Evaluations of a Spectral Gust Model Using *VGH* and *V-G* Flight Data

John M. Firebaugh*
Lockheed-Georgia Company, Marietta, Ga.

A turbulence model for power spectral gust studies is presented and tested against operational gust load factor flight experience of several airplanes as measured by *VGH* and *V-G* recorders. The gust model is compatible with current spectral gust concepts but is generally less severe than most previously published models. The tests of the gust model are applied to three currently operational commercial transport aircraft which have had extensive usage and for which detailed knowledge of analytical response, mission profiles, and flight measured gust load factors is available. Direct comparisons of predicted with measured gust load factor spectra are also shown for several other transport aircraft using a simplified mission segment analysis approach based on NASA data and statistics. A large sample (8818 flight hours) of *VGH* data from C-130-type aircraft is utilized in evaluations of the gust model to show the effect of altitude on gust loads spectra predictability. Where applicable, samples of B-52 service operational *VGH* data are included for comparative purposes. The favorable comparisons shown for all airplanes indicate that the gust model is a reliable turbulence model for the prediction of gust loads spectra for airplanes in routine flight operations.

Nomenclature

A	=	ratio of rms response to rms gust velocity
AR	=	aspect ratio
b_1, b_2	=	turbulence intensity parameters used in spectral description of environment
$C_{L\alpha_A}$	=	airplane lift curve slope, per rad
KEAS	=	equivalent airspeed, knots
$K\sigma$	=	spectral gust alleviation factor
L	=	scale of turbulence, ft
M	=	Mach number
N_0	=	characteristic frequency of response, cps
$N(y)$	=	cumulative number of cycles of response y
P_1, P_2	=	proportions of flight time in turbulence used in description of environment
T	=	flight time spent in a given mission segment, sec
V_T	=	true airplane speed, fps
V-G	=	flight data record of airplane velocity and center of gravity acceleration
VGH	=	flight data record of airplane velocity, center of gravity acceleration, and altitude
W/S	=	airplane wing loading, psf
Ω	=	reduced frequency, rad/ft
$\Phi(\Omega)$	=	power spectral density function of gust input
ρ	=	air density, slugs/ft^3
ρ_0	=	sea level air density, slugs/ft^3
σ_w	=	rms vertical gust velocity, fps

Introduction

THE development of gust design criteria which utilize power spectral techniques has advanced in the past several years through the comparative stages to the establishment of absolute values for use in both fatigue and design load calculations. Since the design loads spectra computed by power spectral techniques are dependent upon the gust model parameters selected, these parameters may directly influence fatigue loads design spectra, ultimate design gust loads, and the attendant fatigue, static, and flight tests for verification of structural design. Thus, the establishment of reasonably accurate spectral gust model parameters has become of far reaching importance in the structural aspects of gust-critical aircraft. Even though large amounts of gust response data have been utilized in a statistical sense to deduce the turbulence environment for certain classes of turbulence activity, estimates of the primary parameters defining an over-all atmospheric gust model applicable to routine airplane operations vary widely and in some cases show contradictory trends as in Fig. 1. The purpose of this paper is to present a resolved estimate of the gust model parameters and to show the results of testing this model against operational gust load factor experience.

Recently, the results of a FAA-sponsored study[1,2] have been published which provide sufficient engineering information to evaluate the over-all power spectral gust design procedure as applied to three different types of transport airplanes. The airplanes chosen for this study were the Lockheed Models L-188 (Electra) and L-749 (Constellation) and the Boeing B-720B turbojet. The choice of the specific gust model was based on the latest gust information available at the time as related to civil aircraft operations. The analytical and flight measured center of gravity gust load factor comparative data are sufficiently well in agreement to

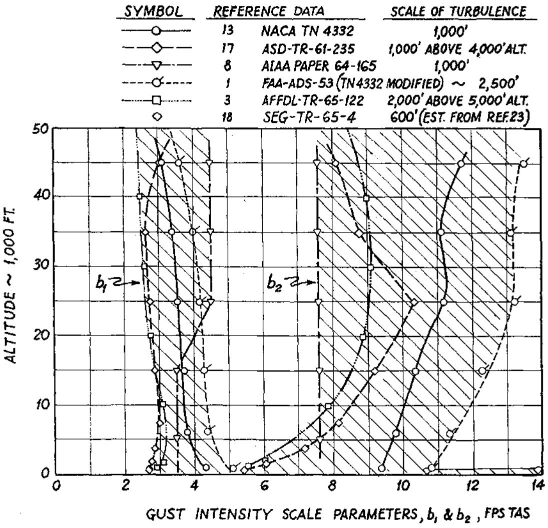

Fig. 1 Range in estimates of spectral gust intensity parameters.

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* Aircraft Development Engineer, Dynamics Specialist. Member AIAA.

indicate that the choice of the atmospheric model was reasonable for the purpose of establishing spectral gust design procedures. However, some reduction in over-all severity of the gust model is clearly indicated by the comparisons for two of these airplanes. As will be discussed subsequently, a reduction in gust environment severity for the third airplane could also be justified.

