Summary of Flight Load Environmental Data Taken on B-52 Fleet Aircraft

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This paper presents a summary of gust and maneuver environmental data recorded on a large number of B-52 aircraft during fleet operations. Random gust environment concepts and power spectral density analysis techniques were used in the data reduction, and the results are presented in a general form considered useful for calculation of load history on aircraft. Comparisons are made with the environment presented by government specifications and other publications. Discussions of the use of this data for the determination of structural reliability are included. Approximately 15,000 hr of flight data have been recorded and converted to a suitable statistical form. Emphasis is given to low-level flight load environment, and effects of type of operation, season of the year, and type of terrain are indicated. Estimates of the extreme values of the gust velocities are made based on fleet experience. Although many programs have been conducted to define the structural load environment caused by random gusts and maneuvers, this paper includes the following features generally lacking in other presentations of this type of information: 1) statistical reliability is high because of the large quantity of recorded data, 2) an indication of the extreme values of the environment is given, 3) data are presented for altitudes from low level to above 30,000 ft, and 4) vertical and lateral environments are compared.

Nomenclature

A = ratio of rms response to rms gust velocity
$F(\sigma_u)$ = cumulative probability distribution of rms gust velocity
L = scale of turbulence (1000 ft)
$M(y)$ = average number of crossings per second with positive slope of specified response level
$M(y_u)$ = average number of crossings per second with positive slope of ultimate load for specified response
N_0 = average number of crossings per second with positive slope of mean level for specified response
P_1, P_2 = turbulence parameters used in functional representation of environment
$R(y_u)$ = structural reliability in terms of number of lifetimes per ultimate load
$T_y(\Omega)$ = frequency response function for specified response
V_T = airplane true airspeed, fps
b_1, b_2 = turbulence parameters used in functional representation of environment
d_i = distance flown in ith data block or mission segment
$f(\sigma_u)$ = probability density distribution of rms gust velocity
t_i = time in seconds for ith mission segment per lifetime
y = response item
y_u = ultimate value of response item
$\Phi_y(\Omega)$ = power spectral density function for specified response
$\Phi_u(\Omega)$ = power spectral density function for gust
Ω = reduced frequency, rad/ft
σ_u = rms gust velocity

Introduction

THE need for the best information possible on gust and maneuver environment for aircraft design is self-evident. As a result, several load history programs were conducted during the past few years and are being continued to provide this description of the environment. These programs were initiated to obtain repeated load experience for structural fatigue evaluations. However, the results are applicable to define structural reliability for overload as well as use in fatigue evaluations.

Much effort has been devoted during the past decade to describe the atmospheric turbulence as a continuous (rather than discrete) process and to the use of spectra for analysis of gust velocities and dynamic response of aircraft.[1] This analysis technique allows the determination of the airplane response to random atmospheric turbulence. The determination of the response power spectrum depends on a knowledge of the power spectral density of atmospheric turbulence and the frequency response function of the airplane. Assuming a Gaussian probability distribution of the disturbance, the average number of times per second that a given level of the response is crossed may be obtained from the power spectrum. The expected number of times a particular load will be exceeded may be estimated from this statistical description of the airplane response time history. In the same manner the design ultimate load may be determined from given structural reliability criteria. Therefore, use of the power spectral analysis technique provides a rational approach to the determination of structural reliability or design load requirements as related to random atmospheric turbulence.

The success of the application of these random disturbance analysis procedures depends on the determination of the disturbance environment. The atmospheric turbulence model assumed in this paper is made up of discrete patches of disturbances of different mean square intensity; each is Gaussian, stationary, and with the same spectral shape. The description of the atmospheric turbulence is then given in terms of a spectral shape and the probability distribution of the rms gust velocity. This information represents the heart of the probability approach and allows the determination of the statistical load environment for any assumed mission and any aircraft.

This paper presents a description of the probability distribution of the rms gust velocity derived from a large sample of flight load environment data taken on B-52 aircraft. The derivation of this description of the turbulence environment is based on an assumed spectral shape and theoretically determined transfer functions.

The major portion of this paper is devoted to the presentation and discussion of the gust and maneuver load environment data recorded on B-52 fleet aircraft. A discussion of the application of these results for the determination of structural reliability or design loads is also given. The

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final conclusions reached are discussed, and the areas are noted that should be considered for future research.

Calculation of Operational Flight Loads Data

A statistically large sample of flight load history data was recorded on all of the models of the B-52 aircraft during all of the phases of fleet operation for approximately two years. The objective of these service load recording programs was to expedite the collection of fleet load experience on the B-52 that would provide a basis for determining or re-evaluating the loading spectrum for full-scale cyclic tests and to refine estimates of airplane service life. An additional objective was to investigate the low-level environment. In this paper, low level is considered as operation of the aircraft at low absolute altitudes, generally less than 1000 ft above the terrain. The load history data obtained from these programs provided the opportunity to define the atmospheric turbulence environment using a large sample of data collected and reduced on one aircraft configuration under carefully controlled conditions.

Acquisition of Data from Fleet Aircraft

The fleet load history data was collected from January 1962 to January 1964. The recording of this data is continuing at present. The load history instrumentation consisted of provisions for recording velocity, vertical acceleration at the airplane center of gravity, altitude, and other control parameters used in the data editing process. In addition, a stress gage was installed on the empennage of some aircraft to measure a parameter sensitive to the lateral environment. The time histories were recorded on oscillograph-type recorders. The recordings began with brake release, continued throughout the entire flight, and ended after the final taxi. By the end of January 1964, over 50,000 hr of load history data were recorded during these fleet load history programs.

Data Reduction Program

The general data reduction program consisted of counting the positive and negative acceleration and stress time history peaks and sorting these peaks into categories with respect to amplitude, airplane configuration, and flight condition. Only primary peaks were counted, where a primary peak is defined by the maximum excursion between consecutive crossings of the mean level. The categories of airplane configuration included model, external store configuration, and gross weight as shown in Table 1. The categories of flight condition considered were airspeed, altitude, and mission segment as shown in Table 2. All of the recorded data were reviewed for unusual load history occurrences and to determine the relative importance of each mission segment. The method used to select the records for additional analysis was designed to provide a random sample with an even distribution with respect to month, Air Force Base, and aircraft. A total of 15,000 hr of acceleration (vertical environment) data and 1700 hr of stress (lateral environment) data was reduced to peak count form as of January 31, 1964.

