Improved Methods of Atmospheric Turbulence Prediction for Aircraft Design and Operation

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New atmospheric turbulence prediction techniques have been developed to define the existence and magnitude of turbulence. These empirical methods were developed from the vast amount of recorded atmospheric turbulence data in several forms. Early data from aircraft response to turbulence was collected, primarily by NACA, with recorders on board civil transport aircraft. Recently, the gust probe method has been used in several programs to define atmospheric turbulence magnitudes under a variety of conditions. These atmospheric turbulence environment data, used in empirical prediction techniques, provide potential improvement in gust design criteria and in avoidance planning of high-risk flight regions.

Nomenclature

$\bar{A}$ = gust response factor, σ_Y/σ_{GW}
AA = average terrain route altitude, ft
a = inverse slope parameters for response distribution, $0.791\sigma_Y$
b = inverse slope parameters for gust distributions (derived equivalent or true gust velocity peaks), 0.791σ
$\bar{C}$ = gust response parameter, $\Delta n_z/U_{de}$, g/fps
e = 2.718
FA = airplane flight altitude, ft
LR = lapse rate, °F/1000 ft
N_0 = characteristic frequency, cps
n = load factor, g
P = proportion of time in atmospheric turbulence
PTW = proportion of time wind is greater than 5 knots
ST = average air temperature at terrain surface, °F
T = time in severe turbulence, hrs
TRF = terrain roughness factor
U_{de} = equivalent derived gust velocity, fps
Ve = equivalent airspeed, fps
WS = wind speed, mph
Y = airplane response
α = angle of attack, rad
Δ = incremental
ρ_0 = air density, slug/ft^3
ρ_0 = air density at sea level, slug/ft^3
σ = standard deviation (root mean square)
$\sigma_{U_{de}}$ = standard deviation equivalent derived gust velocity, $\approx \sigma_{GW}(\rho/\rho_0)^{1/2}/1.1$, fps

Subscripts

G = gust
tr = terrain roughness
U_{de} = equivalent derived gust velocity
W = true vertical velocity
Y = airplane response
z = normal
1 = nonstorm turbulence
2 = storm or severe turbulence
3 = hail

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Introduction

THE purpose of this paper is the presentation of new methods for determining when atmospheric turbulence will occur and its magnitude. Also, recommendations for turbulence avoidance and aircraft design criteria revisions are considered for decreasing the risk of structural overload and fatigue failures.

The proposed concepts are applicable to all types of aircraft with major benefits for small aircraft and for low-design load factor (gust critical) aircraft.

A number of atmospheric turbulence models exist in the form of P and b turbulence values, which cover all significant altitude ranges. The more detailed information presented in this paper will supplement these models for critical regions of the atmospheric turbulence environment.

Low-Terrain Clearance Average Atmospheric Turbulence

One objective of this paper is to define the most significant variables which contribute to the existence of turbulence and turbulence magnitude. To meet this objective it was necessary to have unbiased sampling of atmospheric turbulence at a number of locations, at night, at day, and for all seasons of the year.

B-52 data[1,2] were available in sufficient quantity and statistical sample size to meet this data requirement. However, many other data sources[3–6] in the form of documented test results were used as supplemental data in defining the contribution of independent variables relative to turbulence magnitude.

These B-52 data are published in several reports and cover the complete range of the terrain types. The location of the B-52 Data Route Groups is shown in Fig. 1. The form of the B-52 data was derived gust velocity distributions for night and day by season for each Route Group. The derived gust velocity data were converted to true gust velocity standard deviation values by using $\bar{C}$, $\bar{A}$, a_1, and $b_{1U_{de}}$. These types of computations are well covered in many papers[6–8]; therefore, the details are not explained in this paper.

