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DEVELOPMENT OF IMPROVED GUST LOAD CRITERIA FOR UNITED STATES AIR FORCE AIRCRAFT

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SYSTEMS ENGINEERING GROUP
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AIR FORCE SYSTEMS COMMAND
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FOREWORD

This report was prepared by William H. Austin, Jr., Requirements Branch (SEFSR), Directorate of Airframe Subsystems Engineering, Systems Engineering Group. The work was conducted under SEG Task 066A-70054, "Application of Statistical Concepts to Structural Design Criteria," and was administered by the Systems Engineering Group, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

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This technical report has been reviewed and is approved.

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ABSTRACT

Gust loads criteria have been developed which represent a considerable improvement over the current discrete gust criteria. These new criteria are based on the strength level of previously successful aircraft, and result from a probabilistic assessment of expected gust loads. To supplement the probabilistic criteria, an arbitrary criterion for limit design gust velocity is presented. The analyses to be used in conjunction with the new criteria are based on the continuous turbulence concept which allows the realistic determination of aircraft loads in atmospheric turbulence.

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SYMBOLS

A	gust response factor, $\frac{\sigma\ y}{\sigma\ u}$, $\frac{\text{units}}{\text{ft/sec}}$
b	turbulence field parameter denoting intensity, ft/sec
F_p	failure probability for an individual aircraft
L	scale of turbulence, feet
M(y)	average number of cycles of the specified response, y, per sec equalling or exceeding y, cyc/sec
N_o	average number of cycles of the specified response per sec, cyc/sec
P	turbulence field parameter denoting proportion of time in turbulence
T	airplane life, hours
T_{ex}	time to reach or exceed ultimate load in turbulence, hours
$\|T(\Omega)\|^2$	square modulus of the airplanes' frequency response function in terms of spatial frequency, $(\text{units}^2/(\text{ft/sec})^2$
t_i	time in ith mission segment, hours
V	velocity, ft/sec
y	any response parameter (incremental value)
y_{DU}	design ultimate value of response parameter (incremental value)
y_M	mean value of response parameter
σ_u	root mean square value of gust velocity
σ_y	root mean square value of any response parameter
$\Phi_N(\Omega)$	normalized power spectral density function, 1/rad/ft
Ω	spatial frequency, rad/ft

SECTION I

INTRODUCTION

For many years, the design gust loads on aircraft were established based on the assumption that atmospheric turbulence could be adequately represented by an isolated discrete gust of a specified magnitude and wavelength. This procedure was very successful on the relatively rigid, low-speed airplanes of the past, but the procedure cannot properly define the gust response of the flexible, high-speed airplanes of the present.

Due to this fact, the determination of gust loads on aircraft using the concept of continuous atmospheric turbulence and power spectral density techniques has gained wide acceptance, both in the United States and abroad. Further, probabilistic considerations have been introduced to establish a satisfactory level of design.

It should be noted that, as early as 1954, the United States Air Force stated its intention was to base aircraft designs on a logical consideration of the probability of encountering gusts of a known magnitude (reference 1). Little was done in this area, however, until the B-52 bomber encountered structural difficulties arising from loads generated in severe atmospheric turbulence. Although the strength level of the B-52 was adequate to meet its discrete gust design load level, the airplane was encountering turbulence severe enough to cause loss of the fin. Based on this experience, engineers of the Boeing Company and the Air Force were forced to come up with some new ideas on required gust loads, so the airplane could be appropriately modified. The new gust load criteria were based on the concept of continuous turbulence and probabilistic considerations. This came to be known as the rational probability analysis (RPA), and its application was discussed by the author in 1964 (reference 2).

The application of the RPA concept to Air Force airplanes has not, however, been consistent. Although such a concept has been applied to some Air Force aircraft, rapid changes in technology caused a considerable amount of variability to exist in RPA application to individual airplanes. The current state-of-the-art is considered to be a study conducted by the Lockheed-California Company under the sponsorship of the Federal Aviation Agency. This study considered power spectral density applications to design of civil aircraft (reference 3) and has resulted in sufficient engineering information to establish a more realistic basis for the rational probability analysis. The purposes of this paper are to present a recommended RPA based on a previously successful aircraft and to present a design envelope analysis that may be used to supplement the RPA. The procedures described herein may be incorporated into formalized specification requirements in the future. Further refinements to some of the details of the input data and the exact method for treating the mean load may be added, but the basic procedure is established. Subsequent sections of the paper will briefly cover the analysis and present the rationale behind the suggested gust loads criteria.

SECTION II

THE POWER SPECTRAL DENSITY ANALYSIS

The first step in establishing gust loads criteria on a probabilistic basis is to determine the frequency of exceedance of gust loads. The power spectral density analysis allows this to be done in a realistic fashion, as both the continuous nature of atmospheric turbulence and the variations in turbulence intensity with wavelength are considered. The basic techniques of this analysis are presented by the NACA in References 4 and 5 so only the highlights will be covered here.