Subsequent to the studies mentioned previously, the atmospheric turbulence model evaluation of Ref. 3 was published which differed in many respects from the gust model used in the FAA-sponsored studies. However, previous independent studies at Lockheed-Georgia had resulted in gust model parameters which were supported by the values and trends of Ref. 3 but were still different in some details. At this stage it was decided to test the model developed at Lockheed-Georgia against significant samples of operational data using the best available analytical values for the gust response of the airplanes being studied. The airplanes for which detailed analyses for gust response are available, along with the associated flight load factor experience, are the three airplanes of Refs. 1 and 2 and the C-130 *VGH* flight loads data[4,5] with related Lockheed analyses. Additionally, the extensive gust load factor data summary of Ref. 6 is also used in part in simplified mission analyses. Some detailed evaluations of the gust environment as derived from B-52 *VGH* data from Refs. 7 and 8 are also included where applicable.

The variety of airplanes covered in the comparative studies that follow include a twin-engine and several four-engine propeller driven transports, two turboprop transports, and a four-engine swept-wing turbojet. Including the data for the latter airplane and the B-52 bomber, the evaluation of the gust model extends from altitudes of about 1000 to 40,000 ft altitude. For altitudes below 5000 ft, however, the flight operations are assumed to be associated with low altitude cruise or normal takeoff and landing procedures and do not necessarily reflect the turbulence environment for contour flying types of operation.

Power Spectral Gust Analyses

The methods of gust analyses using power spectral techniques are well documented so that only brief reminders on the basic equations are given here. More detailed information as well as general concepts of the problem formulation may be found in the discussions of Refs. 9–11.

The methods developed at NASA[12,13] lead to a simple, convenient expression for the gust load exceedance spectrum,

$$N(y) = N_0T\{P_1 \exp(-y/b_1A) + P_2 \exp(-y/b_2A)\} \quad (1)$$

In general, Eq. (1) is applicable only to a given mission pro-

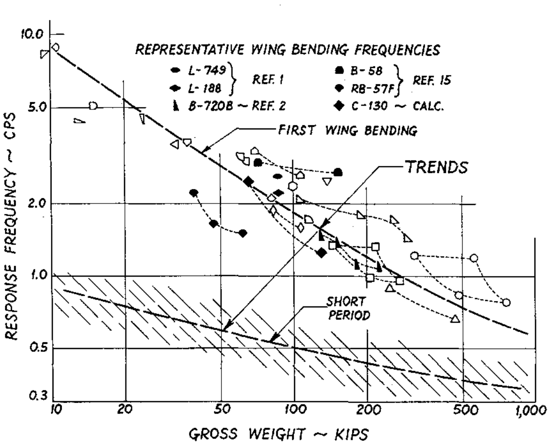

Fig. 2 Effects of gross weight on wing bending and short period frequencies.

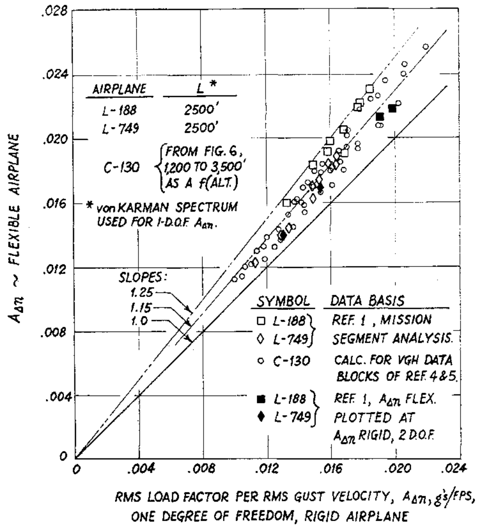

Fig. 3 Correlation of one-degree-of-freedom and more complete gust response analyses.

file segment wherein the flight conditions are considered to be essentially constant over a reasonable period of time. The total gust load experience is obtained by adding the contributions from all mission segments.

The computation of A and N_0 constitutes the core of the analytical flight dynamics problem, and these analyses range in complexity from one-degree-of-freedom approximations such as in Ref. 14 to the multi-degree-of-freedom programs required for structurally flexible aircraft. For very large or relatively flexible aircraft, the presence of highly responding wing bending modes may completely dominate the responses in the short period mode.[15] Figure 2 shows some approximate trends in wing bending frequencies as related to the short period pitching frequencies which indicate a trend toward coalescense of these response frequencies for very large aircraft. Because of these significant effects, the analyses for A and N_0 as used herein for the C-130, B-52, and the transport aircraft of Refs. 1 and 2 include structural flexibility effects as well as unsteady lift effects and gradual gust penetration in accordance with state-of-the-art practice.

Although the previous effects lead to a fairly complex analytical problem, several studies have shown[10,15,16] that current techniques for computing A will yield reasonable agreement with flight test results. For many aircraft, the effects of flexibility may be approximated through the use of appropriate factors applied to rigid airplane response values. Figure 3 shows the correlation between A's computed by a simplified one-degree-of-freedom analysis with approximate unsteady lift effects and by more complex analyses which include a more complete treatment of unsteady lift, gust penetration lags, and flexibility effects. This correlation includes all differences between a simplified one-degree-of-freedom analysis and a more complete analysis and should not be regarded solely as a measure of structural flexibility effects. To illustrate this point, four additional data points have been superimposed on Fig. 3 as noted to show analytical results with and without flexibility effects.