This definition of turbulence magnitude per B-52 Data Route Group, season, night and day was the first step in the development of an equation to predict turbulence magnitude. The significant independent variables to be used in this equation were required for each of the B-52 data samples. In most cases, several weather stations were located in the vicinity of the B-52 Route Groups. Statistics on average lapse rate (LR) and surface temperature (ST) were extracted from the records of these weather stations. Typical average wind speed

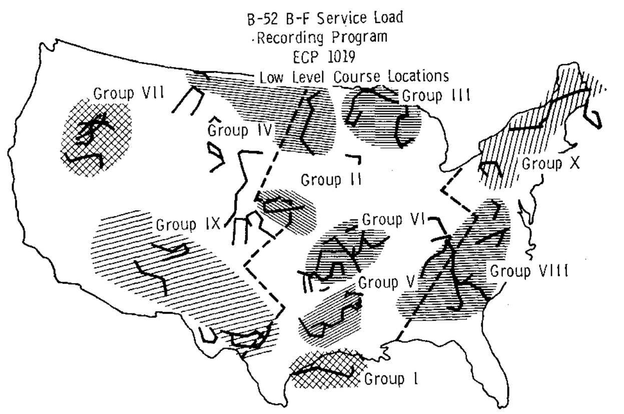

Fig. 1 Identification of B-52 data route groups for low-level turbulence.

values[3] for February are shown in Fig. 2 and were used with factors to obtain wind speed (*WS*) per night and day. The monthly wind speed data was then converted to seasonal data. Interpolation between weather stations were made for application to B-52 Route Groups.

The collection of the average dependent and independent atmospheric turbulence variables for approximately the same time period and place was adequate for equation development. However, the effects of terrain type had not been accounted for at this stage of equation development.

It has been known for some time that terrain roughness and wind speed are strong contributors to atmospheric turbulence magnitude. A number of reports[4–6] have used wind speed as an independent variable in predicting gust velocity standard deviation. Factors have been developed for terrain roughness in some cases and in other cases equations have been developed for a terrain type with wind speed as the only independent variable.

A solution to the effects of terrain roughness was required for predicting the gust velocity standard deviation at low altitude (low-terrain clearance) under most conditions except the storm category.

The ground rules for the attack on the terrain roughness effect were the following: 1) The terrain roughness standard deviation must be used in computing a terrain roughness factor (*TRF*). 2) The terrain roughness factor must decrease with an increase in terrain clearance. 3) The equation for computing *TRF* must be applicable to terrain following flight and 1000 ft peak terrain clearance such as the B-52 data. 4) Documented gust probe results would be used extensively in the derivation of the *TRF* equation.

The logic in applying these ground rules was to start with documented[4–6] equations for the standard deviation of gust velocity with wind speed being the independent variable. Each equation was for only one terrain type and the equation coefficient for wind speed would reflect the effects of terrain roughness. Maximum use was made of these coefficients during the derivation of the Terrain Roughness Factor (*TRF*) equation.

To comply further with these ground rules, terrain roughness standard deviation values of Table 1 were estimated using the data in Fig. 3 as typical route data. Data points (Lo-Locat Program)[5] are for forty different route legs.

Equation (1) is the product of applying the above ground rules in the proper manner to those variables believed to have an effect on the Terrain Roughness Factor

$$TRF = \{FA/[FA - (AA/3.) - \sigma_{tr}] - 1.1\}/3. \qquad (1)$$

Flight altitude (*FA*), estimated average terrain altitude (*AA*), and estimated terrain roughness standard deviation (σ_{tr}) used in Eq. (1) are presented in Table 1.

Table 1 B-52 route group data

Route groups	Flight altitude ft	Avg. terrain ft	σ_{tr} ft
I	1000	0	10
II	3700	1850	80
III	3700	1650	110
IV	3700	1850	80
V	1700	475	175
VI	3000	1400	190
VII	8000	5000	680
VIII	3700	1350	190
IX	9500	6000	680
X	5600	3100	350

