



Advisory Circular

Subject: Dynamic Gust Loads

Date: 12/12/14

AC No: 25.341-1

Initiated By: ANM-115

1 **PURPOSE.**

This advisory circular (AC) describes acceptable means for showing compliance with the requirements of Title 14, Code of Federal Regulations (14 CFR) 25.341, *Gust and turbulence loads*. Section 25.341 specifies the discrete gust and continuous turbulence dynamic load conditions that apply to the airplane and engines.

2 **APPLICABILITY.**

2.1 The guidance provided in this document is directed to airplane manufacturers, modifiers, foreign regulatory authorities, and Federal Aviation Administration (FAA) transport airplane type certification engineers and their designees.

2.2 The material in this AC is neither mandatory nor regulatory in nature and does not constitute a regulation. While these guidelines are not mandatory, they are derived from extensive FAA and industry experience in determining compliance with the relevant regulations. These means are issued, in the interest of standardization, for guidance purposes and to outline a method that has been found acceptable in showing compliance with the standards set forth in the rule. If, however, we become aware of circumstances that convince us that following this AC would not result in compliance with the applicable regulations, we will not be bound by the terms of this AC, and we may require additional substantiation or design changes as a basis for finding compliance.

2.3 The material in this AC does not change or create any additional regulatory requirements, nor does it authorize changes in, or permit deviations from, existing regulatory requirements.

3 **RELATED REGULATIONS.**

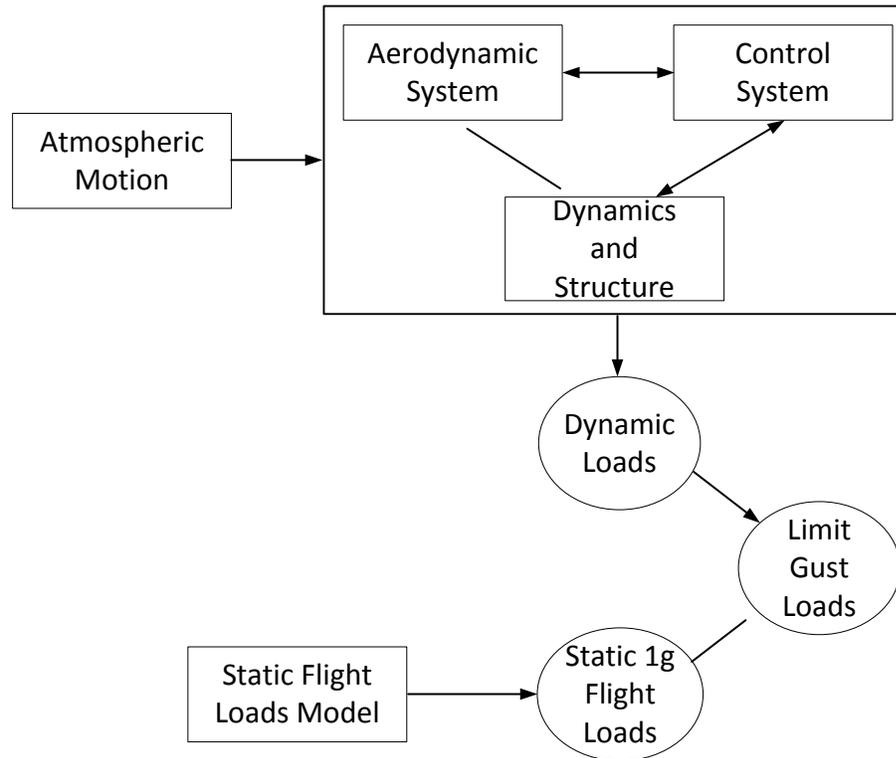
The following 14 CFR regulations are related to this AC. The full text of these regulations can be downloaded at the [U.S. Government Printing Office e-CFR](#). You can order a paper copy by sending a request to the U.S. Superintendent of Documents,

U.S. Government Printing Office, Washington, D.C. 20402-0001; or by calling telephone number (202) 512-1800; or by sending a request by facsimile to (202) 512-2250.

- Section 25.301, *Loads*.
- Section 25.303, *Factor of safety*.
- Section 25.305, *Strength and deformation*.
- Section 25.321, *Flight Loads: General*.
- Section 25.335, *Design airspeeds*.
- Section 25.343, *Design fuel and oil loads*.
- Section 25.345, *High lift devices*.
- Section 25.349, *Rolling conditions*.
- Section 25.371, *Gyroscopic loads*.
- Section 25.373, *Speed control devices*.
- Section 25.391, *Control surface loads: General*.
- Section 25.427, *Unsymmetrical loads*.
- Section 25.445, *Auxiliary aerodynamic surfaces*.
- Section 25.571, *Damage-tolerance and fatigue evaluation of structure*.
- Section 25.1517, *Rough air speed V_{RA}* .

4 **OVERVIEW.**

- 4.1 This AC addresses both discrete gust and continuous turbulence (or continuous gust) requirements of part 25. It provides some of the acceptable methods of modeling airplanes, airplane components, and configurations, and the validation of those modeling methods for the purpose of determining the response of the airplane to encounters with gusts.
- 4.2 How the various airplane modeling parameters are treated in the dynamic analysis can have a large influence on design load levels. The basic elements to be modeled in the analysis are the elastic, inertial, aerodynamic, and control system characteristics of the complete, coupled airplane. (See figure 1 of this AC.) The degree of sophistication and detail required in the modeling depends on the complexity of the airplane and its systems.

Figure 1. Basic Elements of the Gust Response Analysis

- 4.3 Design loads for encounters with gusts are a combination of the steady, level 1g flight loads and the gust incremental loads including the dynamic response of the airplane. The steady 1g 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.
- 4.4 The gust incremental loads result from the interaction of atmospheric turbulence and airplane rigid body and elastic motions. They may be calculated using linear analysis methods when the airplane and its flight control systems are reasonably or conservatively approximated by linear analysis models.
- 4.5 Nonlinear solution methods are necessary for airplane and flight control systems that are not reasonably or conservatively represented by linear analysis models. Nonlinear 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.
- 4.6 The modeling parameters discussed in the following sections include:
- 4.6.1 Design conditions and associated steady, level 1g flight conditions.
- 4.6.2 The discrete and continuous gust models of atmospheric turbulence.