Analytical estimates for N_0 for relatively rigid airplanes converge rapidly to values which characteristically are somewhat higher than the short period response frequency. For the typical flight conditions used in this paper for the C-130, L-188, and L-749, values for N_0 are in the range of 1.0 ± 0.3 cps. For more flexible aircraft, N_0 may be sensitive to the analytical techniques or assumptions employed. In either case, minor variations in N_0 due to analytical techniques are of secondary importance in the product N_0P in Eq. (1) because of the lack of preciseness in the environmental parameter P.

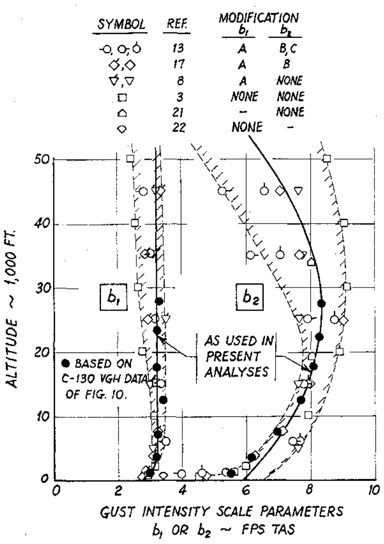

Fig. 4 Variation with altitude of modified spectral gust intensity parameter estimates.

Atmospheric Turbulence Models

Atmospheric turbulence models for spectral calculations as currently used are defined primarily by the variation of the parameters P, b, and the power spectral function $\Phi(\Omega, L)$ with altitude. Additional considerations are given to terrain, meteorological, climatological, or other effects as required. Several different models[1,3,12,13,17] have been developed in the past decade for altitudes from sea level to 50,000 ft or more while other models pertain only to low-level gusts.[18–20] Most of these previously published estimates for the turbulence model parameters are summarized in Figs. 1 and 4–6 with the Lockheed-Georgia model shown superimposed on the latter three figures.

Figure 4 shows the results of a re-evaluation of previously published estimates of the gust intensity parameters. The modifications to previous estimates included, where applicable, corrections to A's used in the original data reduction based on correlations such as in Fig. 3, corrections or modification to original data to account for changes in trends observed in later, more reliable estimates, and correction or elimination of estimates that were obviously questionable or not reasonably compatible with established trends. The favorable resolution of the b_1 and b_2 estimates using such subjective techniques as shown in Fig. 4 appears to justify the significant modifications to some of the data of Fig. 1. The data points shown for the thunderstorm data of Ref. 21 and the B-66B low-level gust data[22] shown in Fig. 4 are composite rms values of the true gust velocities obtained from gust boom measurements taken during those programs. These composite values are determined by extracting the square root of the sum of the mean square gust velocities tabulated for each data source.

A summary of estimates of P_1 and P_2 from several data sources is shown in Fig. 5. The values used in subsequent comparative analyses, indicated by the solid lines, were basically established in earlier studies and thus do not reflect all current data trends.

Figure 6 presents several estimates for the scale of turbulence which are typical of recent evaluations. Estimates which utilize the von Karman power spectrum defined below are identified with flags. The estimates from Ref. 21 are based on a minimum value of L to fit the average straight-line character of log-log plots of these data over the measured frequency range. Estimates of L from the low-level data of Refs. 22 and 23 are based on curve-fits of the normalized gust spectral densities using the von Karman gust spectrum.

The variation of L with altitude which has been used in the comparative studies is shown by the solid line of Fig. 6. This variation reflects a compromise of the more recent turbulence scale estimates which indicate scales of turbulence considerably larger than 1000 ft at high altitudes. Although there is evidence that L may vary with rms gust velocity,[3] average values are desired here in a manner compatible with the use of a single composite value of b_1 or b_2 to represent all exposures to various rms gust velocity intensities. Although the trend of L to increase with altitude is apparent, the estimates at any altitude vary widely and are still subject to question. In particular, it may eventually be necessary to use different power spectral functions, or L's, for clear air and for storm turbulence. Current U.S. Air Force gust data collection programs will be of use here. Since the value of L and the input spectral function $\Phi(\Omega,L)$ affect the response parameter A and therefore are interrelated with b, some effects of $\Phi(\Omega,L)$ on A will be briefly considered.

