Comparison of Discrete and Continuous Gust Methods for Airplane Design Loads Determination

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The discrete and continuous gust methods often have different results. A comparison of these methods on the basis of simple airplane models shows that the power spectral density method becomes the critical one for modern aircraft with high mass parameter and large dimensions. The character of the turbulence or the response behavior are not the main sources of the discrepancy. It is mainly due to the difference in the relation between gust velocity and gust length in the two methods.

Nomenclature

a	= lift curve slope
$\bar{A}$	= ratio of standard deviations of load and turbulence
c	= mean geometric chord
$C(j\nu)$	= transformed Wagner function (motion)
$D(j\nu)$	= transformed Küssner function (gust)
$F(H)$	= maximum response to discrete gust with length H
g	= constant of gravitation
H	= discrete gust length
$\bar{H}$	= gust length giving maximum response
$H_{yw}(j\Omega)$, $G(j\nu)$	= transfer function
K_g	= gust alleviation factor, discrete gust
K_φ	= gust alleviation factor, continuous gusts
L	= scale length turbulence
m	= airplane mass
n	= vertical acceleration, g
S	= wing area
t	= time
T	= nondimensional time, $T=Vt/L$
T_n	= time constant
U	= gust velocity
U_{de}	= derived, equivalent gust velocity, discrete gust method
U_L	= gust velocity of gust with length L
U_σ	= design gust velocity, power spectral density method
$U_{\sigma d}$	= gust velocity, giving the same load as the discrete gust method
V	= true airplane velocity
V_e	= equivalent airplane velocity
W	= airplane weight
y	= load
$\gamma(H)$	= response factor, statistical discrete gusts
ζ	= damping coefficient of the short period motion
ζ_m	= parameter airplane model
μ_g	= mass ratio
ν	= nondimensional frequency, $\nu=L\omega/V$
ν_n	= nondimensional natural frequency of the short period motion
ρ	= air density
σ	= standard deviation
$\Phi(\Omega)$	= power spectrum
ω	= frequency
Ω	= spatial frequency, $\Omega=\omega/V$

Subscripts

0	= at sea level
w	= gusts
y	= load

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Introduction

THE problem of the determination of airplane loads due to atmospheric gusts is an old one; but it has certainly not yet been solved. This probably can be illustrated with the requirements of FAR 25[1] and JAR 25.[2]

The loads must be determined assuming a discrete "one-minus-cosine" gust with a length of 25 chords and prescribed velocity for the various airplane flight envelope conditions. In JAR 25, change 7, effective Nov. 24, 1980, a tuned gust length was prescribed for aircraft for which the structural flexibility effects were not negligible. This requirement was not applicable for French-type certification. It has now been deleted, except in the United Kingdom.

The requirements also prescribe that the dynamic response of the airplane to continuous gust must be taken into account. FAR 25 prescribes that the continuous gust design criteria must be used to establish the dynamic response. JAR 25 offers the continuous gust criteria as a means of compliance with this requirement. The principle of the application is to establish whether the structure exhibits characteristics leading to design loads that substantially deviate from the results of the discrete gust analysis.

The criteria for continuous gust, in both JAR 25 and FAR 25, should be applied to a mission or a design envelope analysis.

These requirements express the various views that exist regarding the merits of different descriptions of atmospheric turbulence and analysing methods. Therefore, these requirements can easily lead to a conflict situation as the design loads obtained with the discrete gust concept and the continuous gust concept will usually be different. Short descriptions of the methods will be presented here. A more extensive historical review is given in Ref. 3. It will become clear that the requirements, in fact, are inter- or extrapolation methods. New airplanes are compared on a certain basis to older airplanes assumed to have a satisfactory safety record.

Comparisons of the requirements, based on a relatively simple airplane model will then be made. It will be shown that, even for this simple model, a direct relation between the discrete and the continuous gust methods does not exist. The sources of the discrepancy between the results obtained with these two methods will be investigated. It will be shown that neither the character of atmospheric turbulence, nor the response behavior of the airplane as might be expected, is the main source of the discrepancy. The discrepancy is due mainly to the relations between gust velocity and gust length.

The Discrete Gust Concept

In the discrete gust concept, it is assumed that the airplane is subjected to gusts with the following shape:

$$U=\frac{U_{\rm de}}{2}\left(1-\cos\frac{2\pi Vt}{H}\right) \tag{1}$$

The gust length H is equal to 25 mean geometric wing chords. At the design cruising speed V_c, the prescribed[1,2] values for $U_{\rm de}$ are $U_{\rm de}=50$ ft/s for altitudes between sea level and 20,000 ft, decreasing to 25 ft/s at 50,000.