The load exceedances for any load parameter (acceleration, bending moment, etc) can be expressed:

$$M(y) = N_0 \left[P_1 e^{-y/Ab_1} + P_2 e^{-y/Ab_2} \right] \tag{1}$$

where M(y) denotes the cumulative cycles per second equalling or exceeding the load parameter, y; the P values denote proportion of time in turbulence; the b values represent turbulence intensity; and the subscripts 1 and 2 denote normal and severe turbulence, respectively. The values of P and b recommended for use in conjunction with Equation 1 are presented and discussed in the Appendix.

The quantities, A and N_o, represent airplane response characteristics in turbulence and also reflect the energy content of the turbulence as a function of frequency. A is the ratio of RMS response to RMS gust velocity, and N_o is the characteristic frequency of the response. These quantities are expressed:

$$A = \left[\int_0^{\infty} \Phi_N(\Omega) \left| T(\Omega) \right|^2 d\Omega \right]^{1/2} \tag{2}$$

$$N_0 = \frac{V}{2\pi A} \left[\int_0^{\infty} \Omega^2 \Phi_N(\Omega) \left| T(\Omega) \right|^2 d\Omega \right]^{1/2} \tag{3}$$

where $\Phi_N(\Omega)$ is the normalized power spectrum of atmospheric turbulence and is discussed in the appendix. $|T(\Omega)|^2$ is the square modulus of the frequency response function for the load parameter of interest and is established by solving the equations of motion of the airplane for a unit sinusoidal gust input over a range of frequencies. In the computation of the frequency response functions for the various load parameters of interest, all significant rigid body and elastic airplane modes should be included. If the airplane is equipped with a stability augmentation system, its effects should be realistically included. A typical frequency response function for wing root bending moment is shown in Figure 1.

The quantities, A and N_o, should be computed for an adequate number of stresses and loads to insure that stress or load distributions throughout the entire structure are well defined; and they should be computed for an adequate range of speeds, altitudes, and gross weights to insure complete coverage of the flight envelope. Since A and N_o do vary with flight condition, this variation must be accounted for. In order to determine the overall load exceedance picture for the airplane, the missions of the airplane must be examined to determine the

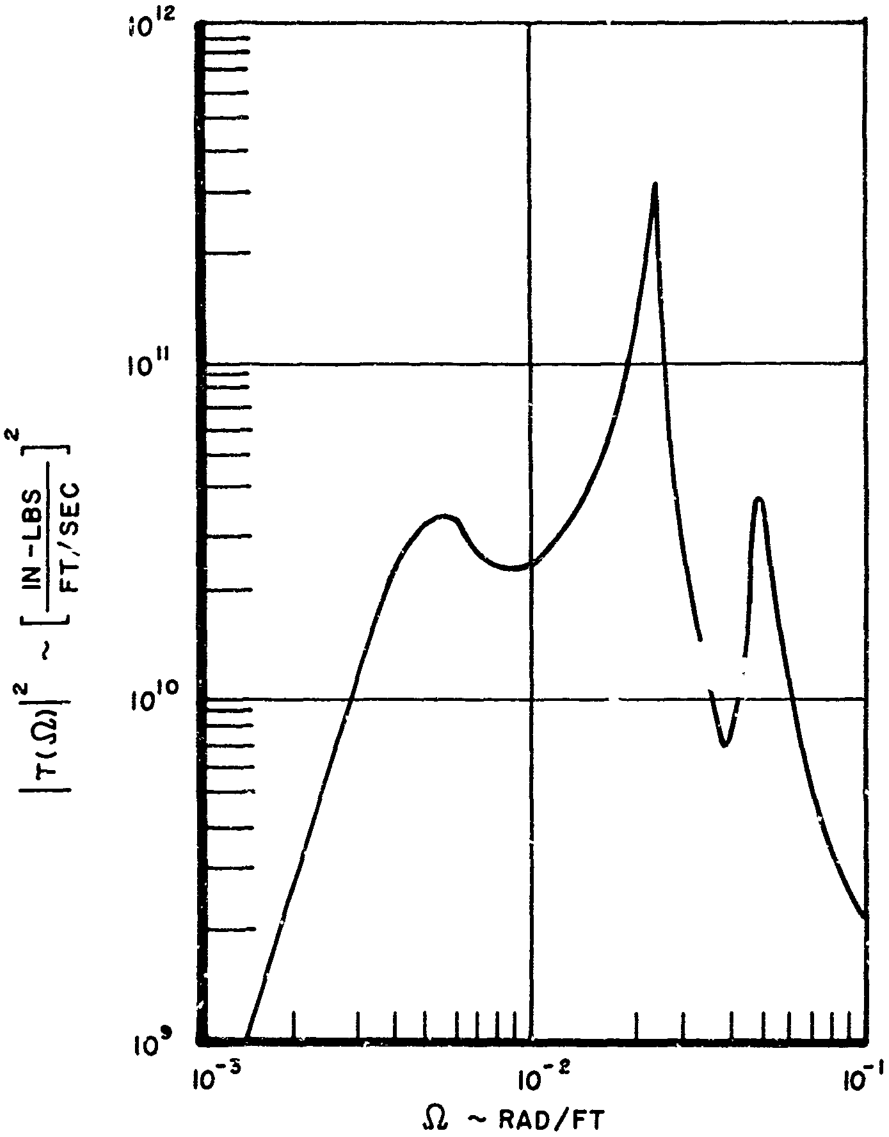


Figure 1. Typical Wing Root Bending Moment Frequency Response Function (L-188 Electra Turboprop Transport)