The most frequently used power spectral density functions for descriptions of the vertical component of atmospheric turbulence are

$$\Phi(\Omega)/\sigma_w^2 = L(1 + 3\Omega^2L^2)/\pi(1 + \Omega^2L^2)^2 \tag{2}$$

$$\Phi(\Omega)/\sigma_w^2 = L(1 + 4.781\Omega^2L^2)/\pi(1 + 1.793\Omega^2L^2)^{11/6} \tag{3}$$

and

$$\Phi(\Omega)/\sigma_w^2 = L/(1 + \Omega L)^2 \tag{4}$$

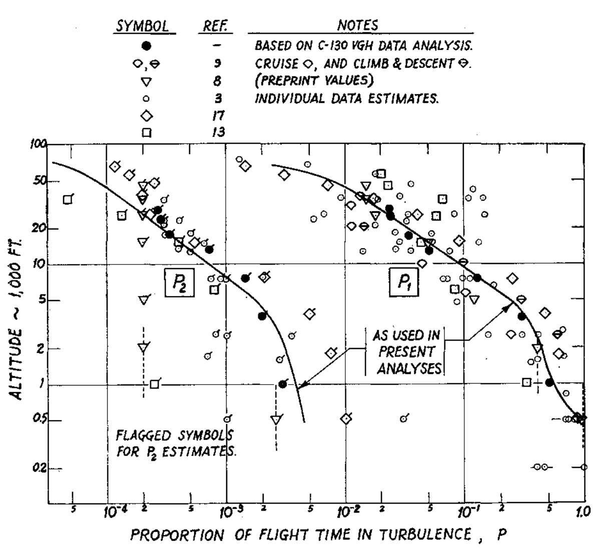

Fig. 5 Estimated variation with altitude of flight time in turbulence.

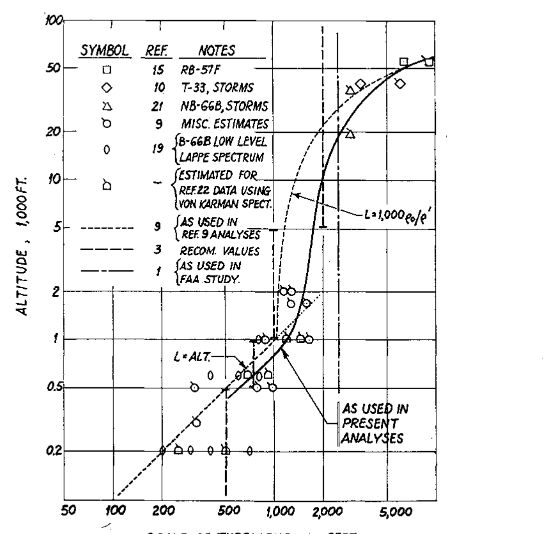

Fig. 6 Estimated or assumed values of the scale of turbulence.

which are attributed to Dryden, von Karman, and Lappe, respectively. Another spectrum used in some studies by Lockheed-Georgia is

$$\Phi(\Omega)/\sigma_w^2 = 0.8L/(1 + \Omega L)^{1.8} \tag{5}$$

which is a modification of the Lappe spectrum that affords a more favorable comparison with the von Karman spectrum at most airplane response frequencies. The simplicity of the Lappe spectrum and the desirable elimination of the sharp knee which is in the Dryden and von Karman spectra are retained in Eq. (5).

The spectral gust input functions (2, 3, and 5) were used in state-of-the-art computations for the responses of a large swept-wing transport for two significantly different flight conditions in order to evaluate the effects of spectral shape. The results for c.g. acceleration response are shown in Fig. 7 along with theoretical approximations which assume all significant responses to occur at $\Omega L \gg 1.0$. For this airplane, an intermediate C-5A configuration, very little differences in results are noted between the use of the von Karman or the Dryden spectrum at a given L for either the high-altitude cruise condition, Fig. 7a, or the low-altitude 350 KEAS condition, Figure 7b. The variations of A with L, however, show significant differences in trends between the two flight conditions. Further, the approximations based on all major response at $\Omega L \gg 1.0$ do not, in general, give satisfactory results for these airplane flight conditions. It should therefore be recognized that if additional data or analyses indicate changes to the values of L used in the comparative analyses herein, then the values of b in Fig. 4 should be modified accordingly so that the product bA remains constant. It may be necessary to obtain data such as in Fig. 7 to evaluate such modifications.

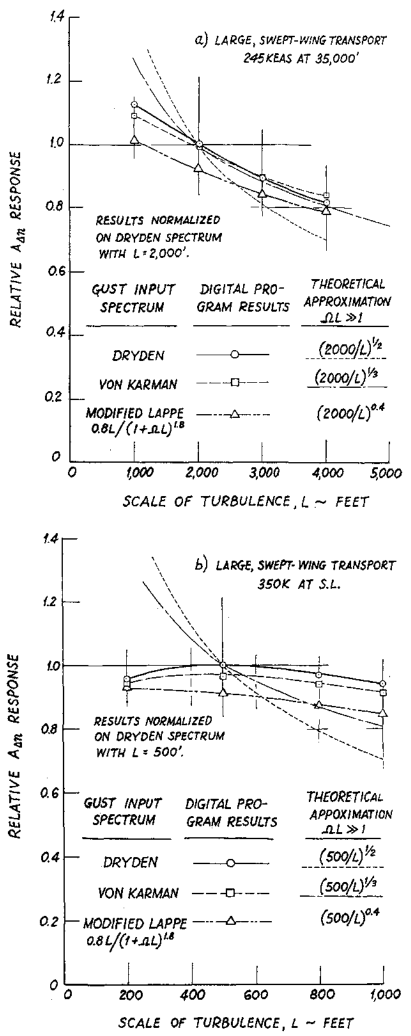

Fig. 7 Effect of gust input spectrum on the rms load factor response of a large swept-wing transport airplane.