In the absence of a more rational analysis, the gust loads must be computed with

$$\Delta n=\frac{a\rho_0 V_e U_{\rm de} S}{2mg}K_g$$

$$=\frac{aV_eU_{\rm de}}{498W/S}K_g \text{ in the ft-s-knot-slug-lb system} \tag{2}$$

or

$$\Delta n=\frac{aSV_eU_{\rm de}}{16m}K_g \text{ in the kg-m-s system} \tag{3}$$

The gust alleviation factor K_g is equal to

$$K_g=0.88\mu_g/(5.3+\mu_g) \tag{4}$$

with

$$\mu_g=2m/\rho Sca \tag{5}$$

The gust alleviation factor K_g as given in Eq. (4) has been derived by Pratt.[4,5] It is an approximation to the gust alleviation factor for a rigid airplane model with one rigid body mode, namely plunge, for which unsteady aerodynamics have been taken into account. Other airplane models and other gust lengths will lead to different values for K_g in Eq. (2).

The gust length $H=25$ chords is a rather arbitrary one and therefore may give rise to feelings of uncertainty. This has led to the concept of the tuned gust, which has been required in JAR 25 for some time. The gust length H should be varied between the limits as agreed with the Civil Aviation Authority and the most unfavorable response of the airplane should be used. This requirement can have a large effect on the design gust load and it may depend largely on the agreed limits, see Fig. 1. This requirement has been deleted in JAR 25.

Figure 1 shows that airplanes with low values of the mass ratio μ_g are more sensitive to short gusts and airplanes with high μ_g values to long gusts.

The concept of discrete gusts acting on an airplane has been and is still being used for the determination of gust design loads for airplanes. It should be realized that the methods described above act as an extrapolation formula. New airplanes are compared to older, satisfactory ones. As long as the new airplanes do not differ too much from the old ones with regard to the influence of pitch mode and flexible modes and if they are in the same bracket of mass parameter values, this extrapolation may be meaningful. However, the conviction has grown that the concept of a discrete one-minus-cosine gust with a gust length $H=25$ chords is unable to describe the irregular behavior of atmospheric turbulence and that extrapolation formulas used for the definition of design gust loads should be based on a physically more consistent description of the gust phenomenon.

The Continuous Gust Concept

The continuous gust concept is based on the assumption that atmospheric turbulence can be described as a quasistationary Gaussian process and that the airplane can be regarded as a linear system. Based on these assumptions, the power spectral density (PSD) method for the derivation of airplane design and fatigue loads has been developed in Refs. 6 and 7, written under contract for the Federal Aviation Agency. The proposed design values are based on the actual strength of existing airplanes assumed to have a satisfactory safety record. This work has resulted in the requirements for the dynamic response of the airplane to continuous gust.[1,2]

It is assumed that the power spectrum of the turbulence can be described with the isotropic or von Kármán spectrum,

$$\phi_{ww}(\Omega)=\frac{\sigma_w^2L}{\pi}\,\frac{1+(8/3)(1.339L\Omega)^2}{[1+(1.339L\Omega)^2]^{11/6}} \tag{6}$$

with $L=2500$ ft $=750$m.

Two types of criteria can be used:

1) Mission analysis, which sets a criterion for the total number of exceedances of the design load level. This criterion will not be discussed here.

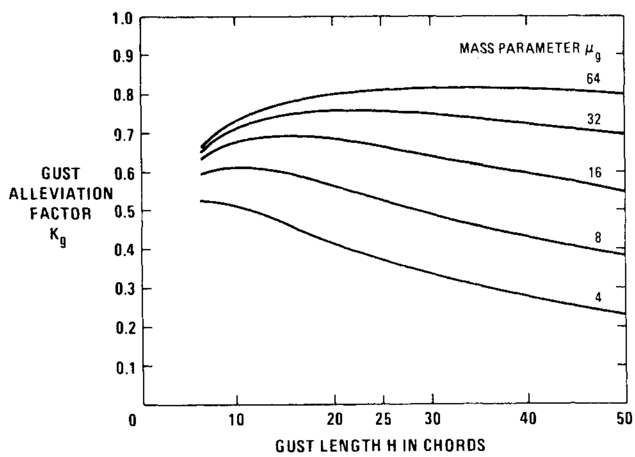

Fig. 1 Gust alleviation factor K_g as a function of gust length.