- 4.6.3 Detailed representation of the airplane system including structural dynamics, aerodynamics, and control system modeling.
- 4.6.4 Solution of the equations of motion and the extraction of response loads.
- 4.6.5 Considerations for nonlinear airplane systems.
- 4.6.6 Analytical model validation techniques.

5 **DESIGN CONDITIONS.**

5.1 **General.**

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

5.2 **Steady, Level 1g Flight Loads.**

The total design load is made up of static and dynamic load components. In calculating the static component, the airplane 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 airplane 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.

5.3 **Dynamic Response Loads.**

The incremental loads from the dynamic gust solution are superimposed on the associated steady, level flight 1g 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 disregarded in the calculation of incremental loads.

5.4 **Damage Tolerance Conditions.**

Limit gust loads, treated as ultimate, need to be developed for the structural failure conditions considered under § 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 airplane may be used and applied to the failed structure. However, when structural failures of the types considered under § 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.

6 GUST MODEL CONSIDERATIONS.

6.1 General.

The gust criteria presented in § 25.341 consist of two models of atmospheric turbulence, a discrete model and a continuous turbulence model. This AC 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 that excite lightly damped modes. Dynamic loads for both atmospheric models must be considered in the structural design of the airplane.

6.2 Discrete Gust Model.

6.2.1 Atmosphere.

The atmosphere is assumed to be one dimensional with the gust velocity acting normally (either vertically or laterally) to the direction of airplane 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 airplane 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, F_g , and an expression that modifies the maximum velocity as a function of the gust gradient distance, H . These parameters are discussed further below.

6.2.1.1 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 § 25.341(a)(5) and are given in terms of feet per second equivalent airspeed for a gust gradient distance, H , of 350 feet.

6.2.1.2 Flight Profile Alleviation Factor, F_g .

The reference gust velocity, U_{ref} , is a measure of turbulence intensity as a function of altitude. In defining the value of U_{ref} at each altitude, it is assumed that the airplane is flown 100 percent 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 airplane flying at any given altitude within its certification altitude range. F_g is a minimum value at sea level, linearly increasing to 1.0 at the certified maximum altitude. The expression for F_g is given in § 25.341(a)(6).

6.2.1.3 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 30 to 350 feet. If 12.5 times the mean geometric chord of the airplane's wing

exceeds 350 feet, consideration should be given to covering increased maximum gust gradient distances.

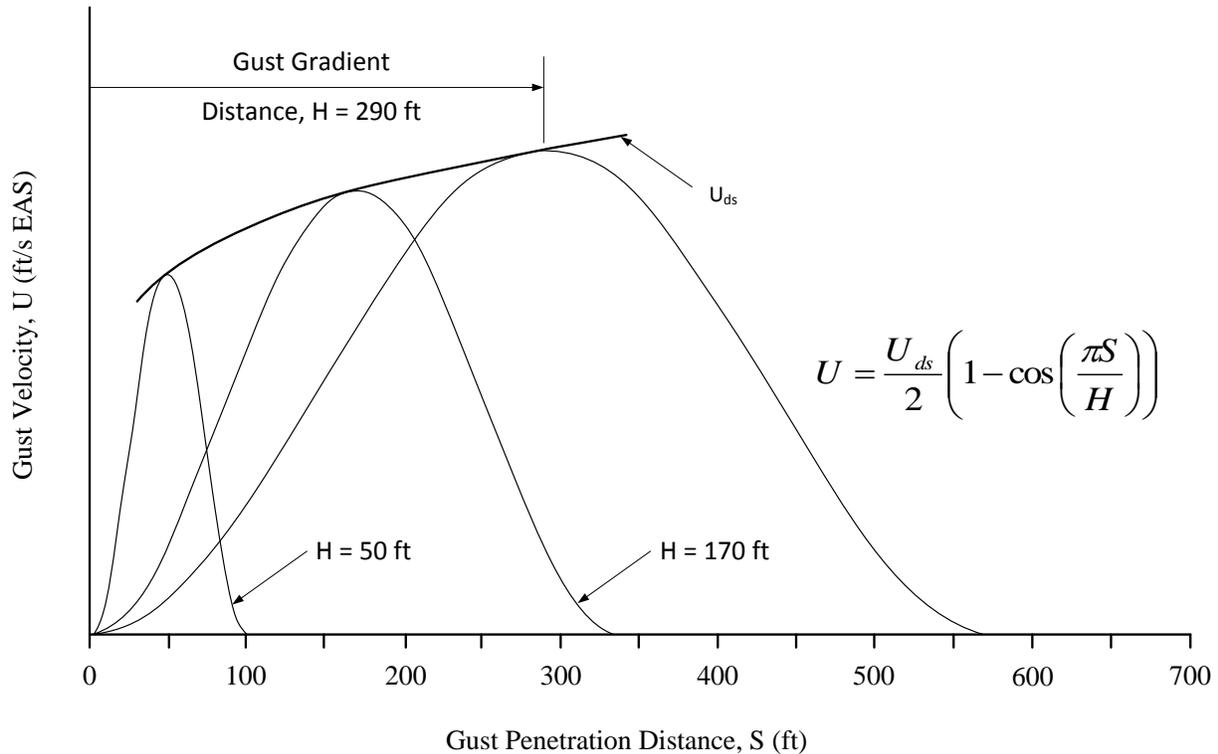
6.2.1.4 Design Gust Velocity, U_{ds} .

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:

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

6.2.1.5 The maximum design gust velocity envelope, U_{ds} , and example design gust velocity profiles are illustrated in figure 2 of this AC.