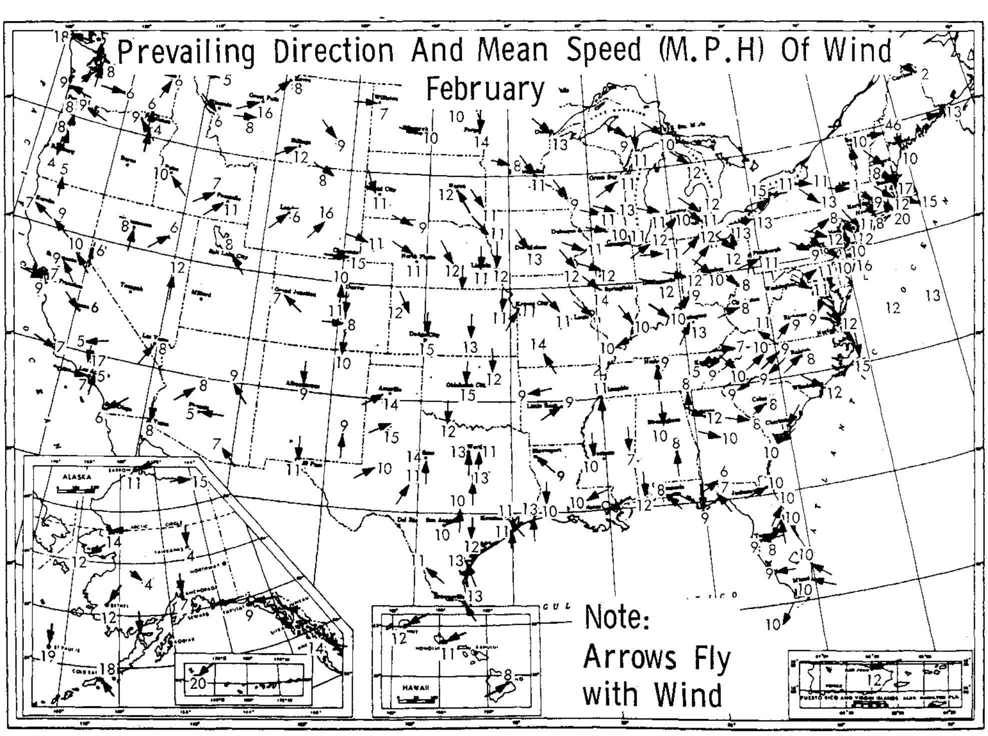

Fig. 2 Typical wind speed data by month for use in season analysis per night and day.

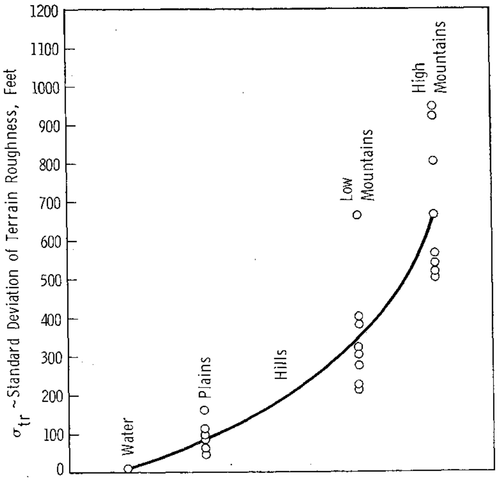

Fig. 3 Standard deviation of terrain roughness by terrain type.

The derivation of Eq. (1) was simply a cut-and-try (revise equation and test) method. Refinements of this equation or a substitute may produce better results. It may be useful to the person who tries to improve Eq. (1) that considerable effort was applied during the derivation period to make sure terrain type effects on turbulence magnitude would be well covered. Also many test data samples were analyzed during the derivation.

In Table 2, additional information is given on the B-52 Route Groups including the terrain-type estimate and computed *TRF* values per route.

The most important independent variables are believed by the authors to be *TRF*, *WS*, *LR*, and *ST* for computing the gust velocity standard deviation at low altitude (nonstorm conditions). These variables were input to a multiregression computed program which output Eq. (2) for computing gust velocity standard deviation.

$$\sigma_1 = 2.70 + 0.619(TRF)(WS) - 0.0768(LR) - 0.0017(ST) \tag{2}$$

The standard error for Eq. (2) predictions was 0.543. This value is approximately one half the standard error of the best similar equation known of by the authors.

In Fig. 4, the input dependent variable is plotted vs the computed dependent variable from Eq. (2) for each of the eighty conditions (10 route groups, 8 conditions per route group). This plot may be used for the consideration of the goodness of fit for Eq. (2).

The dashed line on Fig. 4 represents a significant curve fit improvement of Eq. (2). This dashed line may be approximated by changing the constant in Eq. (2) to about 2.4 and the coefficient of (*TRF*)(*WS*) to 1.0. Improvements of Eq. (2) offer a potential for good turbulence magnitude predictions when the independent variables are known or can be estimated.