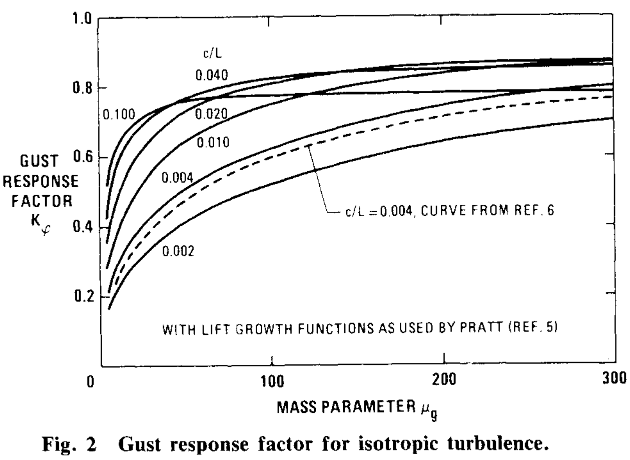

Fig. 2 Gust response factor for isotropic turbulence.

2) Design envelope criterion. Limit gust loads are determined with

$$y = \bar{A}_y U_\sigma \tag{7}$$

$\bar{A}_y$ can be calculated with

$$\bar{A}_y = \frac{\sigma_y}{\sigma_w} = \frac{1}{\sigma_w}\left[\int_0^\infty |H_{yw}(j\Omega)|^2 \phi_{ww}(\Omega)\mathrm{d}\Omega\right]^{1/2} \tag{8}$$

$\bar{A}_y$ for the most critical design envelope condition must be used in Eq. (7). At design cruising speed V_c, the prescribed values for U_σ are in FAR 25[1]

> $U_\sigma = 85$ ft/s ($=25.9$ m/s) on the interval 0-30,000 ft and is linearly decreased to 30 ft/s (9.1 m/s) at 80,000 ft. Under certain conditions, it will be acceptable to select a U_σ value not less than:
> $U_\sigma = 75$ ft/s ($=22.86$ m/s) in the interval 0-20,000 ft linearly decreasing to 30 ft/s ($=9.1$ m/s) at 80,000 ft

and in JAR 25[2]

> $U_\sigma = 25$ m/s on the interval 0-9150 m and is linearly decreased to 9 m/s at 24,400 m.

Comparison of the Methods

The requirements specified in FAR 25 and JAR 25 contain both the discrete gust and the continuous gust concepts. However, there seems to be a difference in the appreciation of the two methods. Both FAR and JAR prescribe that the limit gust loads must be determined on the basis of a one-minus-cosine gust with a length of 25 chords. Both also prescribe that the dynamic response to continuous turbulence must be taken into account.

FAR 25 then prescribes that the continuous gust design criteria must be used to establish the dynamic response unless more rational criteria are shown.

JAR 25 prescribes that, when the effects of the dynamic response to turbulence are assessed by the continuous turbulence method, the criteria described in this paper can be used. The principle of the application of this PSD method is to establish whether the structure exhibits characteristics substantially deviating from the results of the discrete gust analysis. If so, the implication should be discussed with the Authority.

The situation can probably be described by stating that FAR and JAR both demand that the limit loads be determined with the discrete gust method. FAR requires the PSD method as an obligatory complement and JAR regards it as a supplementary requirement. Nevertheless, application of the two methods may result in a conflict situation if the results of these methods are different.

In the following, the PSD design envelope method and the discrete gust method will be compared on the basis of simple airplane models. The comparison will be made for an airplane at design cruising speed V_c and the design value $U_\sigma = 85$ ft/s (true gust velocity) from sea level to 30,000 ft, decreasing to 30 ft/s at 80,000 ft, will be used for the PSD method.

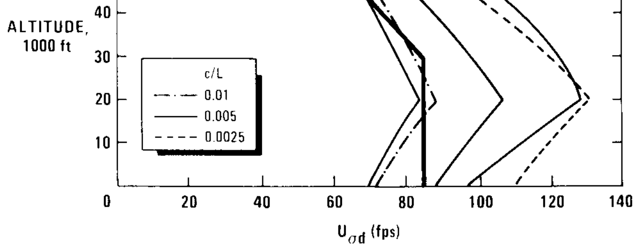

Fig. 3 $U_{\sigma d}$ values for an airplane with one degree of freedom.

A first comparison will be made for an airplane model as used by Pratt.[4,5] This model is rigid and free only to plunge. Unsteady aerodynamic forces are taken into account using an approximation. The limit load factor for a discrete gust with one-minus-cosine gust shape and 25 chords length is

$$\Delta n = \frac{a\rho_0 V_e S}{2mg} K_g U_{\mathrm{de}} \tag{9}$$

with gust alleviation factor K_g as given in Eq. (4) and U_{de} as prescribed.[1,2]

Application of the PSD method to the same airplane model gives as result

$$\Delta n = \frac{a\rho VS}{2mg} K_\varphi U_\sigma \tag{10}$$

with K_φ as given in Fig. 2. K_φ is a function of μ_g and c/L.