Figure 2. Typical (1-Cosine) Design Gust Velocity Profiles



6.2.2 Discrete Gust Response.

6.2.2.1 The solution for discrete gust response time histories can be achieved by a number of techniques. These include the explicit integration of the airplane equations of motion in the time domain and frequency domain solutions using Fourier transform techniques. These are discussed further in section 8 of this AC.

6.2.2.2 Maximum incremental loads, P_{li} , 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 30 to 350 feet. 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. 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.

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

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

where $P_{(1g)i}$ is the 1g 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:

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

Note: With significant nonlinearities, maximum positive incremental loads may differ from maximum negative incremental loads.

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

6.2.3 Round-the-Clock Gust.

6.2.3.1 When the effect of combined vertical and lateral gusts on airplane 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 10°), or components supported by other lifting surfaces, for example, T-tails, outboard fins, and winglets. While the round-the-clock load assessment may be limited to just the components under consideration, the loads themselves should be calculated from a whole airplane dynamic analysis.

6.2.3.2 The round-the-clock gust model assumes that discrete gusts may act at any angle normal to the flight path of the airplane. Lateral and vertical gust components are correlated since the round-the-clock gust is a single discrete event. For a linear airplane 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 in paragraph 6.2.2 of this AC.

6.2.4 Supplementary Gust Conditions for Wing-Mounted Engines.

6.2.4.1 Atmosphere.

6.2.4.1.1 For airplanes equipped with wing-mounted engines, § 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.

6.2.4.1.2 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 6.2.3 of this AC.

6.2.4.1.3 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 § 25.341(a) and described in paragraph 6.2.1 of this AC. 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 airplane specially instrumented to measure vertical and lateral gust components. This information is contained in FAA report number DOT/FAA/AR-99/62¹.

6.2.4.2 Multi-Axis Gust Response.

6.2.4.2.1 For a particular airplane 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 paragraph 6.2.4.1.3 of this AC, such that the

¹ DOT/FAA/AR-99/62, *Studies of Time-Phased Vertical and Lateral Gusts: Development of Multiaxis One-Minus-Cosine Gust Model*, October 1999. Available at <http://www.tc.faa.gov/its/worldpac/techrpt/ar99-62.pdf>.

resulting combined load is maximized. For loads calculated using a linear airplane model, the response load may be based on the separately tuned vertical and lateral discrete gust responses for that load, each calculated as described in paragraph 6.2.2 of this AC. 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.

- 6.2.4.2.2 Denote the independently tuned vertical and lateral incremental responses for a particular airplane 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:

$$\frac{0.85L_{Vi}}{\sqrt{(L_{Vi}^2+L_{Li}^2)}} \text{ and } \frac{0.85L_{Li}}{\sqrt{(L_{Vi}^2+L_{Li}^2)}}, \text{ respectively.}$$

The time-phasing of the two scaled gust components is such that their associated peak loads occur at the same instant.

- 6.2.4.2.3 The combined incremental response load is given by:

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

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

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

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

- 6.2.4.2.4 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:

$$\frac{0.85L_{Vi}}{\sqrt{(L_{Vi}^2+L_{Li}^2)}} \text{ and } \frac{0.85L_{Li}}{\sqrt{(L_{Vi}^2+L_{Li}^2)}}, \text{ respectively.}$$

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_{Ij} for load quantity j .

- 6.2.4.2.5 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:

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

Note: With significant nonlinearities, maximum positive incremental loads may differ from maximum negative incremental loads.

6.3 Continuous Turbulence Model.

6.3.1 Atmosphere.

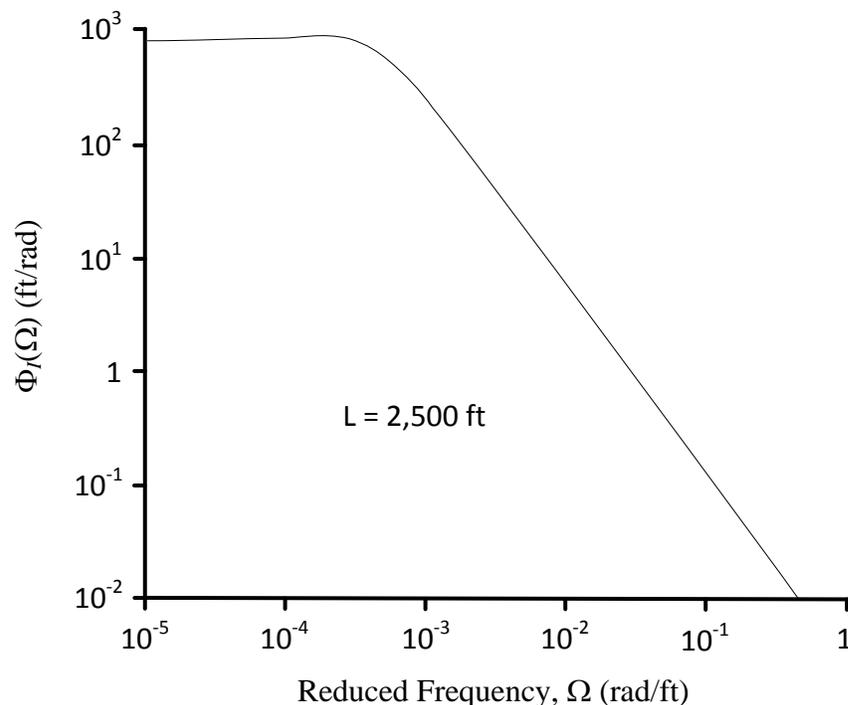
6.3.1.1 The atmosphere for the determination of continuous gust responses is assumed to be one dimensional with the gust velocity acting normal (either vertically or laterally) to the direction of airplane travel. The one-dimensional assumption constrains the instantaneous vertical or lateral gust velocities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

6.3.1.2 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 airplane velocity in feet per second true airspeed.