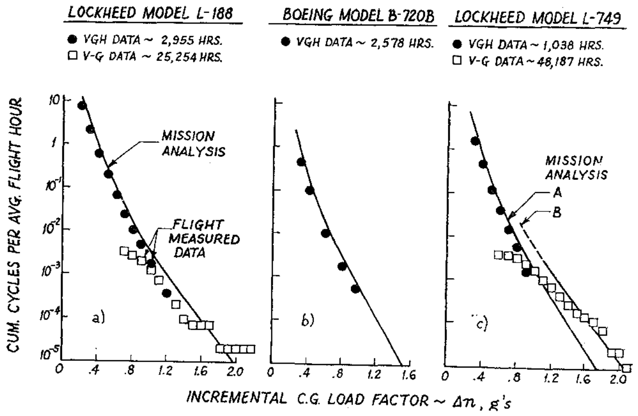

Fig. 8 Comparison of mission analysis results with *VGH* and *V-G* flight measurements of incremental c.g. load factors.

Comparisons of Predicted and Measured Gust Load Factor Spectra

The comparison between the analytically predicted center of gravity gust load factor experience and those measured in routine flight operations of transport category aircraft are shown in Figs. 8–10. All the comparisons utilize the atmospheric gust parameters P, b, and L from Figs. 4–6 labeled "as used in present analyses." All results are based on, or are adjusted to, the modified Lappe spectrum of Eq. (5) except for the simplified mission analysis comparisons of Fig. 9 which are based on the von Karman spectrum Eq. (3). For the airplanes considered in these comparisons, the frequency response characteristics are such that most of the gust response contribution to A is within the range of $0.002 \leq \Omega \leq 0.05$ rad/ft where differences in Eqs. (3) and (5) are a minimum. As a result, the A's computed with the modified Lappe input spectrum are about 4% less than the A's computed with the von Karman spectrum. With this minor correction in mind, the comparisons of Figs. 8 through 10 may be considered equally well to be based on either the von Karman spectrum or the modified Lappe spectrum of Eq. (5).

The development of the mission analysis predictions for these airplanes differs in some details depending primarily on the availability of relevant data as discussed below.

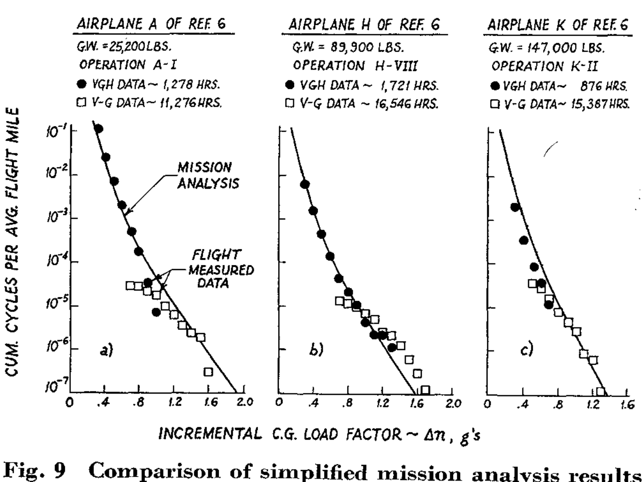

Fig. 9 Comparison of simplified mission analysis results with *VGH* and *V-G* flight measurements of incremental c.g. load factors.

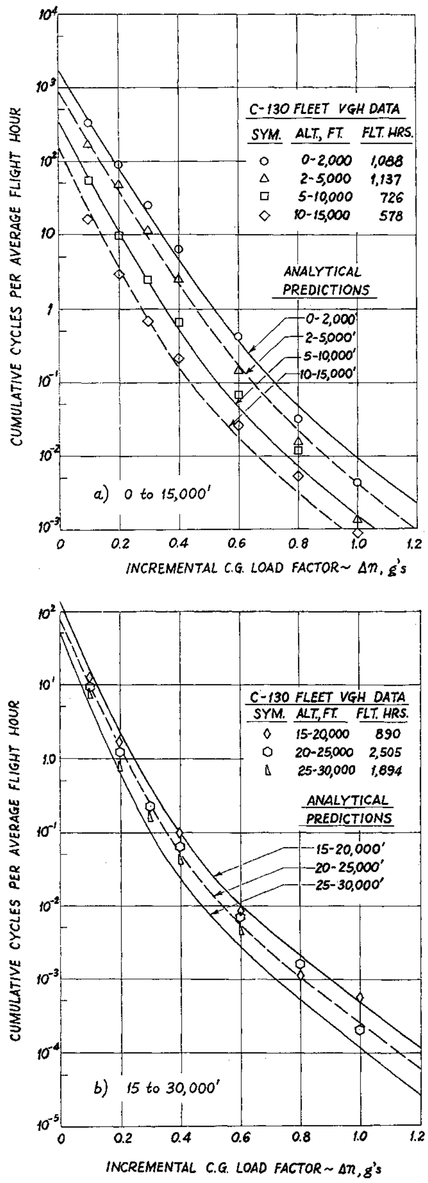

Fig. 10 Comparison of C-130 fleet operational gust load factor experience with analytical predictions.