From Eqs. (9) and (10) it follows that the U_σ value giving the same limit load factor as the discrete gust, with given shape and length, is

$$U_{\sigma d} = \sqrt{\frac{\rho_0}{\rho}}\,\frac{K_g}{K_\varphi} U_{\mathrm{de}} \tag{11}$$

K_g and K_φ are functions of the mass parameter

$$\mu_g = \frac{2m}{\rho acS} = \frac{\rho_0}{\rho}\,\frac{2m}{\rho_0 acS} = \frac{\rho_0}{\rho}\mu_{g0} \tag{12}$$

$U_{\sigma d}$ is depicted in Fig. 3 as a function of altitude, with μ_{g0} and c/L as parameters. The design value U_σ is also given. From Fig. 3 follows that $U_{\sigma d}$ values, giving the same limit load as the discrete gust, tend to become lower for 1) higher values of μ_g, a similar result is given by Jones[10]; 2) higher values of c/L; and 3) lower altitudes. This implies that for these cases the PSD method may become the critical one.

It is thought that another type of presentation is more convenient. The curves in Fig. 3 are a function of μ_{g0} with c/L as parameter. Both depends on chord length c. The mass parameter μ_{g0} is the time constant of the airplane pertaining to nondimensional time $r = VT/c$ and frequency $\lambda = c\omega/V$. In the following, the quantity

$$T_n = \frac{c}{L}\mu_g = \frac{2m}{\rho aLS} = \frac{\rho_0}{\rho} T_{n0} \tag{13}$$

will be used. It is the time constant of the airplane pertaining to nondimensional time $T = Vt/L$ and frequency $\nu = L\omega/V$. Results will be given as a function of $1/T_{n0}$, because airplane models with two degrees of freedom and natural frequency ν_n will also be considered.

$U_{\sigma d}$ values as obtained with Eq. (11) for an altitude of 20,000 ft are given in Fig. 4 as a function of $1/T_{n0}$ and with c/L as parameter. Both depend on chord length c. The mass also given.

In Fig. 4 have been plotted the approximate values $1/T_{n0}$ and c/L of the older airplanes A-J as used by Pratt and Walker[5] for the reevaluation of V-G data and the newer airplanes 1-12, the names of which are given in the legend. The time constants T_n of these airplanes are based on design gross weight or maximum takeoff weight and with lift curve slope a equal to $6A/(A+2)$, in which A is the aspect ratio.

Of course, Fig. 4 offers only a crude way to compare the two methods. The curves are valid for only one altitude and are related to the acceleration for a simple airplane model with one degree of freedom. Thus, if for a certain airplane $U_{\sigma d}$ is greater than 85 ft/s, it should not be concluded that for that airplane the discrete gust method gives higher limit loads than the PSD method.

However, Fig. 4 clearly shows some trends. For the older types of aircraft, the discrete gust method is the critical one. For the newer types of aircraft, the PSD method may lead to limits loads that are equal to or higher than those obtained with the discrete gust method (if for both methods the same simplified airplane model is used).

For a one-degree-of-freedom-airplane, the PSD design method becomes the critical one for airplanes with low values of $1/T_{n0}$ (high μ_g values). It also becomes the critical one for large values of c/L (large airplanes) if $1/T_{n0}$ is not low and if the critical design envelope condition is at a low altitude.

The same method will now be applied to an airplane model with two degrees of freedom, namely pitch and plunge. Unsteady aerodynamic forces will be taken into account, using Pratt's approximation. The transfer function for this airplane model is[3]

$$G(j\nu)=\frac{1}{VT_n}\,\frac{\{-\nu^2+2j\nu\zeta_m\nu_n C(j\nu)\}D(j\nu)}{-\nu^2+2j\nu\zeta\nu_n C(j\nu)+\nu_n^2C^2(j\nu)} \tag{14}$$

where ν_n and ζ are approximately the nondimensional natural frequency ($\nu_n = L\omega_n/V$) and the damping coefficient of the short period motion. For $\zeta=1$ and $\zeta_m=0.5$, Eq. (14) reduces to the transfer function of a one-degree-of-freedom airplane model, with $1/T_n=\nu_n$.