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

6.3.1.3 The von Kármán power spectrum for unit RMS gust intensity is illustrated in figure 3 below.

Figure 3. The von Kármán Power Spectral Density Function, $\Phi_I(\Omega)$



- 6.3.1.4 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, F_g , as follows:

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

where values for $U_{\sigma ref}$ are specified in § 25.341(b)(3) in feet per second true airspeed, and F_g is defined in § 25.341(a)(6). The value of F_g is based on airplane 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.

- 6.3.1.5 As for the discrete gust analysis, the reference continuous turbulence gust intensity, $U_{\sigma ref}$, defines the design value of the associated gust field at each altitude. In defining the value of $U_{\sigma ref}$ at each altitude, it is assumed that the airplane is flown 100 percent of the time at that altitude. The factor F_g is then applied to account for the probability of the airplane flying at any given altitude during its service lifetime.
- 6.3.1.6 It should be noted that the reference gust velocity is comprised of two components, an RMS gust intensity and a peak-to-RMS ratio. The separation of these components is not defined and is not required for the linear airplane analysis. Guidance is provided in paragraph 9.4 of this AC for generating an RMS gust intensity for a nonlinear simulation.

6.3.2 Continuous Turbulence Response.

- 6.3.2.1 For linear airplane systems, the solution for the response to continuous turbulence may be performed entirely in the frequency domain, using the RMS response. \bar{A} is defined in § 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

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

- 6.3.2.2 In the above expressions, $\Phi_I(\Omega)$ is the input von Kármán power spectrum of the turbulence and is defined in paragraph 6.3.1 of this AC; $h_i(i\Omega)$ 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:

$$\begin{aligned}
 P_{Li} &= P_{(1g)i} \pm P_{Ii} \\
 &= P_{(1g)i} \pm U_{\sigma} \bar{A}_i
 \end{aligned}$$

where U_{σ} is defined in paragraph 6.3.1 of this AC, and $P_{(1g)i}$ is the 1g 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.

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

$$\rho_{ij} = \frac{\int_0^8 \Phi_I(\Omega) \text{real} [h_i(i\Omega)h_j^*(i\Omega)] d\Omega}{\bar{A}_i \bar{A}_j}$$

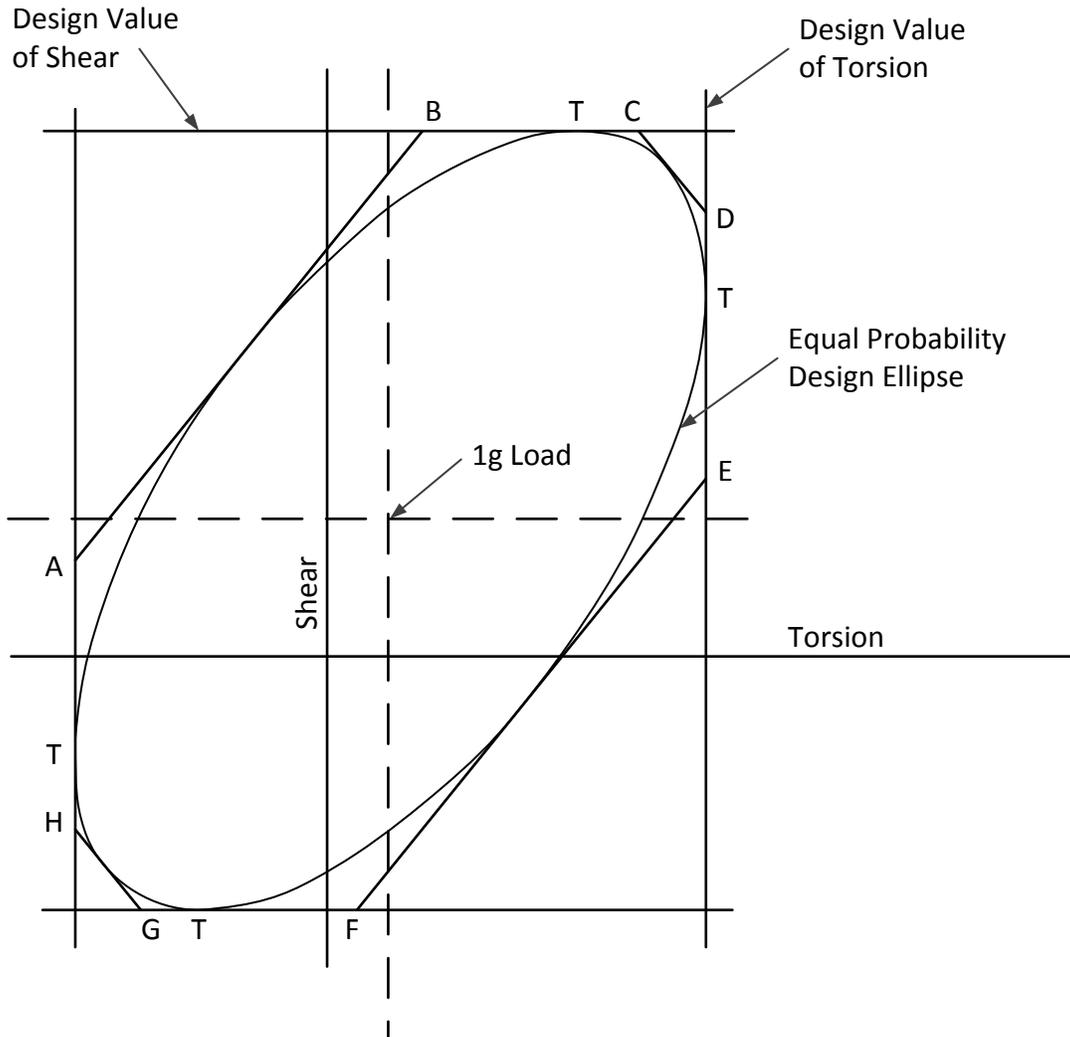
where, ‘real[...]’ denotes the real part of the complex function contained within the brackets. In this equation, the lowercase subscripts i and j denote the responses being correlated. A set of design loads, P_{Lj} , correlated to the design limit load P_{Li} , are then calculated as follows:

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

- 6.3.2.4 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.