Models L-188, L-749, and B-720B

The development of the typical flight profiles and the selection of representative climb, cruise, and descent flight conditions for the subsequent mission analyses for these airplanes is contained in Refs. 1 and 2. These same representative flight segments and percentage of total time allotted to a given segment are used in the mission analyses herein. The values of A and N_0 listed in those reports, however, are based on Eq. (3) with $L = 2500$ ft at all altitudes. Consequently, for L varying with altitude as in Fig. 6, some modification to the originally calculated values is required. Using the available response characteristics of the L-188 and L-749, several approaches were used to approximate the effects of change in spectral shape and L on A which were found to yield essentially the same results. With good accuracy, the modified A's used in the mission analyses herein may be obtained from the values in Ref. 1 by first dividing by 1.04 to account for change in the spectrum functional form, then applying the approximation $A \propto L^{-1/3}$. This last relation, associated with the von Karman spectrum, is valid for these flight conditions since major response was at $\Omega L \gg 1$. The same modifications as the preceding are applied to the A's of the B-720B; however, the previous inequality may be only marginally satisfied for some flight conditions. Values for N_0 from Refs. 1 and 2 are used in the present analyses without alteration since the modifications to account for a slight change in spectral shape would have an insignificant effect on the evaluations of the gust model.

Using the modified A's with the N_0's and representative mission segment utilizations taken directly from Refs. 1 and 2, the analytically predicted gust load factor experience per average flight hour is presented in Fig. 8. These results compare favorably with NASA flight measurements in Figs. 8a and 8b but the comparison shown in Fig. 8c for mission analysis A shows good correlation with the *VGH* measurements and a significantly poor correlation with the *V-G* measurements.

Two factors apparently contribute to the underestimation of the higher load factors for mission analysis A of the L-749. First, the NASA data of Ref. 6 show a 14% increase in gross weight between the period 1947–1950 when the *V-G* data were collected on these type aircraft and the period 1951–1953 when the *VGH* data were collected. Additionally, it is known[1] that this airplane's descent speed policy has been altered over this time span due in part to the extent of airspeed placard exceedances in evidence when *VGH* data became available. In order to judge the effects of these changes on the loads spectra, the mission analysis for the L-749 was repeated (mission analysis B) using 235 KEAS (normal-operating speed) for the descent speed segments instead of the original 220 KEAS and all gross weights were reduced by the ratio of gross weights noted in Ref. 6. These modifications are approximations to the mission segment descriptions for earlier versions of the L-749 and are associated with the *V-G* data of 1947–1950. This adjusted mission analysis coincides satisfactorily with the higher load factors as shown in Fig. 8c.

Simplified Mission Segment Analyses

Reference 6 summarizes a great deal of *VGH* and *V-G* data collected and analyzed by NASA for a number of piston-engine transport airplanes which may also be used as a check of the adequacy of the gust model of Figs. 4–6. The percentage of time spent in rough air for the flight regimes of climb, cruise, and descent is tabulated for each airplane for which *VGH* data are available as well as the average operating speeds in these regimes. Thus, the elements of a mission analysis are available from this data source provided certain assumptions are made regarding gross weight variations and response characteristics of these airplanes. Using only average climb, cruise, and descent segments, these simplified mission analyses for airplanes A, H, and K of Ref. 6 are shown in Fig. 9 along with flight measured *VGH* and *V-G* data. These airplanes were selected to cover the gross weight range of 25,200 to 147,000 lb. (Airplanes E and F of Ref. 6 are versions of the L-749 as discussed previously.)

The assumptions used in the analyses of this section include 1) the use of the factors 0.90, 0.85, and 0.80 applied to the gross weights listed in Ref. 6 to approximate the average gross weights during climb, cruise, and descent, respectively, 2) the use of a single-degree-of-freedom formula to estimate gust response effects which incorporates an approximate factor to account for structural dynamic effects, and 3) estimated values of N_0 of 1.0 cps for airplanes A and H and of 0.5 cps for the heavier airplane K. An average altitude for the climb and descent segments was assumed to be approximately one-half the average cruise altitude, weighted slightly to the lower altitudes.

The single-degree-of-freedom formula used here is identical in form to that of the discrete gust load formula and many similar spectral gust formulas used elsewhere[1,12,17] but the detailed assumptions used in evaluating this formula lead to significantly different results in some cases. The most rational interpretations for this type of formula are found in Ref. 1. For convenience, the formula is repeated here:

$$A = K_\sigma \rho V_T C_{L\alpha A}/2(W/S) \quad (6)$$

As used in this analysis, $C_{L\alpha A}$ is computed from the relation

$$C_{L\alpha A} = 1.15(6 Æ/Æ + 2)\{(Æ + 2)/Æ(1 - M^2)^{1/2} + 2\} \quad (7)$$

where the factor 1.15 accounts for body and tail lift in addition to that of the wing and the remaining terms are the commonly used NASA formulas for estimating wing lift curve slope and correction for compressibility effects. The spectral gust alleviation factor K_σ for this analysis is also taken from Ref. 1 which utilizes the von Karman spectrum and approximate unsteady lift effects for the evaluation. A correction factor of 1.08 to account for more accurate unsteady lift functions is recommended in Ref. 1 and applied here, although this factor was not included in the calculations for Fig. 3. Additionally, the A computed from Eq. (6) is multiplied by an estimated factor, to account for structural dynamic effects, of 1.07 for airplanes A and H and of 1.14 for airplane K.