The $U_{\sigma d}$ value that with the PSD method gives the same limit load factor as the prescribed discrete gust is given in Fig. 5 as a function of the nondimensional frequency $\nu_{n0}=(L/V)(\rho_0/\rho)\omega_n$, for an altitude of 20,000 ft. The curves in Fig. 5 are given for $\zeta_m=0.5$ with c/L and ζ as parameters. Lower values of $U_{\sigma d}$ are obtained for lower values of the damping coefficient ζ of the short-period motion.

In the same figure, the curve for $\zeta_m=0.8$ (with $c/L=0.005$ and $\zeta=0.6$) is given. This coefficient also has an influence on the $U_{\sigma d}$ curve. $U_{\sigma d}$ decreases with increasing ζ_m.

From the foregoing, it can be concluded that there exists no direct relation between the PSD and discrete gust methods. Generally, different results will be found if the two methods are applied; in fact, it is a coincidence if the two methods give approximately the same results.

The PSD method will tend to be the critical one, giving the highest design loads, under the following conditions:

1) If the critical design envelope condition is at a lower altitude.

2) For low values of $1/T_n$ (high μ_g values) for an airplane with one degree-of-freedom (dof) and b) for low values of the natural frequency of the short-period motion $\nu_n = L\omega_n/V$ for an airplane with two dof.

3) For high values of c/L (large airplanes) if $1/T_{n0}$ (one dof) or ν_{n0} (two dof) are not low.

4) For low values of the damping coefficient ζ (two dof).

5) For high values of ζ_m (two dof).

Causes of the Discrepancy

In the foregoing, it has been shown that the discrete gust and the PSD methods generally lead to different results. Both can be regarded as extrapolation methods. Design loads for a new airplane are calculated on the basis of a method that has been used (or could have been used) to calculate the design loads for older, satisfactory airplanes. Such an extrapolation method should be based on a fairly good description of atmospheric turbulence and the airplane response. The design values for the gust strength can then be derived from older airplanes.