Table 2 Terrain roughness factors per route group

Route group	Route location	Terrain type	*TRF*
I	Gulf of Mexico	Water	−0.03
II	Nebraska	Plains	0.043
III	Upper Michigan	Water & hills	0.04
IV	North Dakota	Plains	0.043
V	Southern Arkansas	Forest & hills	0.037
VI	Southern Missouri	Hills	0.06
VII	Idaho-Oregon	High mountains	0.107
VIII	Appalachian States	Hills	0.037
IX	Southwestern States	High mountains	0.097
X	New England	Low mountains	0.077

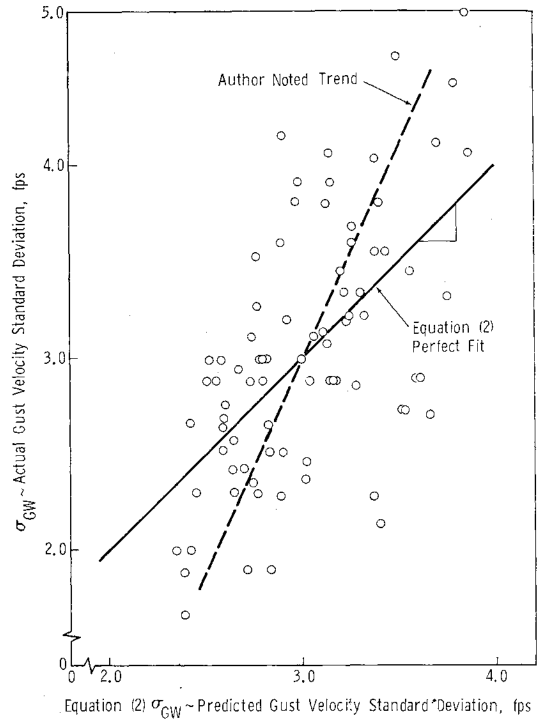

Fig. 4 Prediction of original gust rms values with an equation.

Most of the independent variables are obtainable from weather reports. The terrain roughness standard deviation may be estimated by selecting a typical adjacent peak and valley on the route, then computing the altitude difference and dividing by 2.3 to produce σ_{tr}.

The B-52 data has some bias where aircraft encountered moderate turbulence; thus, the derived gust velocity sample would not represent average conditions. Cases with such a bias made the data more difficult to curve fit. Also, referenced reports[5,6] indicate that the scale of turbulence varies with turbulence magnitude. Equation (1) covers some of the effects of scale of turbulence variations. A constant scale of turbulence value of 1000 ft with a Drydon Spectrum was used in computing the B-52 $\bar{A}$ values. Equation (2) is a big improvement in turbulence magnitude prediction capability and can be easily cross-checked to increase the user's confidence.

The B-52 data[1,2] is the only source data known to the authors for defining in detailed form the proportion of time (P_1) that atmospheric turbulence exists for low-terrain clearance. Equation (3) was computed in the same manner as Eq. (2) to predict P_1 under any condition except thunderstorms. Equation (3) is good for terrain clearances not greater than 5000 ft (assuming Eq. (1) covers this range)

$$P_1 = 0.565 - 0.0556(LR) - 3.196(PTW)(TRF) - 0.00082(ST) \tag{3}$$

Parameters used in computing P_1 from B-52 data were airplane true velocity and N_0.

The percent of time wind speed is greater than 5 knots (*PTW*) is the only independent variable used in Eq. (3) that was not used in Eq. (2). The statistics by location for this variable (*PTW*) were available by season only. Therefore, seasonal values were considered to be applicable for both night and day. The authors believe the day values (of *PTW*) should be higher than the night values, but no modification was applied.

Lapse rate was found to be the most important variable for predicting P_1. The cross product (*PTW*)(*TRF*) was found to be the second most important variable. Improvements of

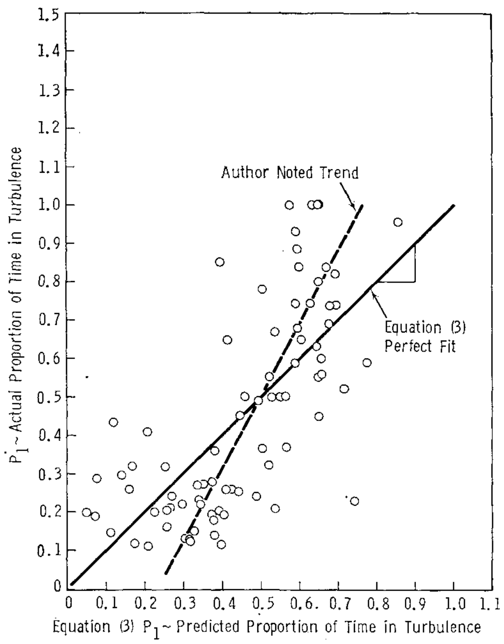

Fig. 5 Equation predictions of proportion of time in atmospheric turbulence.

