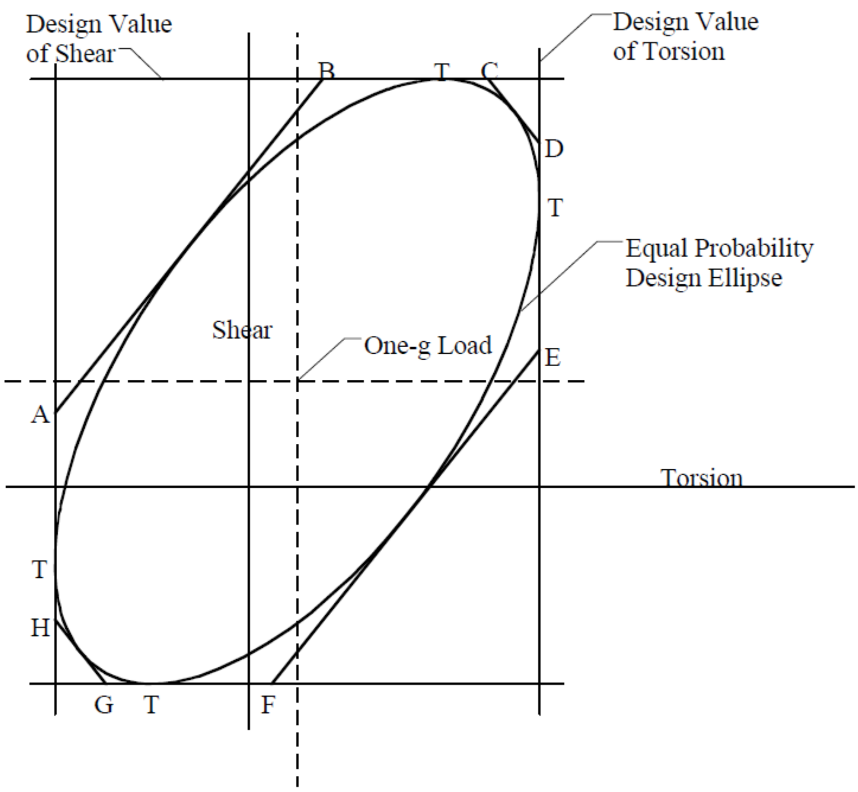

Figure-4 Equal Probability Design Ellipse

In this figure, the points of tangency, T, correspond to the expressions for correlated load pairs given by the foregoing expressions. A practical additional set of equiprobable load pairs that should be considered to establish critical design stresses are given by the points of tangency to the ellipse by lines AB, CD, EF and GH. These additional load pairs are given by the following expressions (where i = torsion and j = shear):

For tangents to lines AB and EF

$$P_{Li} = P_{(1-g)i} +/- \overline{A}_j U_{\sigma} \left[\left(1 - \rho_{ij}\right)/2\right]^{1/2}$$