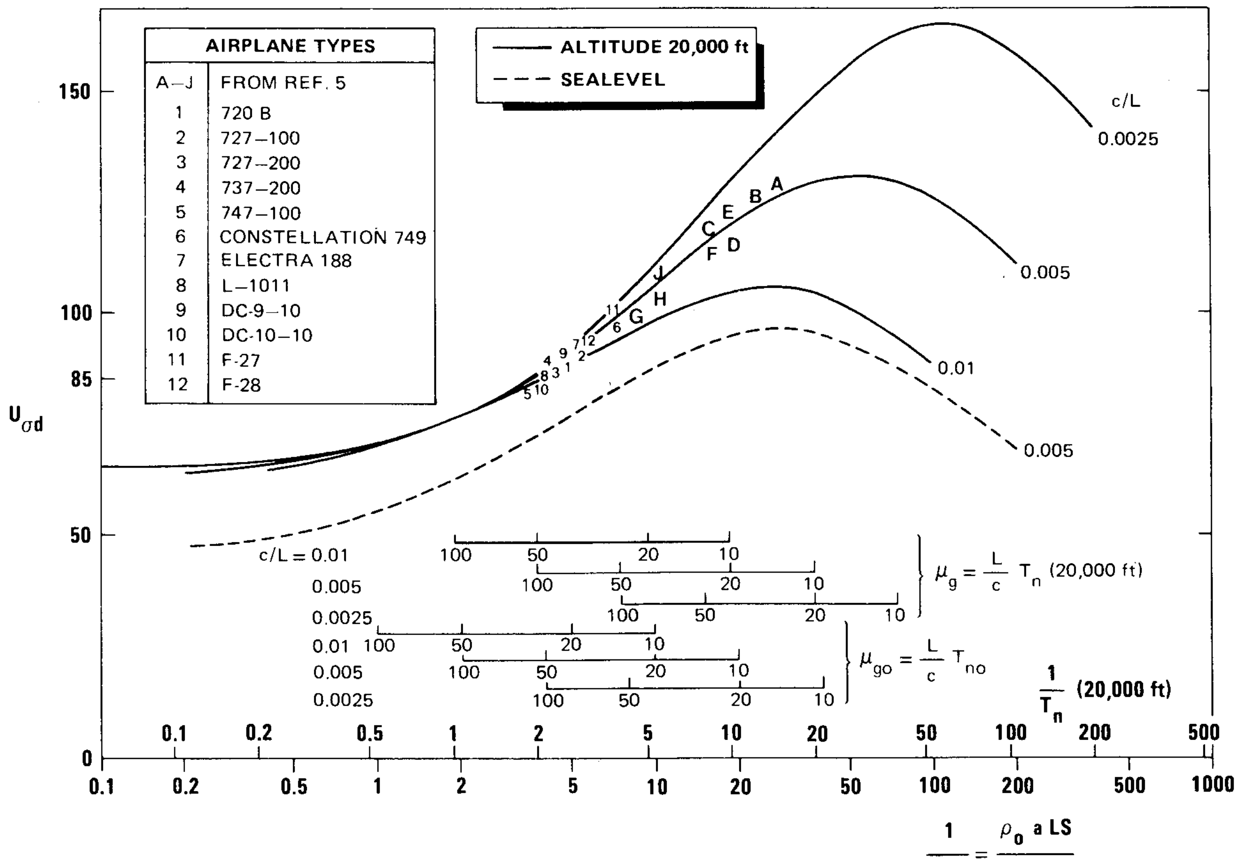

Fig. 4 $U_{\sigma d}$ value equivalent to discrete gust velocity U_{de} for an airplane with one degree of freedom.

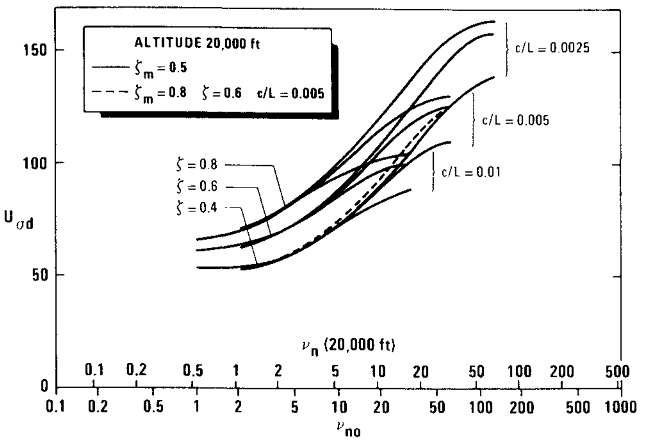

Fig. 5 $U_{\sigma d}$ value equivalent to discrete gust velocity U_{de} for an airplane with two degrees of freedom.

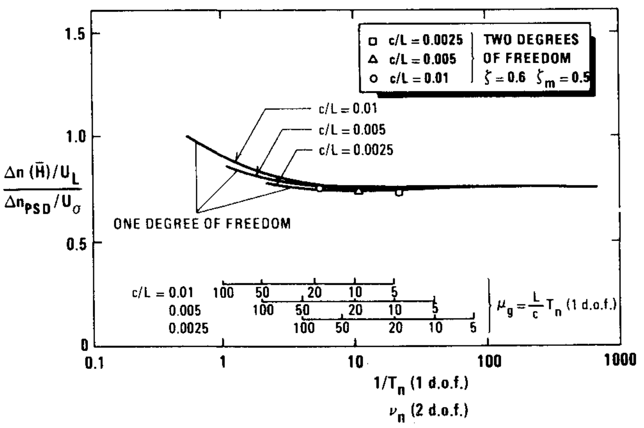

Fig. 6 Ratio $\Delta n(\bar{H})/\Delta n_{PSD}$ as a function of $1/T_n$ and ν_n.

However, even for a rigid airplane with one degree of freedom, the two methods already give different results. Therefore, it is to be expected that, as long as both methods are prescribed in the regulations, conflict situations will arise.

The differences between the two methods can be attributed to the following causes:

1) The character of atmospheric turbulence. In the discrete gust method, only one gust with a prescribed shape is considered. In the PSD method, atmospheric turbulence is assumed to be a random process.

2) The response behavior. In the discrete gust analysis, the maximum response peak is considered. The transient behavior of the airplane is decisive. In the PSD method, the steady-state response is used. It is assumed that transients have died out.

3) Relation between gust velocity and gust length. In the requirements for a discrete gust analysis, only one gust length, expressed in chord lengths, is prescribed. This implies that for large airplanes the prescribed gust length is larger than for small airplanes. The gust velocity is assumed to be independent of gust length. In the PSD method, a power spectrum for atmospheric turbulence is assumed. The shape of this spectrum is such that the energy at lower frequencies (large gust lengths) is higher than at high frequencies.

4) Variation of gust velocity with altitude. In the requirements for the discrete gust analysis, an *equivalent* gust velocity U_{de} is prescribed and, for the continuous gust analysis, a *true* gust velocity U_σ.

The last cause is independent of the method that is used. It depends only on the requirements. This cause of the discrepancy between the two methods can be eliminated by prescribing a constant ratio of the design gust velocities at all altitudes.

It will be shown that the main cause of the discrepancy between the two methods is the third one. Although probably unexpected, the first two causes have only a secondary effect.