An attempt was made to identify the load occurrences according to their cause, either gust or maneuver. The general criteria for separating gusts and maneuvers are defined as follows: 1) a peak or valley with consecutive crossings of the mean less than 2 sec apart was defined as a gust, and 2) a peak or valley with consecutive crossings of the mean greater than 2 sec apart was defined as a maneuver. This method was arbitrary and did not separate the loads according to their cause because of the response characteristics inherent in the B-52. To date, no rational or universally accepted criteria for the separation of gust and maneuver environments have been developed. Therefore, the turbulence environment developed in this paper is based on the total unseparated load history. These combined gust and maneuver environments are considered applicable to normal operation of aircraft in the climb, cruise, descent, and low-level mission segments. Other operations that require an unusual amount of maneuver induced load history must be considered separately.

The load environment data, reduced as a part of these load history programs, forms the basis for the derivation of a statistical description of the atmospheric turbulence. This is further based on the following relationship between the response statistics, airplane response characteristics, and the probability distribution of rms gust velocity:

$$M(y) = N_0 \int_0^\infty f(\sigma_u) \exp\left(\frac{-y^2}{2A^2\sigma_u^2}\right) d\sigma_u \qquad (1)$$

Equation (1) is a statistical equation that applies specifically to the calculation of the number of crossings per second with positive slope of a given value of y. This equation also represents a good approximation of the number of peaks above a given level so long as y is greater than the response rms value.

The relationship between $M(y)/N_0$ vs y/A can be obtained from Eq. (1) if the probability density distribution $f(\sigma_u)$ is known. Therefore, $M(y)/N_0$ vs y/A represents a statistical description of the atmospheric turbulence, and the analysis of the load history results was devoted to a suitable conversion of the peak count to summary curves in this form for the various mission segments.

The response items under consideration are the center-of-gravity vertical acceleration and an empennage stress that senses lateral load. The function $M(y)$ represents the number of times that the response exceeds the level y as a function of y and can be obtained from the peak count for the response being considered. The curve was computed for each category of airplane configuration and flight condition by accumulating the peak count to determine the number of positive and negative peaks exceeding each amplitude level. The positive and negative peaks exceeding a given value were then averaged and divided by the data block time in seconds to obtain a composite curve in terms of cumulative cycles per second equal to or greater than each response level.

The values of the airplane response characteristics A and N_0 were obtained from theoretically determined response

Table 1 Airplane configuration data block categories

Model	External store configuration	Gross weight, lb
B-52B	None	200–240,000
B-52C-F	2 AGM 28's (GAM 77 Hound Dog Missiles)	240–280,000
B-52G		280–320,000
B-52H		320–360,000
...		360–400,000
...		400–440,000
...		440–450,000
...		450–460,000
...		460–470,000
...		470–480,000
...		480–490,000
...		Above 490,000

Table 2 Flight condition data block categories

Airspeed, knots	Altitude, ft	Mission segment
0–150	Low level	Taxi
150–200	0–10,000	Takeoff and landing roll
200–250	10–20,000	Landing impact
250–300	20–30,000	Ascent
300–350	30–40,000	Cruise
350–400	Above 40,000	Descent
Above 400		Low level
		Refueling

power spectra. For a linear system, the following relation exists between the disturbance power spectral density function and that for the response:

$$\Phi_y(\Omega) = |T_y(\Omega)|^2\Phi_u(\Omega) \tag{2}$$

Equation (2) indicates that the response spectral density at a given frequency depends on the spectral density of the disturbance and the amplitude of the transfer function at that frequency.

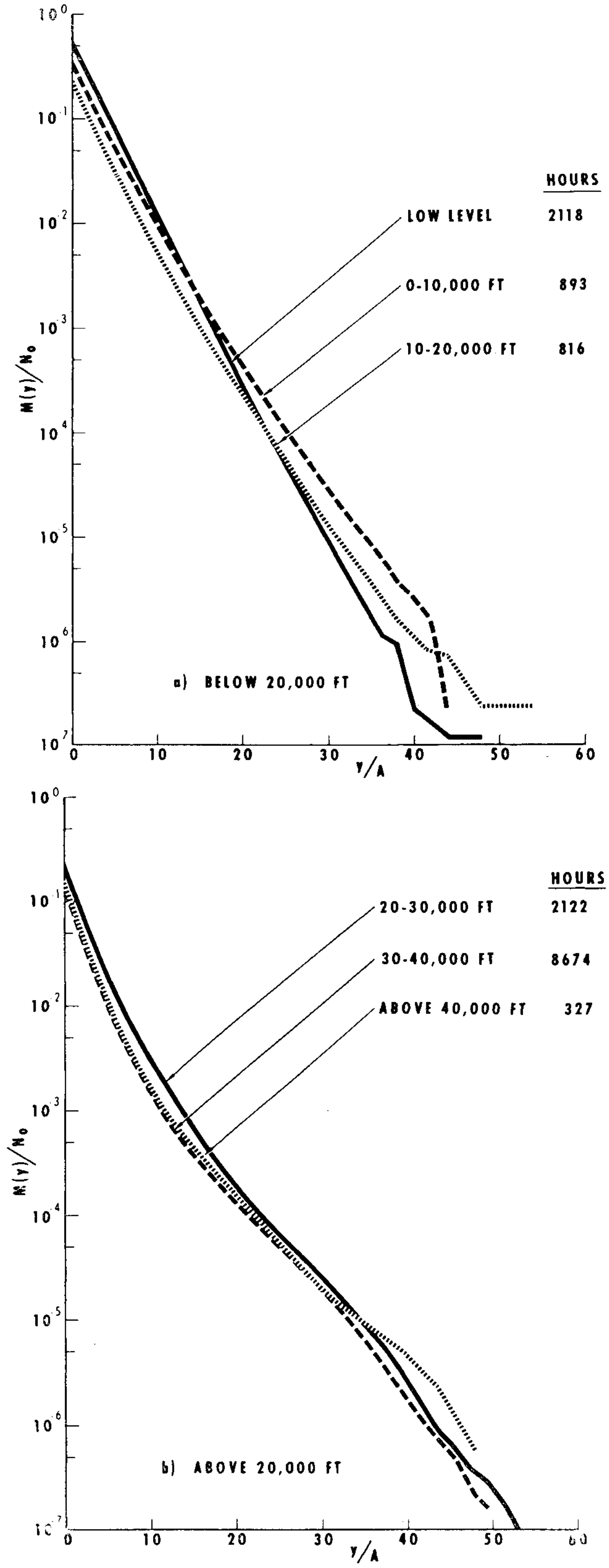


Fig. 1 Vertical turbulence environment by altitude.