- 6.3.2.5 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 of this AC.

Figure 4. Equal Probability Design Ellipse



6.3.2.6 In figure 4 above, 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 is 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):

6.3.2.6.1 For tangents to lines AB and EF:

$$P_{Li} = P_{(1g)i} \pm \bar{A}_i U_\sigma \left[\frac{(1-\rho_{ij})}{2} \right]^{1/2} \text{ and}$$

$$P_{Lj} = P_{(1g)j} \mp \bar{A}_j U_\sigma \left[\frac{(1-\rho_{ij})}{2} \right]^{1/2}$$

6.3.2.6.2 For tangents to lines CD and GH:

$$P_{Li} = P_{(1g)i} \pm \bar{A}_i U_\sigma \left[\frac{(1+\rho_{ij})}{2} \right]^{1/2} \text{ and}$$

$$P_{Lj} = P_{(1g)j} \pm \bar{A}_j U_\sigma \left[\frac{(1+\rho_{ij})}{2} \right]^{1/2}$$

6.3.2.6.3 All correlated or equiprobable loads developed using correlation coefficients will provide balanced load distributions.

6.3.2.6.4 A more comprehensive approach for calculating critical design stresses that depend on a combination of external load quantities is to evaluate directly the transfer function for the stress quantity of interest from which can be calculated the gust response function, the value for RMS response, \bar{A} , and the design stress values:

$$P_{(1g)} \pm U_\sigma \bar{A}$$

7 AIRPLANE MODELING CONSIDERATIONS.

7.1 General.

The procedures presented in this section generally apply for airplanes having aerodynamic and structural properties and flight control systems that may be reasonably or conservatively approximated using linear analysis methods for calculating limit load. Additional guidance material is presented in section 9 of this AC for airplanes having properties and/or systems not reasonably or conservatively approximated by linear analysis methods.

7.2 Structural Dynamic Model.

7.2.1 The model should include both rigid body and flexible airplane degrees of freedom. If a modal approach is used, the structural dynamic model should include a sufficient number of flexible airplane modes to ensure convergence of the modal superposition procedure, and to ensure responses from high frequency excitations are properly represented.

7.2.2 Most forms of structural modeling can be classified into two main categories:

7.2.2.1 The so-called “stick model” characterized by beams with lumped masses distributed along their lengths, and

7.2.2.2 Finite element models in which all major structural components (frames, ribs, stringers, skins) are represented with mass properties defined at grid points.

7.2.3 Regardless of the approach taken for the structural modeling, a minimum acceptable level of sophistication, consistent with configuration complexity, is necessary to

represent satisfactorily the critical modes of deformation of the primary structure and control surfaces. Results from the models should be compared to test data as outlined in paragraph 10.2 of this AC in order to validate the accuracy of the model.

7.3 **Structural Damping.**

Structural dynamic models may include damping properties in addition to representations of mass and stiffness distributions. In the absence of better information, it will normally be acceptable to assume 0.03 (i.e., 1.5 percent equivalent critical viscous damping) for all flexible modes. Structural damping may be increased over the 0.03 value to be consistent with the high structural response levels caused by extreme gust intensity, provided justification is given.

7.4 **Gust and Motion Response Aerodynamic Modeling.**

Aerodynamic forces included in the analysis are produced by both the gust velocity directly and by the airplane response.

7.4.1 Aerodynamic modeling for dynamic gust response analyses requires the use of unsteady two-dimensional or three-dimensional panel theory methods for incompressible or compressible flow. The choice of the appropriate technique depends on the complexity of the aerodynamic configuration, the dynamic motion of the surfaces under investigation, and the flight speed envelope of the airplane. Generally, three-dimensional panel methods achieve better modeling of the aerodynamic interference between lifting surfaces. The model should have a sufficient number of aerodynamic degrees of freedom to properly represent the steady and unsteady aerodynamic distributions under consideration.

7.4.2 The buildup of unsteady aerodynamic forces should be represented. In two-dimensional unsteady analysis, this may be achieved in either the frequency domain or the time domain through the application of oscillatory or indicial lift functions, respectively. Where three-dimensional panel aerodynamic theories are to be applied in the time domain (e.g., for nonlinear gust solutions), an approach such as the “rational function approximation” method may be employed to transform frequency domain aerodynamics into the time domain.

7.4.3 Oscillatory lift functions due to gust velocity or airplane response depend on the reduced frequency parameter, k . The maximum reduced frequency used in the generation of the unsteady aerodynamics should include the highest frequency of gust excitation and the highest structural frequency under consideration. Time lags representing the effect of the gradual penetration of the gust field by the airplane should also be accounted for in the buildup of lift due to gust velocity.

7.4.4 The aerodynamic modeling should be supported by tests or previous experience as indicated in paragraph 10.4 of this AC. Primary lifting and control surface distributed aerodynamic data are commonly adjusted by weighting factors in the dynamic gust response analyses. The weighting factors for steady flow ($k = 0$) may be obtained by comparing wind tunnel test results with theoretical data. The correction of the aerodynamic forces should also ensure that the rigid body motion of the airplane is

accurately represented in order to provide satisfactory short period and Dutch roll frequencies and damping ratios. Corrections to primary surface aerodynamic loading due to control surface deflection should be considered. Special attention should also be given to control surface hinge moments and to fuselage and nacelle aerodynamics because viscous and other effects may require more extensive adjustments to the theoretical coefficients. Aerodynamic gust forces should reflect weighting factor adjustments performed on the steady or unsteady motion response aerodynamics.

7.5 Gyroscopic Loads.

7.5.1 As specified in § 25.371, the structure supporting the engines and the auxiliary power units should be designed for the gyroscopic loads induced by both discrete gusts and continuous turbulence. The gyroscopic loads for turbopropellers and turbofans may be calculated as an integral part of the solution process by including the gyroscopic terms in the equations of motion, or the gyroscopic loads can be superimposed after the solution of the equations of motion. Propeller and fan gyroscopic coupling forces (due to rotational direction) between symmetric and antisymmetric modes need not be taken into account if the coupling forces are shown to be negligible.