percent of time that the airplane spends in a specific flight regime. It should be noted that the turbulence field parameters, P and b, also vary with altitude, so the final relationship for expected gust loads is expressed:

$$\overline{M(y)} = \sum_{i=1}^{k} N_{0_i} \frac{t_i}{T} \left[P_{1_i} e^{-y/A_i b_{1_i}} + P_{2_i} e^{-y/A_i b_{2_i}} \right] \tag{4}$$

where t_i is the amount of time spent in the i th flight regime (mission segment), and T is the total time flown by the aircraft over all k mission segments. Thus the expected gust load exceedances for any load parameter can be established*. A typical load exceedance curve is shown in Figure 2. Once these exceedances are established, a design level of exceedance, M (y_{DU}), must be determined. To do this, we introduce the concept of the acceptable failure probability.

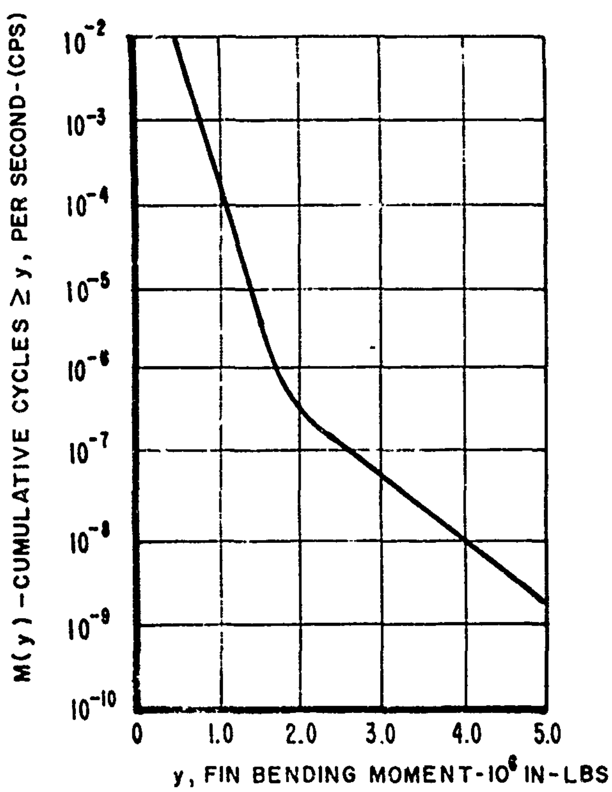


Figure 2. Typical Load Exceedance Curve.
(B-52 Bomber, Fin Bending Moment For Low Level Contour Operations)

* It should be noted that the quantity, y/A, can be thought of as the magnitude of a true gust velocity of average wavelength. The value of this average wavelength is established by the power spectrum and scale of turbulence used to compute A.

SECTION III

THE ACCEPTABLE FAILURE PROBABILITY

Implicit in criteria based on probabilistic concepts is the fact that there is always some non-zero probability that a particular event will happen. In the case of the RPA, this event is structural failure due to overload in turbulence. The objective is to design to a probability of a gust induced failure acceptable to the airplane's user under his particular mission requirements. For this reason, the concept of a failure probability was introduced into structural design criteria for gust loads. In the past, failure probability was defined as the ratio of total fleet exposure time to total time to reach or exceed a gust load that will cause structural failure given a specific airplane usage (reference 2).

In the case of the B-52, this ratio was rather arbitrarily established as 0.7 for 700 airplanes. Subsequently, the value was reduced to 0.01 for 200 airplanes for the C-5A. Again, this choice was arbitrary. As can be noted, such a definition of failure probability requires that fleet size be specified. Since final fleet size is little better than a guess during the design phase of an airplane, it would be best to eliminate fleet size.

To eliminate the undesirable dependence on fleet size, failure probability is re-defined as the ratio of one airplane's exposure time to time to reach or exceed ultimate load. That is,

$$F_p = \frac{T}{T_{EX}}^{*} \qquad (5)$$

As stated previously, Lockheed (reference 3) has generated sufficient information to eliminate some of the arbitrary features of the RPA; thus the acceptable failure probability can be established rather easily for a previously successful aircraft. Lockheed analyzed the L-188 Electra and the L-749 Constellation and established the time required to reach or exceed ultimate load on the wings due to gusts by use of power spectral density techniques.