The airplane frequency response functions were computed by fundamental work and energy theory utilizing the Lagrangian formulation of the equations of motion. The equations of motion were written in terms of 16° of freedom including airplane rigid body and normal vibration modes. The normal vibration modes were determined using the lumped parameter method to idealize the mass and stiffness properties of the airplane as a number of discrete masses connected by weightless springs. The wing, fuselage, nacelle struts, horizontal tail, and vertical tail were considered flexible. The airloads that were considered as acting on the lifting surfaces were expressed in terms of two-dimensional airfoil theory modified to include the Kussner and Wagner lift growth functions, the effects of finite span by Weissinger lifting line theory, and the Glauert correction for compressibility and sweep. The yaw damper effects were included in the lateral dynamic analyses.

The selection of a power spectral shape, used in the derivation of the random turbulence model, is important since the airplane response characteristics depend on this function. The following analytical expression used by Press, Meadows, and Hadlock for the turbulence spectrum was used in this study[2]:

$$\Phi_u(\Omega) = \sigma_u^2(L/\pi)[(1 + 3\Omega^2L^2)/(1 + \Omega^2L^2)^2] \tag{3}$$

The scale of turbulence L was taken to be 1000 ft for all of the flight conditions. As more measurements of turbulence become available, this assumption regarding the power spectral shape may need revision.

The airplane response characteristics are related to their respective power spectrum as follows:

$$A = \left[\int_0^\infty \Phi_y(\Omega)\, d\Omega\right]^{1/2} \tag{4}$$

$$N_0 = \frac{V_T}{2\pi A}\left[\int_0^\infty \Omega^2\Phi_y(\Omega)\, d\Omega\right]^{1/2} \tag{5}$$

Since the airplane frequency response function, the response

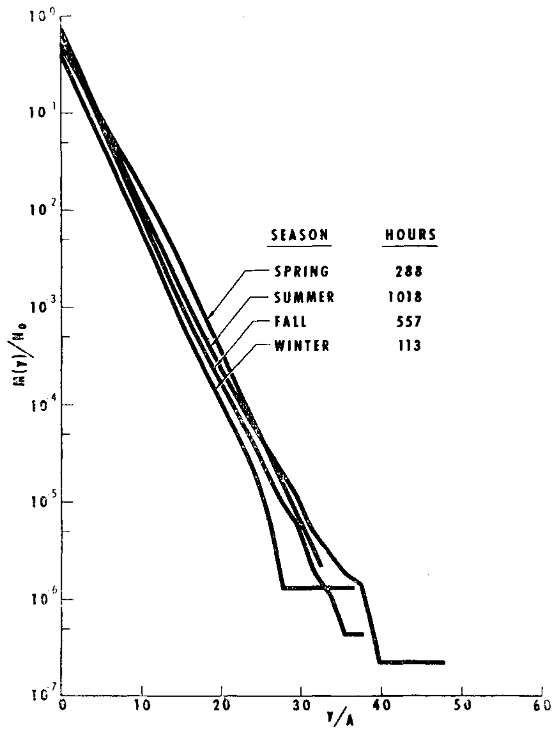


Fig. 2 Low-level vertical turbulence environment by season.

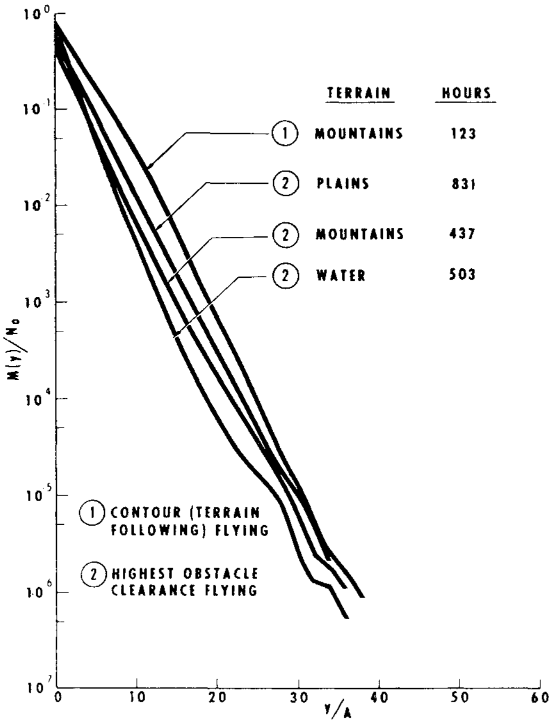


Fig. 3 Low-level vertical turbulence environment by terrain and type of flight.

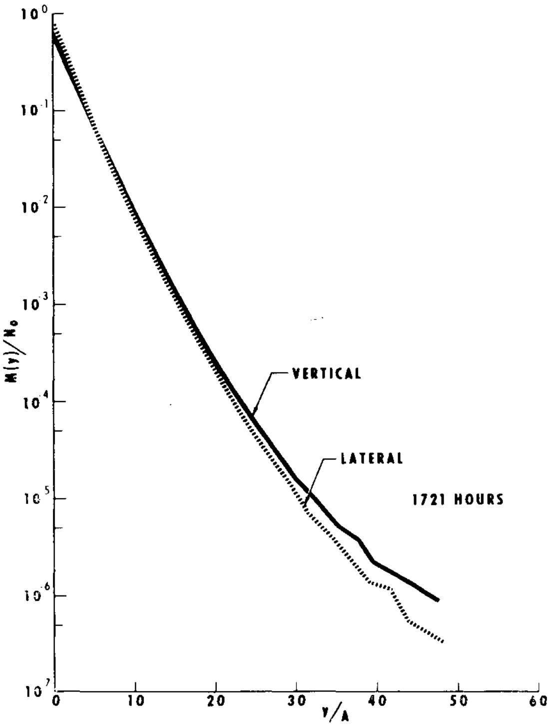


Fig. 4 Comparison of low-level vertical and lateral turbulence environment.

spectrum, and response characteristics vary with gross weight, speed, and altitude, the dynamic analysis was conducted for several conditions. An adequate number of conditions was analyzed to allow interpolation or extrapolation of these theoretical response characteristics to all of the required airplane configurations and flight conditions.

The function $M(y)/N_0$ vs y/A was determined for each data block category. The individual data samples were further summarized into composite form with respect to only those variables for which a description of the turbulence environment was desired. For instance, all of the climb, cruise, and descent mission segment data were summarized in 10,000-ft-alt bands. The weighted average values of $M(y)/N_0$ were calculated for each value of y/A as follows:

$$\left[\frac{M(y)}{N_0}\right]_{\text{avg}} = \sum_{i=1}^{n} d_i \left[\frac{M(y)}{N_0}\right]_i \Bigg/ \sum_{i=1}^{n} d_i \tag{6}$$

where n is the number of individual data samples that fall into the general category being considered. The weighing factor considered d_i is based on the distance flown in each data block.