The discrete gust method assumes that the one-minus-cosine gust has a certain prescribed velocity that is independent of gust length. It has been long known that gust velocity depends on gust length. This can be shown by quoting Rhode,[8] "let us assume that each particle or small unit volume of air contains, at a given isobaric level, the same amount of energy as do all other similar unit volumes at the same level within the sphere of action. Now if, under the action of some more or less general influence associated with the weather conditions in force, these unit volumes are caused to transform their energy into turbulent energy, each at the same rate at any instant, each gust will receive an amount of energy at a rate approximately proportional to the total volume of air involved in the gust. The power available for each gust under these conditions is therefore approximately proportional to H^3. Such a state of affairs could only be transitory as the energy transferred to the gusts would be, in turn, transformed into some other form of energy until a condition of equilibrium was attained, when the atmosphere would become quiescent.

Now in any unidirectional gust of a given shape, the power of the gust is proportional to the cube of the velocity and to the cross-sectional area through the gust, namely, $P \propto U^3 H^2$. We have, then, equating the instantaneous power available to the instantaneous power of the gust: $U^3 H^2 \propto H^3$ or $U^3 \propto H$.

Rhode also showed that measured gust data were reasonably in accordance with this law.

Of course, this has to be interpreted statistically. The probability of observing a gust with length H_1 and velocity U_1 is equal to observing a gust with length H_2 and velocity $U_2 = U_1 (H_2/H_1)^{1/3}$.

This concept is worked out by Jones in the statistical discrete gust (SDG) method. A description of the theory is given in Ref. 9. The maximum response $F(H)$ of an airplane to a discrete gust is calculated as a function of gust length H. The weighted gust response is

$$\gamma(H) = F(H) \cdot H^{1/3} \tag{15}$$

The maximum value $\gamma(\bar{H})$ of this function is the response value that has to be multiplied by an appropriate design value for the gust intensity to provide the gust design load. Jones has extended his theory, expecially for lightly damped airplanes, by considering a sequence of discrete gusts. A formulation of gust load requirements, based on the SDG method is given in Ref. 10.

The maximum response of an airplane to a one-minus-cosine gust with length H is

$$\Delta n(H) = \frac{a\rho VS}{2mg} K_g(H) U_d \tag{16}$$

It will now be assumed that

$$U_d = (H/L)^{1/3} \cdot U_L \tag{17}$$

The maximum response will be found for a gust length $\bar{H}$ and is equal to

$$\Delta n(\bar{H}) = \frac{a\rho VS}{2mg} \left(\frac{\bar{H}}{L}\right)^{1/3} K_g(\bar{H}) \cdot U_L \tag{18}$$

Application of the PSD method gives

$$\Delta n_{\text{PSD}} = \frac{a\rho VS}{2mg} K_\varphi U_\sigma \tag{19}$$

For an airplane with one degree of freedom and unsteady aerodynamic forces, according to Pratt's approximation, the ratio

$$\frac{\Delta n(\bar{H})/U_L}{\Delta n_{\text{PSD}}/U_\sigma} = \frac{(\bar{H}/L)^{1/3} K_g(\bar{H})}{K_\varphi} \tag{20}$$

is given in Fig. 6 as a function of $1/T_n$. This ratio is approximately equal to 0.75, except for small values of $1/T_n$.

In Fig. 6 some values for this ratio for an airplane model with two degrees of freedom are also given. The influence on the value of the ratio, due to changes in both c/L and the aircraft model are relatively small.

It can be concluded that a class of airplane exists, namely, rigid airplanes with one degree of freedom, for which the PSD method and a discrete gust method give approximately the same results, provided that in this discrete gust method a tuned gust with the following relation between gust velocity and gust length is used:

$$U = \left(\frac{H}{L}\right)^{1/3} U_L \cong \left(\frac{H}{L}\right)^{1/3} \frac{U_\sigma}{0.75} \quad . \tag{21}$$

The main difference between the PSD method and the discrete gust method is caused by not taking into account the relation between the gust velocity and the length in the latter. The shape of the power spectrum as used in the PSD method implies that more energy is available at low frequencies (long gusts) than at high frequencies. Both methods are comparable if the relation $U \propto H^{1/3}$ is taken into account. Other differences between the two methods, especially the description of the character of atmospheric turbulence and the response behavior, have a secondary effect.