Using Lockheed's results, failure probabilities for the L-188 and L-749 can be computed. It is assumed that the desired life of a transport such as the L-188 and L-749 is 60,000 hours per airplane. Thus, total exposure time for each L-188 and each L-749 considered in the Lockheed study is 60,000 hours. Lockheed computed the hours to reach or exceed ultimate load in both the positive and negative directions for the L-188 to be 7.14×10^7 hours and 2.38×10^8 hours for the L-749. Determining the failure probabilities for these airplanes as discussed above, we find the values $F_p = 0.000838$ for the L-188 and $F_p = 0.000252$ for the L-749.

Since it is reasonable that design failure probability for a new airplane should be chosen based on the least conservatively designed previously successful airplane, the L-188 is the airplane upon which failure probability should be based. In order to express the failure probability in round numbers, it is suggested that a conservative design failure probability of 0.0005 be adopted. This yields a success probability for each airplane in the fleet of 0.9995, regardless of fleet size. It should be recognized that, the larger the fleet, the larger the possible number of failures will become; however, the failure probability for an individual airplane will remain the same at 0.0005.

* It might be noted that Equation 5 is an approximation to $F_p = 1-e^{-T/T_{EX}}$ where T/T_{EX} is much less than 1.

Recalling that the determination of a design exceedance level was the reason for introducing the failure probability, the design exceedance level can now be established in terms of the failure probability. This appears as the straightforward relationship:

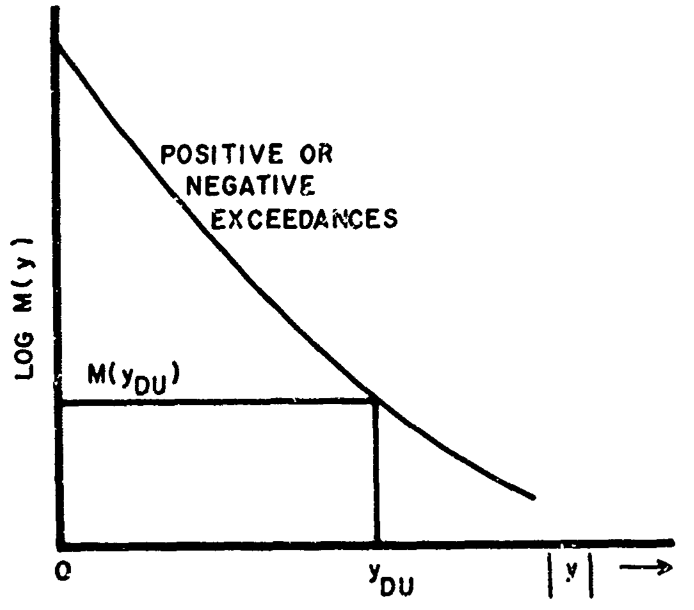
$$M(y_{DU}) = \frac{F_p}{3600T} \tag{6}$$

and the factor of 3600 converts design life in hours to seconds for compatibility with the definition of M(y).

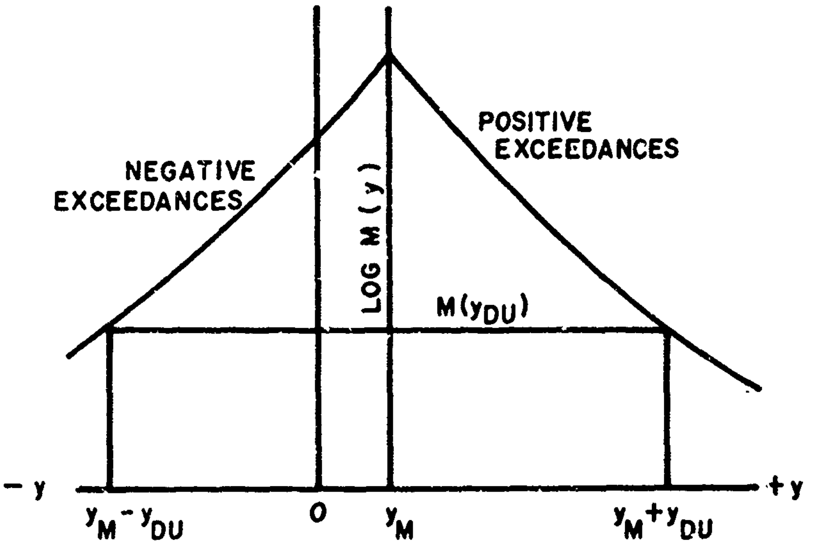
There may be some question regarding the fact that time to reach or exceed ultimate load in both the positive and negative directions implies two failures, that is, one in either direction. This would be the case if the positive and negative loadings were independent statistically. Intuitive reasoning, however, leads to the conclusion that an airplane, flying through turbulence, would probably experience a negative load and a positive load at a given level sequentially. If this is the case, and it is assumed it is, there is no necessity to include a factor of 0.5 in Equation 6 as has been done in the past (reference 2).