Operational Flight Load Environment

The vertical turbulence environment, calculated using the data and analysis technique discussed in the previous paragraphs, is given for each altitude band in Figs. 1a and 1b. The low-level data is shown separately from the 0–10,000-ft data and represents the average of the entire fleet low-level data sample including all of the seasons, terrain types, and types of low-level flight. The data summarized in the 10,000-ft-alt bands include all of the other flaps-up climb, cruise, and descent data blocks. The large data sample in the 30–40,000-ft band is representative of the high-altitude cruise. The data samples from 0–20,000 ft were obtained primarily during the climb and descent. The narrow scatter band of the data above 20,000 ft indicates that the true airspeed gust environment is approximately constant over this entire region.

The vertical turbulence environment for low level is shown by season in Fig. 2. The effect of season indicates that turbulence of a given intensity may be expected about three times more often in the spring than in the winter. A similar comparison was made for the high-altitude cruise environment, and the seasonal variation was negligible.

The effect of terrain and type of low-level flight is shown in Fig. 3. Low-level flight over routes designated by 1 is primarily a contour flight procedure, and a constant height above the local terrain is maintained. Over routes designated by 2, the flight is primarily constant altitude cruise with the pressure altitude based on clearance of the highest obstacle along each route leg. The difference in the 1 and 2 environments for the mountainous terrain is attributed to this variation in the flight procedure. The contour-type flying would result in a much lower average absolute altitude and, therefore, a higher probability of encountering turbulence and increased maneuver environment. The probability of encountering turbulence over water is about four times less than in the plains. Contour flying in the mountains gives about the same average terrain clearance altitude as highest obstacle clearance flying in the plains. This leads to the conclusion that, for the same average absolute altitude, turbulence is encountered about three times more often in the mountains than in the plains. Also, highest obstacle clearance flying in the mountains gives a higher average absolute altitude than does similar flying in the plains, resulting in the somewhat less severe turbulence level.

A comparison of the vertical and lateral turbulence environment is given in Fig. 4. The vertical acceleration at the airplane center of gravity and the empennage stress load history data used to derive the vertical and lateral turbulence environments, respectively, were recorded concurrently. They represent measurements of the vertical and lateral load history for the same flight periods to allow a direct comparison. The agreement between the vertical and lateral environments indicates that the turbulence is approximately isotropic for the low-altitude flight condition. Similar comparisons are not available for the higher altitudes. However, the turbulence is expected to be isotropic at these altitudes as well.

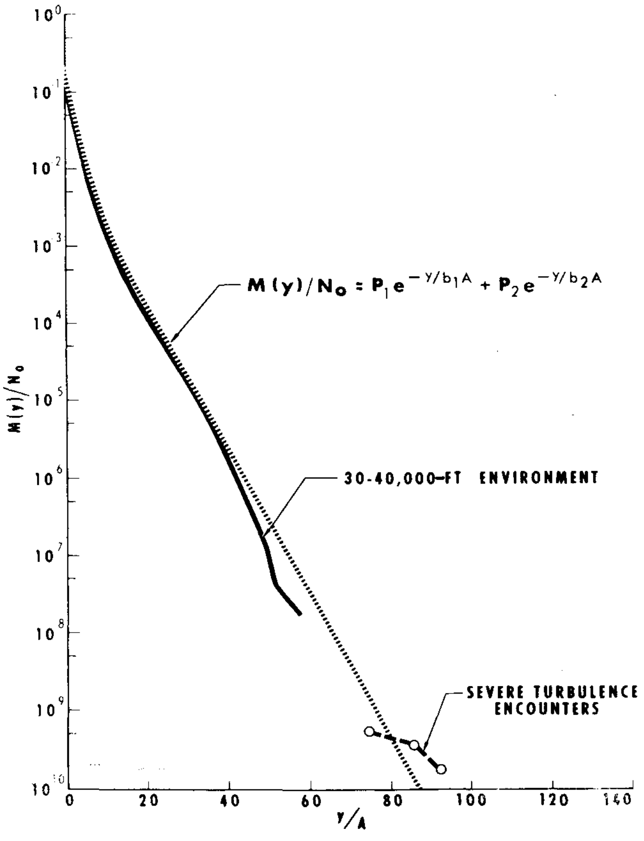


Fig. 5 Severe turbulence encounters for cruise mission segment.

Estimates of the extreme values of the load environment were obtained, based on the total operational experience. A study of the severe turbulence encounters was made to define the higher amplitude portion of the turbulence environment. The airplane configurations and flight conditions for these severe turbulence encounters are given in Table 3 with an estimate of the extreme value of the turbulence in terms of y/A.

The high-altitude cruise severe turbulence encounters are shown in Fig. 5 along with the environment already derived. The value of $M(y)/N_0$ used for plotting these encounters was based on the total time flown by the fleet in the cruise mission segment and an average value of N_0.

A similar presentation for the low-level severe turbulence encounters is given in Fig. 6. These encounters are plotted at two values of $M(y)/N_0$ corresponding to the total low-level time and the total low-level contour operation time flown by the fleet. Also presented in Fig. 6 is a sample of low-level load history data collected during a flight-test program. The low-level missions consisted primarily of contour operation in rough terrain including high mountains. This data sample indicates a higher probability of encountering turbulence than that representative of the composite low-level environment. The sample is also more severe than the fleet contour operation over low-level routes designated by 1 in Fig. 3.

To apply these results in design studies, the environment is conveniently expressed in a functional form. The following function used by Press and Steiner yields a suitable representation[3]:

$$M(y)/N_0 = P_1 e^{-y/b_1 A} + P_2 e^{-y/b_2 A} \qquad (7)$$

The turbulence parameters P_1, P_2, b_1, and b_2, used by Press and Steiner, referred to the storm and nonstorm turbulence environments, but this same meaning was not retained in this paper. Rather, the parameters have been selected to fit best the experimental results. The parameters were selected to match the measured load history data with consideration given to the extreme values of the environment. The derived B-52 turbulence parameters are given in Table 4. Two sets of low-level turbulence parameters are presented. The first is considered representative of low-level contour operation in rough terrain. The turbulence parameter values were derived, based on B-52 flight-test data and the corresponding severe turbulence encounters shown in Fig. 6. The second set is representative of a composite low-level training operation including all of the types of low-level flying and terrain levels. A comparison of the measured and the calculated environment defined by Eq. (7) and the derived turbulence parameters is also given in Fig. 5 for high-altitude cruise and in Fig. 6 for low level.