The simplified mission analyses used herein thus reflect a number of assumptions most of which, however, are supported by relevant data on similar aircraft such as shown in Fig. 3. The favorable comparisons shown in Fig. 9 lend confidence in these assumptions. The importance of including climb and descent segments in a simplified mission analysis in lieu of a single average flight segment based on cruise conditions should be emphasized, however. A detailed check of the contribution of these three flight segments to the total load factor spectrum was made for airplane G of Ref. 6 using supporting information from Ref. 24. This check confirmed the validity of the three-segment subdivision by adequately reflecting the individual contributions of these segments.

C-130 Fleet Gust Load Factor Experience

A very large sample of load factor data (over 14,000 hr) for C-130 type aircraft has been collected in Air Force flight loads programs and reported in detail in Refs. 4 and 5. In these reports, the load factor exceedance experiences are grouped according to gross weight, speed, and altitude bands that are representative of C-130 usage. Although additional subdivisions are given according to the C-130 model, type of mission, and base of operations, for this initial analysis all data are grouped into gross weight-speed-altitude-flight time categories referred to here as *VGH* data blocks. Taken together, these *VGH* data blocks are therefore representative of world-wide C-130 aircraft operations without regard to type of mission.

For this initial evaluation of the C-130 data, the *VGH* data blocks encompassing gross weights of 85 to 125,000 lb, and speeds of 150 to 250 KEAS at all altitude bands are included, which results in a total of 8818 flight hours of data. Using state-of-the-art techniques, values of A and N_0 for these *VGH* data blocks have been computed for the modified Lappe spectrum of Eq. (5) and scale of turbulence from Fig. 6. (The use of the von Karman spectrum would have yielded A's about 4% higher.) These are combined with the gust environment parameters of Figs. 4 and 5 at selected altitude intervals to produce a mission analysis prediction of average load factor experience shown in Figure 10. The predicted and flight measured data are generally in agreement for all altitude bands with a tendency to overestimate the $P_2 - b_2$ contribution of turbulence at the altitudes of 0–5000 ft and a tendency to underestimate this contribution for 25–30,000 ft altitudes. Slight adjustments to the originally assumed values of P and b which would afford better agreement with the flight measured data are plotted as solid round symbols in Figs. 4 and 5.

Environmental Data Derived from Analysis of *VGH* Data

The terms of Eq. (1) may be regrouped by dividing both sides of the equation by N_0T resulting in a form referred to as a generalized exceedance expression. In this form of gust data presentation, the gust load factor exceedances per unit time are divided by the value of N_0 and the magnitude of the gust load factors are divided by the value of A. Regardless of the accuracy assumed in the analytical or flight test evaluations of A and N_0, these modifications to the basic load factor exceedance data are artificial and a direct comparison of predicted with measured gust load factor data is preferred when evaluating over-all gust load prediction procedures. This direct comparative approach is used for Figs. 8–10. For detailed estimates of the gust environment and its variations under given conditions, however, the generalized exceedance approach is more revealing.

C-130 Fleet Generalized Exceedance Data

The C-130 *VGH* data previously used are converted to a generalized exceedance form and presented in Fig. 11 for the grouped altitude bands of 0–5000 and 20–30,000 ft. These two altitude bands include a total of 6623 flight hours of *VGH* data, almost one-half of the total C-130 data collected for all flight conditions. Also shown in Fig. 11 are the predicted environments for these altitudes which are constructed using the parameters P and b of Figs. 4 and 5. It is emphasized that the scattering of data in these figures is mostly due to the variations in the amount and intensities of turbulence encountered by the C-130 aircraft and should be interpreted as being typical of the random nature of turbulence. Secondly, the nonuniform data sample sizes, which individually are rather small, also contribute to data scatter. In spite of these considerations, the actual scatter in data is encouragingly small for the low-altitude data and the higher-altitude data exhibit about the same amount of scatter as similar data in Ref. 7.

Comparisons with B-52 Fleet *VGH* Data

The large amount of B-52 fleet load factor experience reported in Ref. 8 in generalized exceedance form includes an undefined amount of maneuvering load factor experience in addition to that due to turbulence. Additionally, the A and N_0 values used therein are based on the Dryden spectrum with $L = 1000$ ft so that a direct comparison of those data with the gust model used herein is essentially meaningless. Nonetheless, data for the altitude bracket of 0–10,000 ft altitude are taken from Ref. 8 and superimposed on the C-130 data in Fig. 11a on the basis that the larger L's used in this study partially compensate for the nongust load factor experience included in the B-52 data. Though in general agreement, these data comparisons lead to no firm conclusions.