7.5.2 The gyroscopic loads used in this analysis should be determined with the engine or auxiliary power units at maximum continuous revolutions per minute. The mass polar moment of inertia used in calculating gyroscopic inertia terms should include the mass polar moments of inertia of all significant rotating parts, taking into account their respective rotational gearing ratios and directions of rotation.

7.6 Control Systems.

7.6.1 Gust analyses of the basic configuration should include simulation of any control system for which interaction may exist with the rigid body response, structural dynamic response, or external loads. If possible, these control systems should be uncoupled such that the systems that affect “symmetric flight” are included in the vertical gust analysis, and those that affect “antisymmetric flight” are included in the lateral gust analysis.

7.6.2 The control systems considered should include all relevant modes of operation.

7.6.3 The control systems included in the gust analysis may be assumed to be linear if the impact of the nonlinearity is negligible, or if it can be shown by analysis on a similar airplane/control system that a linear control law representation is conservative. If the control system is significantly nonlinear, and a conservative linear approximation to the control system cannot be developed, then the effect of the control system on the airplane responses should be evaluated in accordance with section 9 of this AC.

7.7 Stability.

7.7.1 Solutions of the equations of motion for either discrete gusts or continuous turbulence require the dynamic model be stable. This applies for all modes, except possibly for very low frequency modes that do not affect load responses, such as the phugoid mode. The short period and Dutch roll modes do affect load responses. A stability check

should be performed for the dynamic model using conventional stability criteria appropriate for the linear or nonlinear system in question, and adjustments should be made to the dynamic model, as required, to achieve appropriate frequency and damping characteristics.

- 7.7.2 When control system models are to be included in the gust analysis, it is advisable to check that the following characteristics are acceptable and are representative of the airplane:
- 7.7.2.1 Static margin of the unaugmented airplane. “Unaugmented airplane” means the natural airplane without any feedback control system.
 - 7.7.2.2 Dynamic stability of the unaugmented airplane.
 - 7.7.2.3 The static aeroelastic effectiveness of all control surfaces used by any feedback control system.
 - 7.7.2.4 Gain and phase margins of any feedback control system coupled with the airplane rigid body and flexible modes (aeroservoelastic stability margins).
 - 7.7.2.5 The aeroelastic flutter and divergence margins of the unaugmented airplane and also for any feedback control system coupled with the airplane.

8 **DYNAMIC LOADS.**

8.1 **General.**

This section describes methods for formulating and solving the airplane equations of motion and extracting dynamic loads from the airplane response. The airplane equations of motion are solved in either physical or modal coordinates and include all terms important in the loads calculation including stiffness, damping, mass, and aerodynamic forces due to both airplane motions and gust excitation. Generally, the airplane equations are solved in modal coordinates. For the purposes of describing the solution of these equations in the remainder of this AC, modal coordinates will be assumed. A sufficient number of modal coordinates should be included to ensure that the loads extracted provide converged values.

8.2 **Solution of the Equations of Motion.**

- 8.2.1 Solution of the equations of motion can be achieved through a number of techniques. For the continuous turbulence analysis, the equations of motion are generally solved in the frequency domain. Transfer functions that relate the output response quantity to an input harmonically oscillating gust field are generated, and these transfer functions are used (in paragraph 6.3 of this AC) to generate the RMS value of the output response quantity.

8.2.2 There are two primary approaches used to generate the output time histories for the discrete gust analysis:

8.2.2.1 By explicit integration of the airplane equations of motion in the time domain, and

8.2.2.2 By frequency domain solutions that can use Fourier transform techniques.

8.3 **Extraction of Loads and Responses.**

8.3.1 The output quantities that may be extracted from a gust response analysis include displacements, velocities, and accelerations at structural locations; load quantities such as shears, bending moments, and torques on structural components; and stresses and shear flows in structural components. The calculation of the physical responses is given by a modal superposition of the displacements, velocities, and accelerations of the rigid and elastic modes of vibration of the airplane structure. The number of modes carried in the summation should be sufficient to ensure converged results.

8.3.2 A variety of methods may be used to obtain physical structural loads from a solution of the modal equations of motion governing gust response. These include the Mode Displacement method, the Mode Acceleration method, and the Force Summation method. All three methods are capable of providing a balanced set of airplane loads. If an infinite number of modes can be considered in the analysis, the three will lead to essentially identical results.

8.3.3 The Mode Displacement method is the simplest. In this method, total dynamic loads are calculated from the structural deformations produced by the gust using modal superposition. Specifically, the contribution of a given mode is equal to the product of the load associated with the normalized deformed shape of that mode and the value of the displacement response given by the associated modal coordinate. For converged results, the Mode Displacement method may need a significantly larger number of modal coordinates than the other two methods.

8.3.4 In the Mode Acceleration method, the dynamic load response is composed of a static part and a dynamic part. The static part is determined by conventional static analysis (including rigid body “inertia relief”), with the externally applied gust loads treated as static loads. The dynamic part is computed by the superposition of appropriate modal quantities and is a function of the number of modes carried in the solution. The quantities to be superimposed involve both motion response forces and acceleration responses (thus giving this method its name). Since the static part is determined completely and independently of the number of normal modes carried, adequate accuracy may be achieved with fewer modes than would be needed in the Mode Displacement method.

8.3.5 The Force Summation method is the most laborious and the most intuitive. In this method, physical displacements, velocities, and accelerations are first computed by superposition of the modal responses. These are then used to determine the physical

inertia forces and other motion dependent forces. Finally, these forces are added to the externally applied forces to give the total dynamic loads acting on the structure.

- 8.3.6 If balanced airplane load distributions are needed from the discrete gust analysis, they may be determined using time-correlated solution results. Similarly, as explained in paragraph 6.3 of this AC, if balanced airplane load distributions are needed from the continuous turbulence analysis, they may be determined from equiprobable solution results obtained using cross-correlation coefficients.