Similar spectral presentations of the turbulence environment are given by Press and Steiner[3] and in current military aircraft design criteria for the repeated load environment as related to fatigue.[4] Comparisons of the environment defined in these publications and those derived from the B-52 load history are given in Figs. 7a–7f for each altitude band. For low level in Fig. 7a, the MIL-A-8866 environment for 0–1000 ft is based on a scale of turbulence L of 500 ft. All of the other environments are based on $L = 1000$ ft. In general, the derived B-52 environment agrees with the previously published data, especially for the lower range of y/A values. For all of the altitudes except low level, the derived environment is lower for large values of y/A. Similar unpublished comparisons of these environments in the form of derived equivalent gust velocities (U_{d_e}) indicate that the B-52 environment is more severe over all of the ranges of gust velocity for all of the altitudes. Also, the use of these derived B-52 environments in the spectral form for the determination of design loads based on structural reliability criteria may yield loads in excess of those calculated using current discrete gust design criteria.

Design Applications

The application in design studies of the turbulence environment results presented in this paper requires the use of generalized harmonic analysis. As discussed previously, these procedures represent a rational approach for the determination of the aircraft response to a random environment. The determination of the aircraft response characteristics A and N_0 must be accomplished theoretically in design studies. The response characteristics may be calculated for any item of interest such as acceleration, loads, and stresses. This leads to an estimate of the load history or response statistics for any response that may be used in fatigue analyses and in the determination of design loads. A discussion of the techniques used in calculating structural reliability or design loads is presented in the following paragraphs. Also, the effects of aircraft usage and turbulence avoidance procedures on structural reliability are indicated. In this paper, the term structural reliability pertains to the probability of exceeding design ultimate load due to the environment in which the aircraft is intended to operate.

Table 3 Severe turbulence encounters

Gross weight, lb	Speed, kias	Altitude, ft	Estimated y/A, fps
357,000	270	36,000	75
330,000	325	Low level	53
275,000	390	Low level	55
348,000	280	Low level	71
248,000	260	34,000	93
361,000	350	Low level	63
287,000	260	30,000	87

Table 4 Turbulence parameters derived from B-52 load history

Altitude, ft	P_1	b_1	P_2	b_2
Low level (contour)	0.80	3.6	0.20	4.2
Low level (composite)	0.40	2.6	0.01	4.2
0–10,000	0.30	2.6	0.01	4.8
10–20,000	0.20	2.6	0.01	4.8
20–30,000	0.15	2.4	0.01	4.8
30–40,000	0.13	1.8	0.01	4.8
Above 40,000	0.13	1.8	0.01	4.8

Calculation of Structural Reliability

Airplane structural reliability, in terms of the number of lifetimes per ultimate load occurrence caused by turbulence, may be determined for any aircraft if the design ultimate load, usage, and environment are specified. A definition of the airplane usage is accomplished by representing the lifetime in terms of the number and type of missions considered representative for the expected total utilization of the aircraft. Each mission is further defined by a gross weight, speed, and altitude profile. Other airplane configuration or flight condition parameters may be important depending on the usage or aircraft type. These representative missions are further simplified by division into segments, each of which is assumed to have a constant value of gross weight, speed, and altitude. With a knowledge of A and N_0 for each mission segment, the expected number of cycles of ultimate load per second within any one segment of the usage may be computed as follows:

$$M_i(y_u) = N_{0i}[P_1 e^{-y_u/b_1 A_i} + P_2 e^{-y_u/b_2 A_i}] \tag{8}$$

The subscript i refers to the ith mission segment, and y_u is the ultimate load for the specified response. The turbulence parameters P_1, P_2, b_1, and b_2 depend upon the altitude band of the ith mission segment. The expected number of cycles of ultimate load per lifetime is then

$$M(y_u) = \sum_{i=1}^{n} t_i M_i(y_u) \tag{9}$$

where t_i is the time in seconds in the ith mission segment per lifetime, and the summation includes all of the segments. The structural reliability in units of lifetimes per ultimate load occurrence is

$$R(y_u) = 1/2M(y_u) \tag{10}$$

The expected number has been doubled since there are two peaks associated with one cycle, and each may represent an ultimate load occurrence.

The preceding discussion pertaining to the reliability based on ultimate load is equally applicable to limit load or any load level of interest. Also, the equations apply specifically to response items with a zero mean value but are easily extended to include variable mean response items.

Design Load Calculations

The preceding information describes how statistical methods are used to determine aircraft structural reliability. Conversely, the design ultimate load can be determined when the reliability is specified.

Referring to Eqs. (8–10), it is not possible to solve for y as an explicit function of $R(y)$. However, the load level

Table 5 Reliability levels vs usage

Usage	$R(y_u)/R(y_u)$ 100% at $L.L.$
100% at contour low level	1
100% at 30,000-ft alt	40

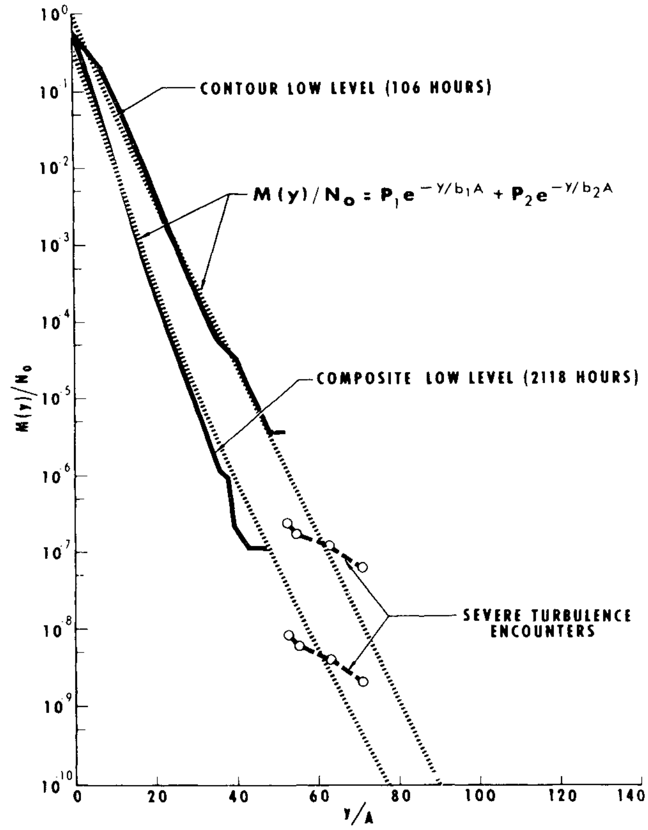


Fig. 6 Severe turbulence encounters for low-level mission segment.

can be obtained by several methods including the following iterative procedure. Estimate a load level y_u and calculate the associated reliability by the method described in the previous section. If the calculated reliability is not the same as the desired value, make a new estimate for y_u and repeat until the calculated reliability level becomes equal to the desired one. A rational method for the nth estimate that results in greatly accelerated convergence is

$$y_n = y_{n-1} + \frac{[\log M(y_u) - \log M(y_{n-1})](y_{n-2} - y_{n-1})}{\log M(y_{n-2}) - \log M(y_{n-1})} \tag{11}$$

Here again, the procedures described for determination of ultimate load are applicable for any response item or level of interest.