For the altitude bracket of 30–40,000 ft, however, an obviously large sample of B-52 fleet data in generalized exceedance form is available[7] in which the effects of maneuvers have been removed in the same manner as for the C-130 data. As in Ref. 8, these data are also based on the Dryden spectrum with $L = 1000$ ft but in this case, with maneuvers excluded, a reasonable conversion of these data to the input spectral function and L used herein may be made on the following basis.

Comparisons[25] of the B-52H and C-5A wing root bending moment gust response for typical low-level flight conditions indicate a high degree of similarity in frequency response of the short period and first elastic modes of these aircraft. Other calculations[25] show that A's for a midspan wing bending moment of the B-52 decrease about 5% due to a change in the input spectral function with $L = 500$ ft from the Dryden spectrum to the von Karman spectrum. This percentage

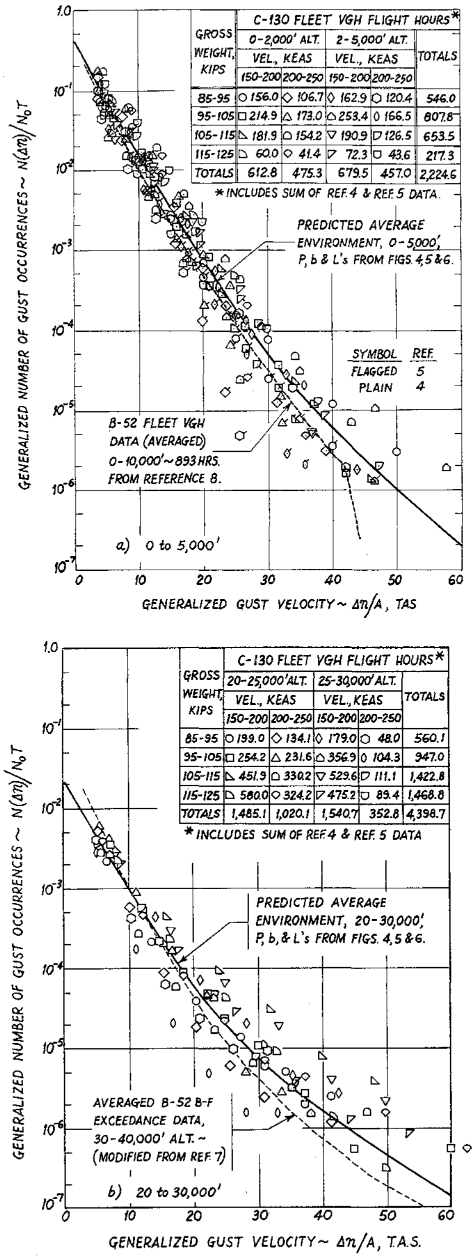

Fig. 11 Generalized exceedance data based on C-130 fleet *VGH* flight loads data.

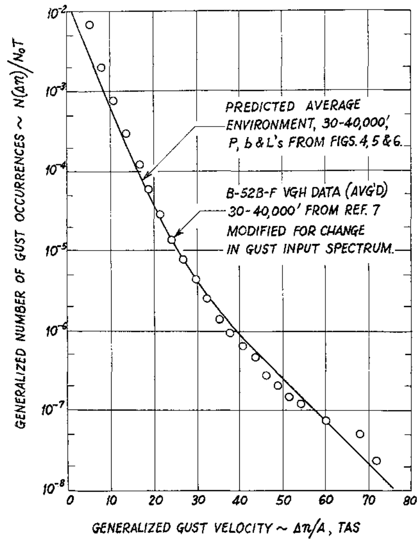

Fig. 12 Generalized exceedance data based on B-52B-F *VGH* flight loads data—30,000 to 40,000 ft altitude.

variation is identical to that shown in Fig. 7b for c.g. acceleration response. Considering these similarities in aircraft responses, it is considered reasonable to use the data of Fig. 7 for an early C-5A configuration to account for differences in c.g. gust acceleration response of the B-52 due to a change from the Dryden spectrum with $L = 1000$ ft to that of the modified Lappe spectrum with $L = 4000$ ft from Fig. 6. An approximate correction factor for A of 0.73 was derived from Fig. 7a and has been applied to the data of Ref. 7 shown as modified in Fig. 12. These same modified data are also superimposed on the data of Fig. 11b for comparison with the C-130 data.

Conclusions

The comprehensive comparisons of predicted and flight measured c.g. gust load factor experience show good agreement. This indicates that the gust model used is a reliable model for the prediction of average operational gust load factor spectra for airplanes with known or predictable mission segment utilizations. The more detailed evaluations of the gust model at various altitudes to 40,000 ft substantiate the gust model on a more refined basis. For short time durations, however, variations from the average gust environment are very pronounced due to the random nature of the turbulence intensities encountered under operational conditions. The more severe variations from the average gust environment indicate extreme values of the generalized gust velocities (y/A) to be on the order of 60 to 75 fps true airspeed (TAS) as derived from routine operational data. These severe gust encounters during short periods of exposure to a highly turbulent atmosphere have important implications in limit or ultimate gust design gust loads criteria and should be investigated further in relation to current and proposed design procedures. For many fatigue analysis or preliminary design purposes, however, the simplified mission segment analyses which utilize only climb, cruise, and descent flight segments with the gust model presented herein will yield sufficiently accurate results.

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