For structures such as the vertical tail, which have a zero mean load, design ultimate load is determined by entering the load exceedance curve, M(y) vs y at the value of $M(y_{DU})$ established from Equation 6 and the design ultimate load, y_{DU}, is read out directly, and has the same value in the positive and negative directions.

When a mean load is introduced, as is the case on the wing and fuselage, the procedure becomes somewhat more complicated. A standard procedure would be to include the mean load for each mission segment in the construction of a two-sided exceedance curve for that mission segment, and to take a weighted average, based on time in that segment of these curves. The resulting two-sided curve is then entered at the value of $M(y_{DU})$ specified and a positive design ultimate load is read out on the positive side of the curve, and a negative design ultimate load is read out on the negative side of the curve. Since the mean load for a wing or fuselage of an airplane is usually positive, positive design ultimate load is usually larger than the negative design ultimate load. The procedure is illustrated in Figure 3a for the zero mean load case and in Figure 3b for a positive mean load case. Design ultimate loads throughout the structure are thus determined.



a. Zero Mean Load



b. Positive Mean Load

Figure 3. Determination of Design Ultimate Load

SECTION IV

THE DESIGN ENVELOPE FLOOR

From the previous sections, it can be seen that a design ultimate gust load can be established using the RPA. The greatest drawback to the RPA, however, is the fact that mission profiles for an airplane can and do vary during the airplane's life, and it is difficult to establish realistic profiles for an airplane during its design stage. Actually, the results of the RPA are more sensitive to changes in airplane speeds and gross weights than to the percent of time in a particular mission segment. It takes considerable insight to determine just what the airplane's operation is going to be like, so it would seem advisable to have a back-up, or floor, below which design loads would not be allowed to drop, regardless of what the RPA results are.

Lockheed (reference 3) recommended that this floor be established by determining the gust velocity, y/A, that would cause limit load to be reached in the wing of a previously successful commercial aircraft at the critical speed-altitude-gross weight condition for that aircraft. The logic behind this recommendation is that no new aircraft should be designed with less structural capability than a previously successful aircraft.

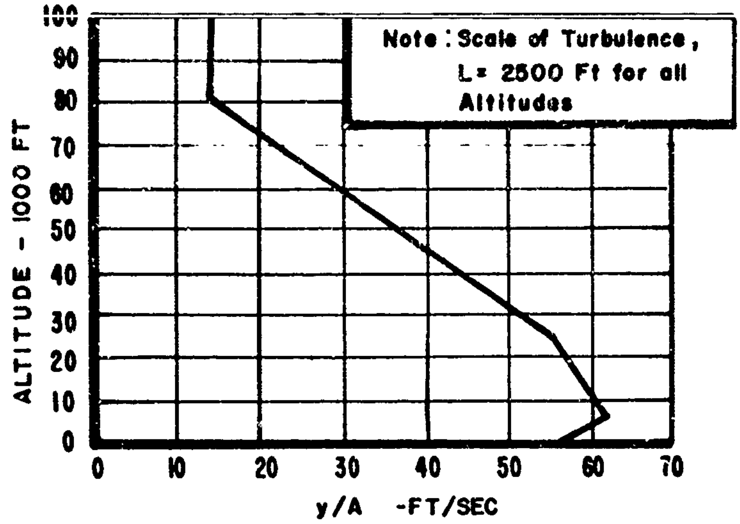
The basic problem with this philosophy is that it must be assumed that the new aircraft operates no nearer its design limits than the previously successful aircraft did, and that the new aircraft operates in the same environment as the older aircraft. It should be noted that both of these problems are eliminated when the RPA is used.

Lockheed (reference 3) found that the most critical airplane they investigated was the L-188, and determined that limit load was reached in the wing at a gust velocity of 62 ft/sec at 7,000 ft. This is based on a scale of turbulence* of 2,500 feet. They then postulated that design limit gust velocity should vary with altitude such that the design gust velocities at other altitudes would be reached or exceeded with the same frequency as 62 ft/sec would be reached or exceeded at 7,000 feet. The resulting design envelope is shown in Figure 4a. No variation of scale of turbulence with altitude was considered.*