Effect of Aircraft Usage on Structural Reliability

The structural reliability level as discussed previously is affected by type of usage. Table 5 indicates the relative reliability levels of two idealized usages with the same airplane weight, equivalent airspeed, and flight hours per lifetime. The numbers represent a highly simplified situation but serve to illustrate the effects of usage on reliability level and the relative severity of low-altitude contour operation. The plots of $M(y)/N_0$ vs y/A for the environment also indicate that a small change in y/A will give a large change in $M(y)/N_0$. Thus, a small increase in strength (about 10%) can provide a large increase in structural reliability (about a factor of 5).

Effect of Avoiding Severe Turbulence

As turbulence forecasting techniques are improved, the ability of aircraft to avoid severe turbulence will be improved. Also, research is under way to develop airborne devices for detecting severe turbulence ahead of the aircraft. The effect of avoiding this portion of the total environment

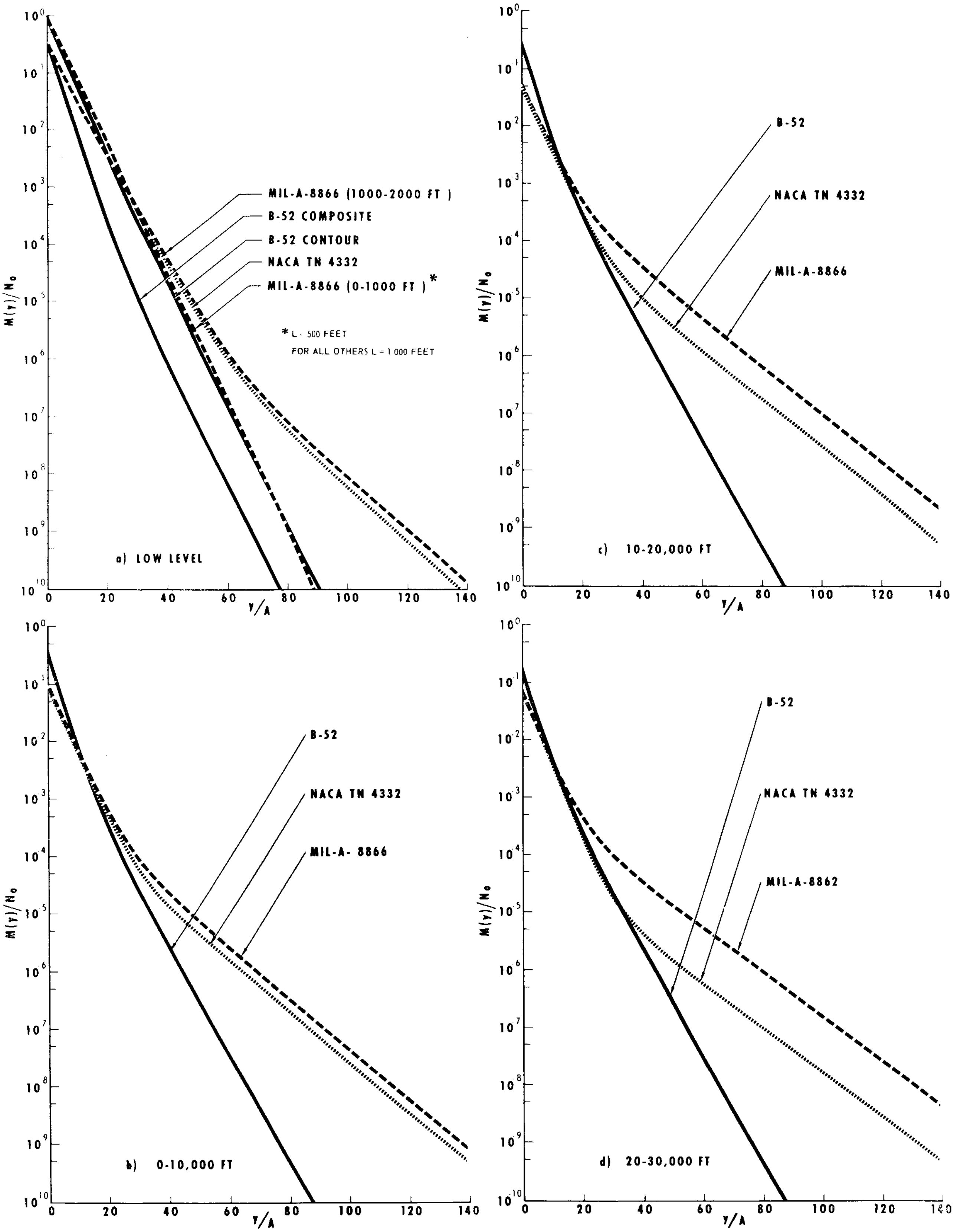


Fig. 7 Comparison of derived turbulence environment with similar published data (Figs. 7e and 7f on opposite page).

on the aircraft structural reliability is derived in the following discussion.