9 **NONLINEAR CONSIDERATIONS.**

9.1 **General.**

- 9.1.1 Any structural, aerodynamic, or automatic control system characteristic that may cause airplane response to discrete gusts or continuous turbulence to become nonlinear with respect to intensity or shape should be represented realistically or conservatively in the calculation of loads. While many minor nonlinearities are amenable to a conservative linear solution, the effect of major nonlinearities cannot usually be quantified without explicit calculation.

- 9.1.2 The effect of nonlinearities should be investigated above limit conditions to assure that the system presents no anomaly compared to behavior below limit conditions.

9.2 **Structural and Aerodynamic Nonlinearity.**

A linear elastic structural model and a linear (unstalled) aerodynamic model are normally recommended as conservative and acceptable for the unaugmented airplane elements of a loads calculation. Aerodynamic models may be refined to take account of minor nonlinear variation of aerodynamic distributions due to local separation, etc., through simple linear piecewise solution. Local or complete stall of a lifting surface would constitute a major nonlinearity and should not be represented without account being taken of the influence of rate of change of incidence, i.e., the so-called “dynamic stall” in which the range of linear incremental aerodynamics may extend significantly beyond the static stall incidence.

9.3 **Automatic Control System Nonlinearity.**

- 9.3.1 Automatic flight control systems, autopilots, stability control systems, and load alleviation systems often constitute the primary source of nonlinear response. For example:

- Non-proportional feedback gains.
- Rate and amplitude limiters.
- Changes in the control laws or control law switching.
- Hysteresis.
- Use of one-sided aerodynamic controls such as spoilers.

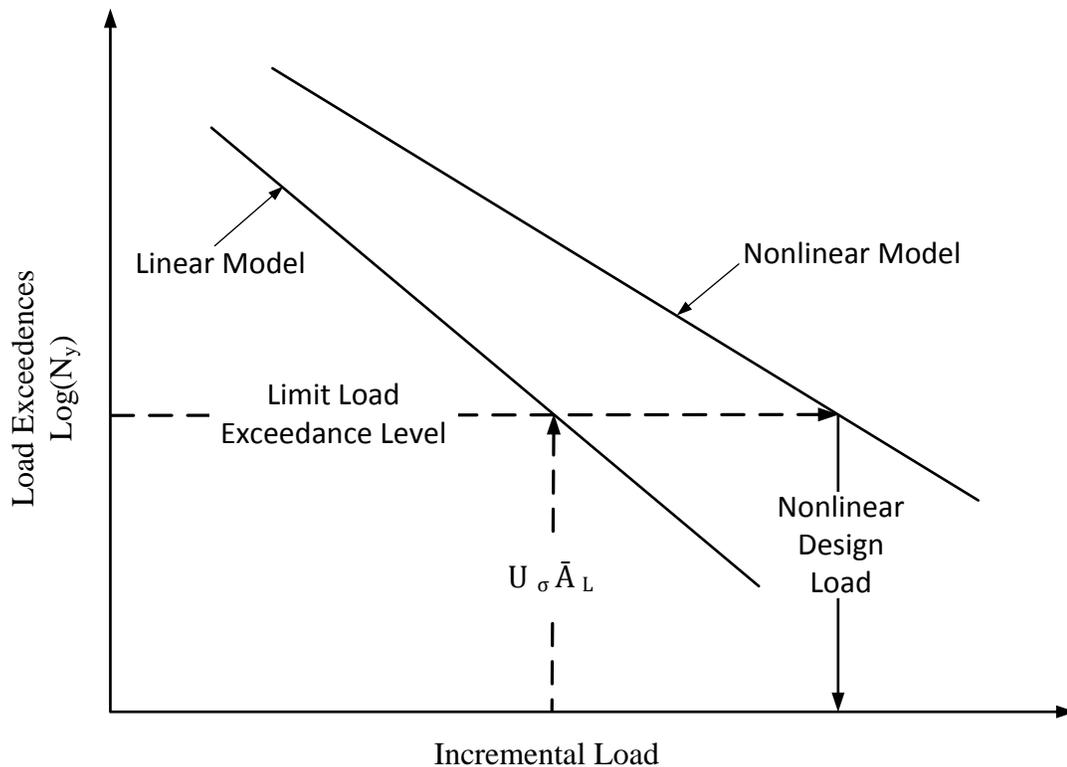
- Hinge moment performance and saturation of aerodynamic control actuators.
- 9.3.2 The resulting influences on response will be airplane design dependent, and the manner in which they are to be considered will normally have to be assessed for each design.
- 9.3.3 Minor influences such as occasional clipping of response due to rate or amplitude limitations, where it is symmetric about the stabilized 1g condition, can often be represented through quasi-linear modeling techniques such as describing functions or use of a linear equivalent gain.
- 9.3.4 Major and unsymmetrical influences, such as application of spoilers for load alleviation, normally require explicit simulation and, therefore, adoption of an appropriate solution based in the time domain.
- 9.3.5 The influence of nonlinearities on one load quantity often runs contrary to the influence on other load quantities. For example, an aileron used for load alleviation may simultaneously relieve wing bending moment while increasing wing torsion. Since it may not be possible to represent such features conservatively with a single airplane model, it may be conservatively acceptable to consider loads computed for two (possibly linear) representations that bound the realistic condition. Another example of this approach would be separate representation of continuous turbulence response for the two control law states to cover a situation where the airplane may occasionally switch from one state to another.