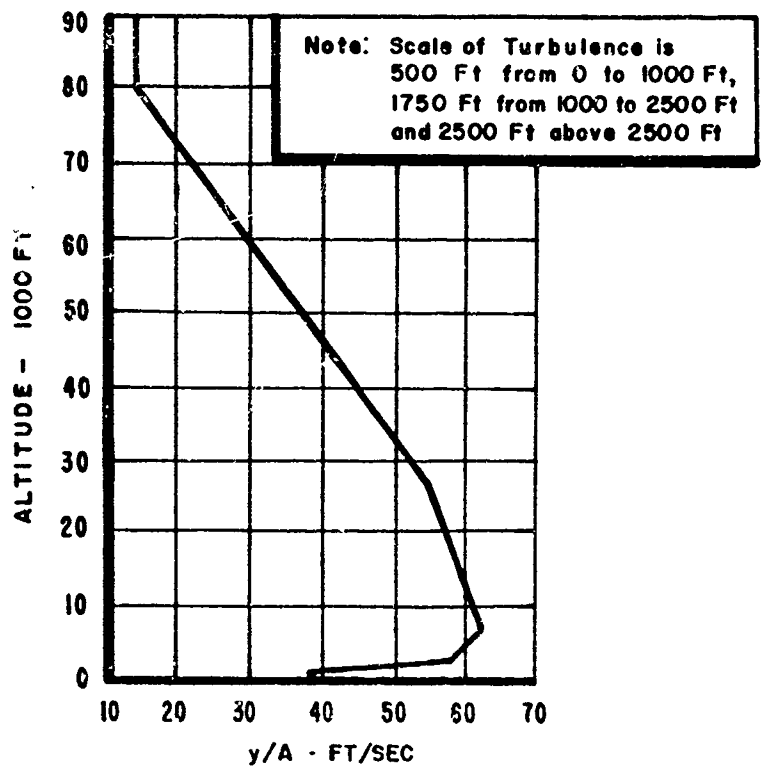
While this design envelope is satisfactory for both commercial and military aircraft at higher altitudes (above 2,500 feet), it would be unwise to assume that this envelope is satisfactory for military aircraft that must operate at low altitudes for extended periods - something that the commercial transports such as the L-188 never do. Thus, some modification to Figure 4a is in order to account for the low altitude military mission. The modification should be based on a previously successful military aircraft that has a low altitude mission requirement. For consistency with the turbulence model used with the RPA, consideration should also be given to the variation of scale of turbulence with altitude.

The B-58 bomber, which has a low altitude mission requirement and has been operating successfully for several years, is considered an appropriate choice for a previously successful military aircraft. Peloubet et al (reference 6) have analyzed the limit gust capability of the B-58 on a power spectral density basis, and have determined it to be 39 ft/sec at sea level based on a scale of turbulence of 500 feet. It might be noted that, on most current aircraft, a gust velocity of 39 ft/sec with a scale of turbulence of 500 feet would give higher loads than the value of 56 ft/sec with a scale of turbulence of 2,500 feet at sea level which was recommended by Lockheed.

* The scale of turbulence and its variation with altitude is discussed in the appendix.



a. Design Limit Gust Velocity Versus Altitude (Reference 3)



b. Military Aircraft

Figure 4. Design Envelopes

Based on this information, the proposed design envelope floor for military aircraft is shown in Figure 4b. Note that the scale of turbulence is 500 feet for 0-1000 ft altitude band, 1750 feet from 1000-2500 ft altitude, and 2500 feet for altitudes above 2500 feet. Using Figure 4b, incremental limit loads can be established for a new aircraft by multiplying the gust velocity, y/A, by the gust response factor, A, for a sufficient number of points throughout the structure that insure that load distributions are well defined. A is computed as discussed in Section II and should be computed for several speed-altitude-gross weight conditions to insure that the most critical loads have been established. The incremental limit loads thus derived are added to the appropriate mean load, and this result is multiplied by a safety factor of 1.5 to establish an ultimate load that is comparable to the load established by the RPA.

The design envelope floor concept actually limits the flexibility of the RPA, and, in some cases, might be eliminated. At the present time, however, the retention of the design envelope floor is recommended. It reflects a more traditional approach to gust load design and, thus, may be more acceptable to many people than the harsh reality of the failure probability which must be used in the RPA.

SECTION V

CONCLUSIONS

Gust load criteria for U.S. Air Force aircraft have been presented based on previously successful commercial and military aircraft. The criteria are based on the continuous turbulence concept, using power spectral density techniques. The rational probability analysis is based on a probabilistic assessment of expected ultimate gust loads and may be backed up by a design envelope analysis that specifies a level of true gust velocity for determination of limit gust loads. The acceptable failure probability, $F_p = 0.0005$, is recommended for design and a maximum true gust velocity of 62 ft/sec at 7,000 ft altitude may be used in the design envelope analysis to supplement the RPA results. The acceptance and application of the criteria presented here could result in the abandonment of the discrete gust approach for design of aircraft for gust loads.

APPENDIX

THE ATMOSPHERIC TURBULENCE MODEL

Although there is some controversy concerning the model of atmospheric turbulence, such a model must be specified in order to apply the gust loads design criteria presented in this paper. The complete definition of the turbulence model requires the functional form of the power spectrum of atmospheric turbulence, $\Phi_N(\Omega)$; the scale of turbulence L; and the turbulence field parameters, P and b. It is assumed that the functional form of the power spectrum does not vary with altitude, while the scale of turbulence and the turbulence field parameters do.