The relation between gust velocity and gust length was derived by Rhode using energy considerations. The von Kármán power specrum is proportional to $\Omega^{-5/3}$ for higher frequencies. This is related to the relation $U \propto H^{1/3}$ for discrete gusts.[3,10] Measurements of atmospheric turbulence show the same trends.[3] Although this relation has been known for many years, it never has been integrated in the requirements for the discrete gust method. Jones advocates the use of the statistical discrete gust (SDG) method that takes this relation into account.

The foregoing is not a plea to use this SDG method, but it is intended as a warning against further reliance on the discrete gust method as described in the regulations.

Conclusions and Recommendations

Both FAR and JAR demand that load limits be determined on the basis of a discrete one-minus-cosine gust with a length of 25 chords. To take into account the dynamic response to continuous turbulence, FAR requires the PSD method as an obligatory complement and JAR regards it as a supplementary requirement. Numerical values for U_σ are still under discussion.

The comparison of a PSD design envelope analysis and a discrete gust analysis, based on simple airplane models, indicates that the PSD method tends to become the critical one for large aircraft with high mass ratio or low natural frequency and/or low damping of the short-period motion. This is especially true if the critical design envelope condition is at a low altitude.

It is not possible to make a direct link between the two methods, discrete gust and PSD, even for simple airplane models. Four possible sources for the discrepancy can be indicated: the character of atmospheric turbulence, the response behavior, the relation between gust velocity and gust length, and the variation of gust velocity with altitude. To overcome the last cause of the discrepancy, the regulations should prescribe true or equivalent gust design velocities that have a constant ratio for all altitudes.

The wording of the regulations suggests that the character of atmospheric turbulence and the response behavior are the main sources of the discrepancy between the results obtained with PSD and the discrete gust methods. However, it turns out that the main source of the discrepancy between the two methods is the relation between gust velocity and gust length. In the discrete gust method, the velocity is independent of length. In the PSD method, the energy for high frequencies is lower than for low frequencies.

If the discrete gust method is applied, using a tuned gust and taking into account that gust velocity is proportional to gust length to the one-third power, then the two methods give approximately the same results for simple airplane models. Of course, if more complex airplane models are used, the results of the PSD method and the discrete gust method (with $U \propto H^{1/3}$) may deviate much more. Indications for the relation $U \propto H^{1/3}$ exist. If this relation is true, then those airplanes for which the PSD method is the critical one may be relatively less strong than (older) airplanes for which the PSD method is not critical.

The discussion on the relative merits of the discrete gust and the PSD methods should first be devoted to the relation between gust velocity and gust length. Agreement on this property of atmospheric turbulence should then result either in adopting a discrete gust method in which this relation is incorporated (for example, the statistical discrete gust method as developed by Jones) or in raising the power spectral density method as being decisive for the determination of design loads.

References

[1]Federal Aviation Regulations, Part 25: Airworthiness Standards: Transport Category Airplanes, Change 15, Eff. 10/14/80, U.S. Department of Transportation, Federal Aviation Administration, Washington, DC, 1980.

[2]Joint Airworthiness Requirements, JAR-25: Large Aeroplanes, Civil Aviation Authority, Cheltenham, England, Nov. 1980.

[3]Noback, R., "Review and Comparison of Discrete and Continuous Gust Methods for the Determination of Airplane Design Loads," National Aerospace Laboratory, Amsterdam, Rept. NLR TR 82134 U, 1982.

[4]Pratt, K.G., "A Revised Formula for the Calculation of Gust Loads," NACA TN 2964, June 1953.

[5]Pratt, K.G. and Walker, W.G., "A Revised Gust Load Formula and a Re-evaluation of V-G Data Taken on Civil Transport Airplanes from 1933 to 1950," NACA Rept. 1206, 1954.

[6]Hoblit, F.M., Paul, N., Shelton, J.D., and Ashford, F.E., "Development of a Power-Spectral Gust Design Procedure for Civil Aircraft," FAA-ADS-53, Jan. 1966.

[7]Fuller, J.R., Richmond, L.D., Larkins, C.D., and Russell, S.W., "Contributions to the Development of a Power-Spectral Gust Design Procedure for Civil Aircraft," FAA-ADS-54, Jan. 1966.

[8]Rhode, R.V., "Gust Loads on Airplanes," *SAE Journal (Transactions)*, Vol. 40, March 1937, pp. 81-88.

[9]Jones, J.G., "Statistical Discrete Gust Theory for Aircraft Loads—A Progress Report," Royal Aeronautical Establishment, Tech. Rept. 73167, Nov. 1973.

[10]Jones, J.G., "On the Formulation of Gust Load Requirements in Terms of the Statistical Discrete Gust Method," Royal Aeronautical Establishment, Tech. Memo FS 208, Oct. 1978.