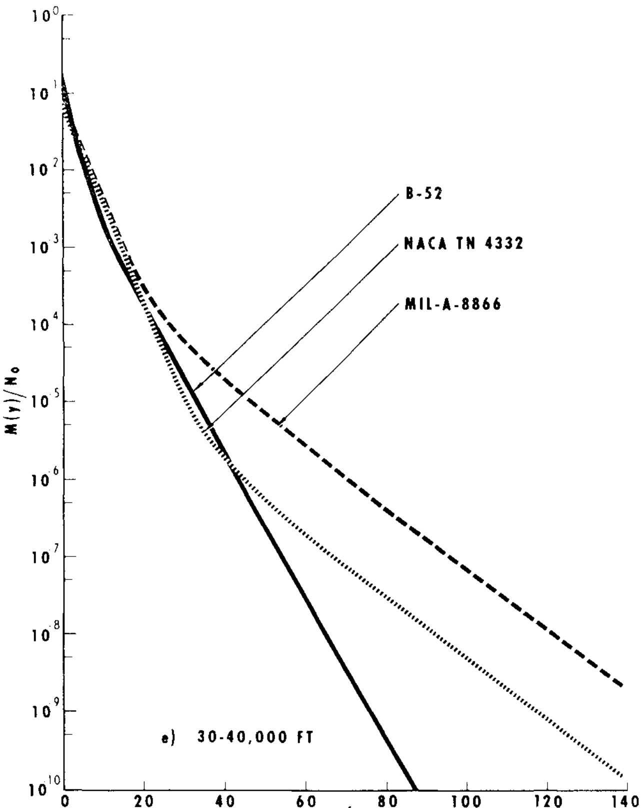
The cumulative probability distribution of the rms gust velocity is related to the probability density distribution by

$$F(\sigma_u) = \int_0^\infty f(\sigma_u)d\sigma_u - \int_0^{\sigma_u} f(\sigma_u)\, d\sigma_u \tag{12}$$

The functional form for the probability density distribution in terms of the turbulence parameters may be written as follows:

$$f(\sigma_u) = \frac{P_1}{b_1}\left(\frac{2}{\pi}\right)^{1/2} \exp\frac{-\sigma_u^2}{2b_1^2} + \frac{P_2}{b_2}\left(\frac{2}{\pi}\right)^{1/2} \exp\frac{-\sigma_u^2}{2b_2^2} \tag{13}$$

Substitution of this expression into Eq. (1) and integration yields Eq. (7). The cumulative probability distribution for



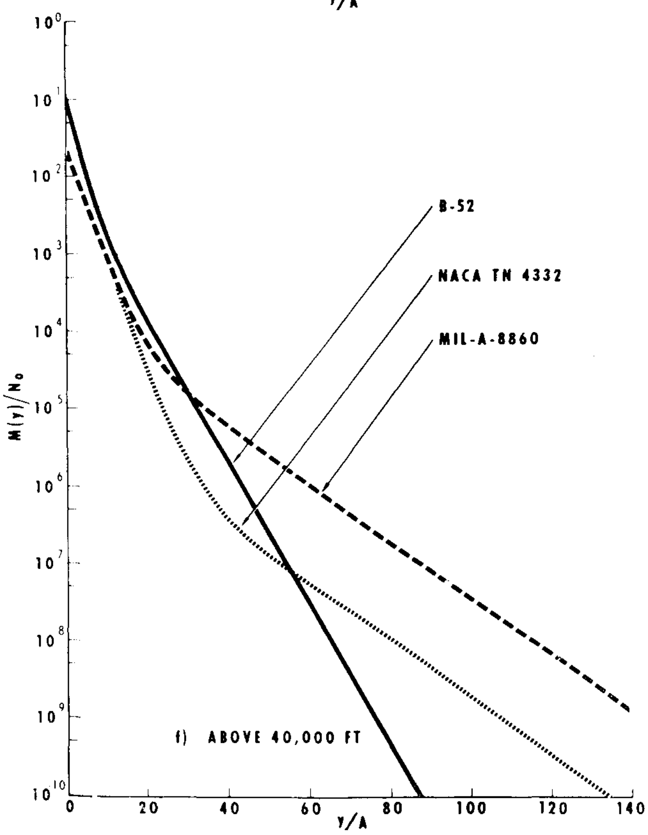


Fig. 7 Continued.

the contour low-level environment derived from the B-52 load history program is presented in Fig. 8.

If the most severely turbulent areas, the areas with the highest rms gust velocity, could be avoided, this would effectively truncate the cumulative probability distribution of rms gust velocity curve at the appropriate level of σ_u. In Table 6 are the maximum rms gust velocities encountered if the corresponding percentages of most severe low-level

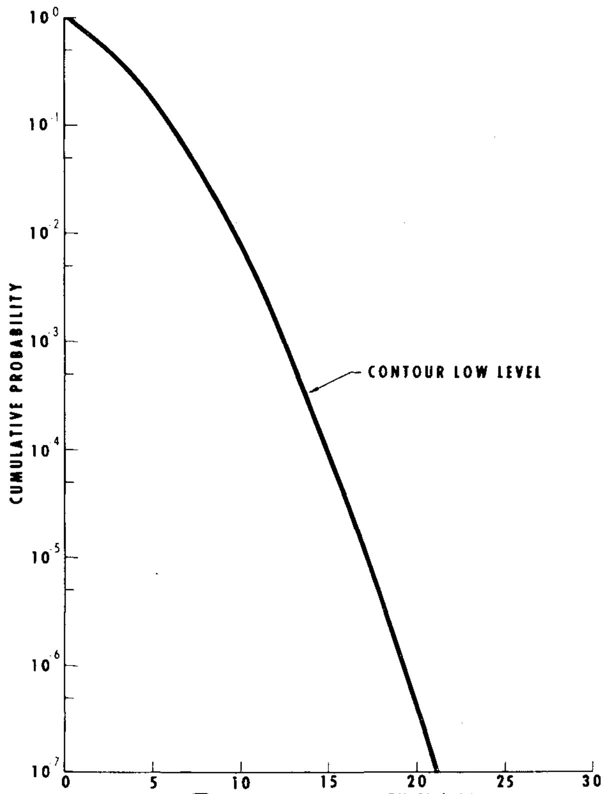


Fig. 8 Cumulative probability distribution of rms gust velocity.

turbulence are avoided. These numbers can be further interpreted as follows: 0.001% of low-level flight or flight distance is in turbulence having an rms gust velocity of 17.2 fps or greater, and 0.01% of the flight is in turbulence having an rms gust velocity of 15 fps or greater, etc.

The relative environments after deletion of these various amounts of the most severe turbulence may be obtained through the evaluation of Eq. (1) between the limits of zero and the appropriate value of σ_u as shown below:

$$M(y) = N_0 \int_0^{\sigma_u} f(\sigma_u) \exp\left(-\frac{y^2}{2A^2\sigma_u^2}\right) d\sigma_u \qquad (14)$$

This equation was solved for $M(y)/N_0$ vs y/A for the upper limits of σ_u, as previously tabulated for the B-52 contour low-level environment. These environments are shown in Fig. 9. The ratio of the reliability obtained by using severe turbulence avoidance to the nominal reliability vs the percentage of flight that it will be necessary to avoid is given in Table 7.