The functional form of the power spectrum that has been used for most previous gust work is the one suggested by the work of Dryden (reference 7) and recommended by the NACA (reference 4) in 1956.

This form is expressed

$$\Phi_N(\Omega) = \frac{L}{\pi} \frac{1 + 3\Omega^2 L^2}{(1 + \Omega^2 L^2)^2} \tag{7}$$

Another form was suggested by the work of Von Karman (reference 8) and was recommended by the NASA in 1964 (reference 9). This form is expressed

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

As can be seen from Figure 5, there is not too much difference in these two spectra except for the difference in slopes at the higher frequencies. Most test results (reference 10) have shown that the power spectrum decays with increasing frequency as - 5/3, which agrees with the Von Karman representation. Further, theoretical considerations indicate that the -5/3 decay is most appropriate (reference 9). For these reasons, the Von Karman representation shown in Equation 7, is recommended for use in the turbulence model.

Far more important than the functional form of the power spectrum is the scale of turbulence L, and the turbulence field parameters P and b. The value or values of L chosen for the turbulence model have a large impact on the response parameter, A, and the turbulence field parameter, b, is highly dependent on the value or values of L. This dependence does not pose a significant problem in criteria work, however, if a consistent procedure is used.

Due to the difficulties encountered in the measurement of power spectra at low frequencies, values of L ranging from 200 feet to 5000 feet have been postulated by various investigators. Most of the past work in the gust loads area has been conducted using L = 500 feet for altitudes below 1000 ft and L = 1000 ft for altitudes of 1000 ft and above. Lockheed, (reference 3) seeking a compromise, proposed using L = 2500 ft for all altitudes and made their response calculations based on this value. Such an assumption is reasonable as long as the aircraft under consideration spend most of their time at altitudes above 2500 feet, but it is doubtful that the assumption holds below altitudes of 2500 feet.

Since most military aircraft are required to operate at altitudes below 2500 feet for long periods, modifications must be made to Lockheed's assumptions (reference 3) for these lower altitudes. Basically, however, the compromise figure of L = 2500 feet seems to be

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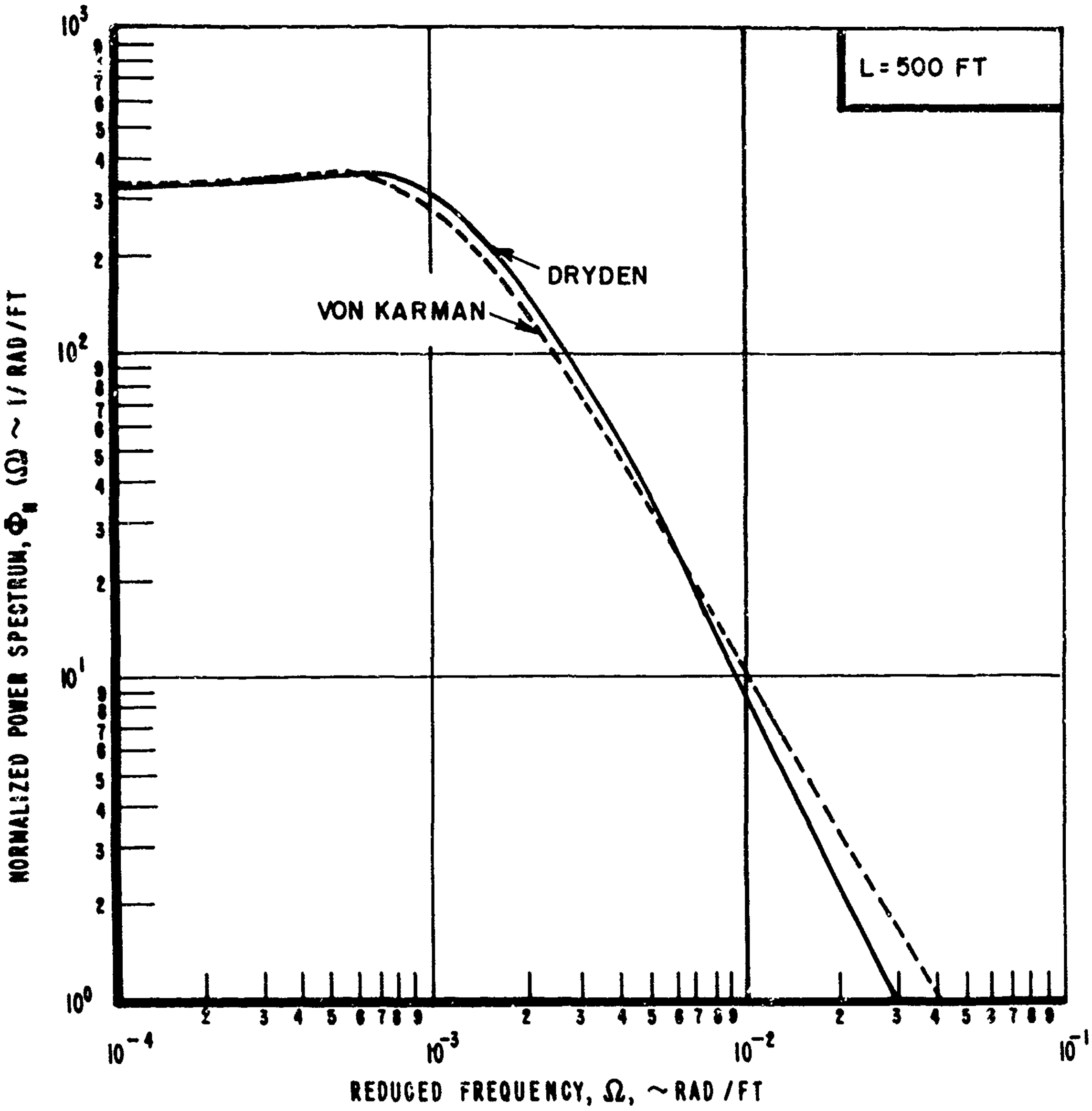