9.4 **Nonlinear Solution Methodology.**

- 9.4.1 Where explicit simulation of nonlinearities is required, the loads response may be calculated through time domain integration of the equations of motion.
- 9.4.2 For the tuned discrete gust conditions of § 25.341(a), limit loads should be identified by peak values in the nonlinear time domain simulation response of the airplane model excited by the discrete gust model described in paragraph 6.2 of this AC.
- 9.4.3 For time domain solution of the continuous turbulence conditions of § 25.341(b), a variety of approaches may be taken for the specification of the turbulence input time history and the mechanism for identifying limit loads from the resulting responses.
- 9.4.4 It will normally be necessary to justify that the selected approach provides an equivalent level of safety as a conventional linear analysis and is appropriate to handle the types of nonlinearity on the airplane. This should include verification that the approach provides adequate statistical significance in the loads results.
- 9.4.5 A methodology based on stochastic simulation has been found to be acceptable for load alleviation and flight control system nonlinearities. In this simulation, the input is a long, Gaussian, pseudo-random turbulence stream conforming to a von Kármán spectrum with an RMS amplitude of 0.4 times U_σ (defined in paragraph 6.3.1 of this AC). The value of limit load is that load with the same probability of exceedance as $\bar{A}U_\sigma$ of the same load quantity in a linear model. This is illustrated graphically in

figure 5 of this AC. When using an analysis of this type, exceedance curves should be constructed using incremental load values up to, or just beyond, the limit load value.

Figure 5. Establishing Limit Load for a Nonlinear Airplane



- 9.4.6 The nonlinear simulation may also be performed in the frequency domain if the frequency domain method is shown to produce conservative results. Frequency domain methods include, but are not limited to, Matched Filter Theory and Equivalent Linearization.

10 ANALYTICAL MODEL VALIDATION.

10.1 General.

The intent of analytical model validation is to establish that the analytical model is adequate for the prediction of gust response loads. The following paragraphs discuss acceptable, but not the only methods, of validating the analytical model. In general, it is not intended that specific testing be required to validate the dynamic gust loads model.

10.2 Structural Dynamic Model Validation.

The methods and test data used to validate the flutter analysis model should also be applied to validate the gust analysis model. These procedures are addressed in

AC 25.629-1B, *Aeroelastic Stability Substantiation of Transport Category Airplanes*, dated October 27, 2014, or later revision.

10.3 **Damping Model Validation.**

In the absence of better information, it will normally be acceptable to assume 0.03 (i.e., 1.5 percent equivalent critical viscous damping) for all flexible modes. Structural damping may be increased over the 0.03 value to be consistent with the high structural response levels caused by extreme gust intensity, provided justification is given.

10.4 **Aerodynamic Model Validation.**

10.4.1 Aerodynamic modeling parameters fall into two categories:

- Steady or quasi-steady aerodynamics governing static aeroelastic and flight dynamic airload distributions.
- Unsteady aerodynamics that interact with the flexible modes of the airplane.

10.4.2 Flight stability aerodynamic distributions and derivatives may be validated by wind tunnel tests, detailed aerodynamic modeling methods (such as computational fluid dynamics), or flight test data. If detailed analysis or testing reveals that flight dynamic characteristics of the airplane differ significantly from those to which the gust response model has been matched, then the implications on gust loads should be investigated.

10.4.3 The analytical and experimental methods for flutter analyses presented in AC 25.629-1B, or later revision, provide acceptable means for establishing reliable unsteady aerodynamic characteristics both for motion response and gust excitation aerodynamic force distributions. The aeroelastic implications on airplane flight dynamic stability should also be assessed.

10.5 **Control System Validation.**

10.5.1 If the airplane mathematical model used for gust analysis contains a representation of any feedback control system, then this segment of the model should be validated. The level of validation that should be performed depends on the complexity of the system and the particular airplane response parameter being controlled. Systems that control elastic modes of the airplane may require more validation than those that control the airplane rigid body response. Validation of elements of the control system (sensors, actuators, anti-aliasing filters, control laws, etc.) that have a minimal effect on the output load and response quantities under consideration can be disregarded.

10.5.2 It will normally be more convenient to substantiate elements of the control system independently, i.e., open loop, before undertaking the validation of the closed loop system.

10.5.3 System Rig or Airplane Ground Testing.

10.5.3.1 Response of the system to artificial stimuli can be measured to verify the following:

- The transfer functions of the sensors and any pre-control system anti-aliasing or other filtering.
- The sampling delays of acquiring data into the control system.
- The behavior of the control law itself.
- Any control system output delay and filter transfer function.
- The transfer functions of the actuators, and any features of actuation system performance characteristics that may influence the actuator response to the maximum demands that might arise in turbulence, e.g., maximum rate of deployment, actuator hinge moment capability, etc.

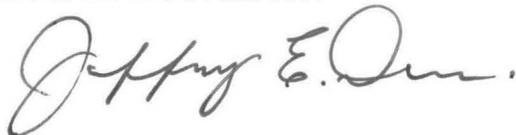
10.5.3.2 If this ground testing is performed, it is recommended that following any adaptation of the model to reflect this information, the complete feedback path be validated (open loop) against measurements taken from the rig or ground tests.

10.5.4 Flight Testing.

The functionality and performance of any feedback control system can also be validated by direct comparison of the analytical model and measurement for input stimuli. When this testing is performed, input stimuli should be selected such that they exercise the features of the control system and the interaction with the airplane that are significant in the use of the mathematical model for gust load analysis. These might include:

- 10.5.4.1 Airplane response to pitching and yawing maneuver demands.
- 10.5.4.2 Control system and airplane response to sudden artificially introduced demands such as pulses and steps.
- 10.5.4.3 Gain and phase margins determined using data acquired during the flight flutter test program or flight controls validation program. These gain and phase margins can be generated by passing known signals through the open loop system during flight test.

If you have any suggestions for improving this AC, you may use the Advisory Circular Feedback form at the end of this AC.



Jeffrey E. Duven
Manager, Transport Airplane Directorate
Aircraft Certification Service

Advisory Circular Feedback

If you find an error in this AC, have recommendations for improving it, or have suggestions for new items/subjects to be added, you may let us know by (1) emailing this form to 9-AWA-AVS-AIR500-Coord@faa.gov or (2) faxing it to the attention of the Aircraft Certification Service Directives Management Officer at (202) 267-3983.

Subject: AC 25.341-1, Dynamic Gust Loads

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