Note that a gain of several orders of magnitude in structural reliability is possible through severe turbulence avoidance. Although the ability to avoid always the most severe turbulence is perhaps questionable, if a reliable turbulence avoidance capability is developed, it may then be possible to lower the gust design requirements and maintain an acceptable level of structural reliability. However, a complete study of the structural reliability must include the fatigue or wear-out factors. The avoidance of a small percentage of the most severe turbulence may have a negligible effect on the fatigue life since the lower amplitude, higher frequency load occurrences may be important.

Table 6 Maximum rms gust velocity vs turbulence avoidance

Percent	σ_u
0.001	17.2
0.01	15.0
0.1	12.5
1.0	9.7

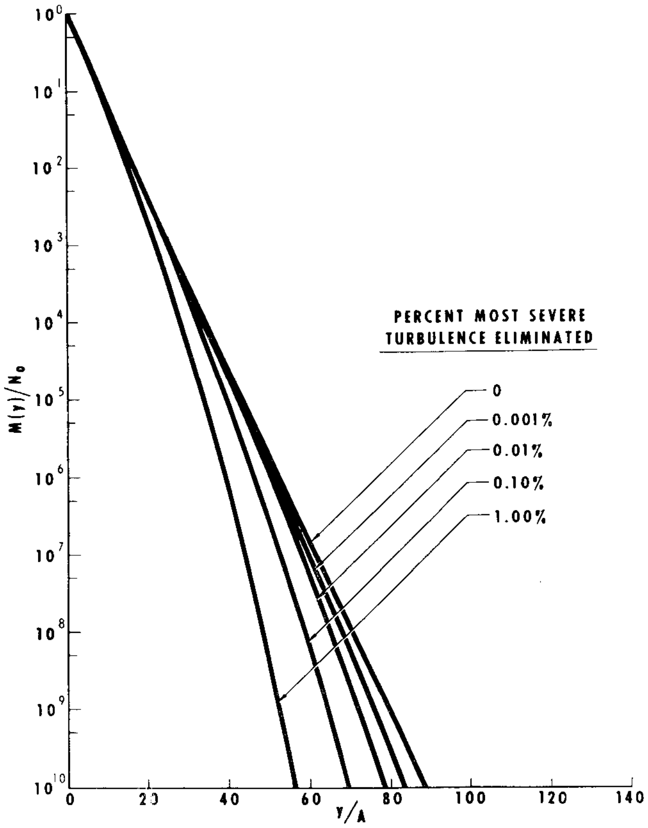


Fig. 9 Contour low-level turbulence environment with severe turbulence eliminated.

Conclusions

Conclusions from the derivation of the atmospheric turbulence environment are listed for emphasis as follows:

1) The spectral description of the turbulence environment derived from measured load history agrees with previously published data, especially in the lower amplitude region. For all of the altitudes except low level, the derived environment is lower for the large values of y/A. However, the use of this data for the determination of design loads based on structural reliability criteria may yield loads in excess of those calculated using current discrete gust design criteria.

2) The probability of encountering turbulence at low level depends on season, type of terrain, and absolute altitude above the terrain.

3) The derived atmospheric turbulence for altitudes above 20,000 ft is approximately a constant true airspeed gust environment.

4) The vertical and lateral turbulence environments agree for the low-level mission segment.

The following additional conclusions are drawn from the examples presented in the application of the results:

5) The usage of the aircraft can lead to variation in the structural reliability. In particular, the percentage of total time spent at low level is significant.

6) The structural overload reliability of aircraft can be increased several orders of magnitude through avoidance of a very small percentage of the most severe turbulence.

7) A relatively small increase (10%) in design strength will yield a large improvement (about a factor of 5) in structural reliability.

Areas for Further Research

The results of the load history programs to date provide valuable data for use in design analyses related to atmospheric turbulence. The work also emphasizes the need for further research in the following areas.

Table 7 Reliability levels vs turbulence avoidance

Percent	$R(y_u)/R(y_u)$ nominal
0	1.0
0.001	25
0.01	9×10^2
0.1	3×10^6
1.0	3×10^{15}

A definition of the atmospheric turbulence is necessarily based on a relatively small sample. Although the sample considered here appears large, the derived environment may be an insufficient sample to be truly representative. Therefore, it is necessary to assess the statistical accuracy of these results, perhaps by establishing confidence bands.

The atmospheric turbulence is generally recorded indirectly by measuring an aircraft response because of the problems associated with a direct measurement of the gust. This technique was used in the programs discussed in this paper. Problem areas in the reduction and analysis of this data include separation of gust and maneuver induced responses, determination of response transfer functions, and the determination of a gust spectral shape. As previously stated, suitable methods for separating maneuvers from the total response are not available. Several programs have been conducted to compare theoretical and experimental transfer functions, and, in general, adequate agreement was obtained. However, additional studies are required to provide uniform analysis techniques acceptable in aircraft design programs. Also, many programs have been conducted to define the gust spectral shape. The majority have been accomplished at low altitudes. Additional programs are required to study the high-altitude spectral shape and to define other important variables.

Additional load history data are being recorded and reduced at the present time, and programs of this type are continuing. These data will form a basis for increasing the statistical accuracy of the results presented in this paper and will allow a definition of other variables such as time of day, geographical location, and new operating procedures. These results will be updated as these additional data or new analysis techniques become available.

Work completed in the area of computing theoretical transfer functions has shown the importance of the airplane dynamic stability characteristics. The response of an airplane to random atmospheric turbulence depends on the dynamic stability. This dependence was not apparent in discrete gust studies used in previous design analyses. The use of the power spectral density analysis techniques will lead to a structural design compatible with the dynamic stability characteristics of the airplane.

An area in need of further research is improved turbulence avoidance procedures, since the structural overload reliability of an aircraft can be increased several orders of magnitude through turbulence avoidance. Therefore, research in the areas of forecasting turbulence and developing an airborne instrument to "see" turbulence must be continued.

References

[1] Houbolt, J. C., Steiner, R., and Pratt, K. G., "Dynamic response of airplanes to atmospheric turbulence including flight data on input and response," NASA TR R-199 (June 1964).

[2] Press, H., Meadows, M. T., and Hadlock, I., "A re-evaluation of data on atmospheric turbulence and airplane gust loads for application in spectral calculations," NACA Rept. 1272 (1956).

[3] Press, H. and Steiner, R., "An approach to the problem of estimating severe and repeated gust loads for missile operations," NACA TN 4332 (September 1958).

[4] "Airplane strength and rigidity—reliability requirements, repeated loads, and fatigue," Military Specification MIL A-8866, Aeronautical Standards Group (May 18, 1960).