Figure 5. Comparison of Dryden and Von Karman Spectra

reasonable and would yield appropriate results for any aircraft operating above 2500 feet altitudes at supersonic or subsonic speeds.

Based on the results of the B-66 Low Altitude Gust Study (reference 10) and the preliminary results from the Low Level Critical Air Turbulence Program (reference 11) it appears that L = 500 feet is reasonable for altitudes of about 500 feet. If it can be assumed that L is equal to altitude up to 2500 feet altitudes, the complete variation of L with altitude is established. For simplicity, it would be appropriate to let L = 500 feet for altitudes below 1000 feet, L = 1750 feet for altitudes between 1000 feet and 2500 feet, and L = 2500 feet for altitudes greater than 2500 feet. This permits use of Lockheed's results (reference 3), yet considers the fact that military aircraft must operate at low altitudes for extended periods.

The turbulence field parameter, b, can now be specified to be consistent with the scales of turbulence previously chosen. These parameters can be specified from (reference 3) directly for altitudes above 2500 feet, but the parameters must be modified for the lower altitudes. This modification consists of adjusting the b values at the 1000-2500 ft altitude band for a scale of turbulence of 1750 feet instead of 2500 feet and adjusting the b values at the 0-1000 ft altitude band for a scale of turbulence of 500 feet. The turbulence field parameter, P, represents proportion of time in turbulence and is assumed to be unaffected by variations in L. In addition, for the case of low level contour operation, an entirely new set of turbulence field parameters as specified by the author (reference 12) are employed. The final turbulence model is shown in Table I.

TABLE I

TURBULENCE FIELD PARAMETERS

MISSION SEGMENT	ALTITUDE	DIRECTION	P_1	b_1	P_2	b_2	L (FT)
Low Level Contour	0-1000 ft	Vertical	1.0	2.7	10^{-5}	10.65	500
Low Level Contour	0-1000 ft	Lateral	1.0	3.1	10^{-5}	14.06	500
Climb, Cruise, Descent	0-1000 ft	Vert & Lat	1.0	2.51	.005	5.04	500
Climb, Cruise, Descent	1,000-2,500 ft	Vert & Lat	.42	3.02	.0033	5.94	1750
Climb, Cruise, Descent	2,500-5,000 ft	Vert & Lat	.30	3.42	.0020	8.17	2500
Climb, Cruise, Descent	5,000-10,000 ft	Vert & Lat	.15	3.59	.00095	9.22	2500
Climb, Cruise, Descent	10,000-20,000 ft	Vert & Lat	.062	3.27	.00028	10.52	2500
Climb, Cruise, Descent	20,000-30,000 ft	Vert & Lat	.025	3.15	.00011	11.88	2500
Climb, Cruise, Descent	30,000-40,000 ft	Vert & Lat	.011	2.93	.000095	9.84	2500
Climb, Cruise, Descent	40,000-50,000 ft	Vert & Lat	.0046	3.28	.000115	8.81	2500
Climb, Cruise, Descent	50,000-60,000 ft	Vert & Lat	.002	3.82	.000078	7.04	2500
Climb, Cruise, Descent	60,000-70,000 ft	Vert & Lat	.00088	2.93	.000057	4.33	2500

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13 ABSTRACT

Gust loads criteria have been developed which represent a considerable improvement over the current discrete gust criteria. These new criteria are based on the strength level of previously successful aircraft, and result from a probabilistic assessment of expected gust loads. To supplement the probabilistic criteria, an arbitrary criterion for limit design gust velocity is presented. The analyses to be used in conjunction with the new criteria are based on the continuous turbulence concept which allows the realistic determination of aircraft loads in atmospheric turbulence.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Gust Loads Probabilistic Design Criteria Continuous Turbulence Power Spectral Density Analysis Rational Probability Analysis						

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