Eq. (1) to define *TRF* may result in better prediction of P_1 with Eq. (3). The standard error for predictions with this equation is 0.194.

Figure 5 is used to present the goodness of fit for Eq. (3). The B-52 data P_1 values were the actual or input data to the computer program, with the predicted P_1 values of Fig. 5 being the Eq. (3) computed values for the same set of independent variables. Equation (3) gives a good curve fit as shown in Fig. 5; however, the dashed line strongly indicates Eq. (3) can be improved.

Equation (3) may be used in prediction of P_1 values for aircraft flying at low altitude. These predicted P_1 values are needed in computing the probability of structural overload and fatigue damage accumulation on a given aircraft with an estimated usage.

Equations (2) and (3) cover most of low-altitude aircraft flight time for all terrain types. The turbulence magnitude of the data had a maximum gust velocity standard deviation of 5.0 as shown in Fig. 4. Let us look at the more severe turbulence domain.

The severe clear air turbulence at low altitude would probably be associated with high-wind conditions in mountainous terrain. In such a case, the downwind side of the peaks would be the most severe environment. Structural overload or loss of control could cause catastrophic results in this case.

Thunderstorm Turbulence

Press and Steiner[8] covered both average and severe turbulence in their derivation of an atmospheric turbulence description. A number of more recent papers[6,9] have covered portions of the same material with additional test data being analyzed.

Radar in commercial transports today makes possible the avoidance of thunderstorms. Documented data[9] is available for defining the magnitude of thunderstorm turbulence. Also, the percent of time severe turbulence (primarily thunderstorms) exists[8] has been approximated with recorded commercial aircraft response data which was collected before radar was used for thunderstorm avoidance.

The locations where thunderstorms occur most often in the U.S.[10] are shown in Fig. 6. Equation (4) may be used in

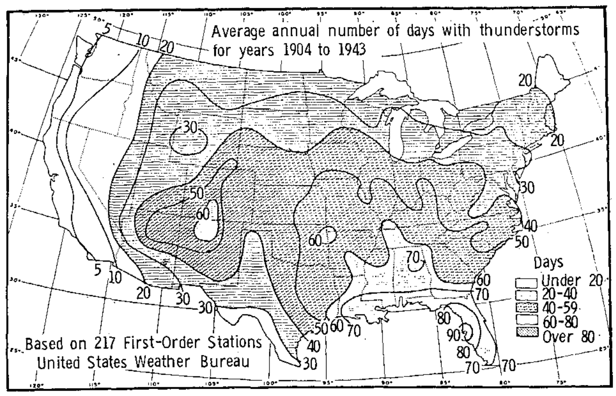

Fig. 6 Annual thunderstorm distribution over the U.S.

conjunction with Fig. 6 to compute the proportion of time thunderstorms exist over the U.S.

$$P_2 = (0.000055)(\text{numbers in Fig. 6}) \tag{4}$$

Equation (4) was computed using the medium-sized thunderstorm[11] as a standard with the characteristics as tabulated in Table 3.

The most severe thunderstorms may be associated with frontal movements and may be much larger than the medium size storms. The magnitude of cumulus cloud and storm turbulence is presented in Table 4 in terms of gust velocity standard deviation. It is generally considered that thunderstorms cover an altitude range of 10,000 to 40,000 ft. The severe thunderstorms may cover the altitude range from the surface of 50,000 ft. The buildup or early stages of a thunderstorm may not be visible on radar. At the severe stage, lightning and tornadoes may exist in a thunderstorm. The probability of a thunderstorm containing a tornado (a violent whirlwind) may be calculated.

During the summer season the early transports would often fly through thunderstorms with a high probability of structural overload and much discomfort for the passengers. Modification of Eq. (4) to reflect seasonal change would not be beneficial for design criteria purposes. It is expected that these storms will be avoided by a change in flight path.

Another reason for avoiding thunderstorms is the probability of hail damage to any aircraft type. Many early transport aircraft experienced hail damage.[10] Also hail damage for unhangered aircraft on the ground causes a significant amount of aircraft structural damage yearly.

Areas of the U.S. where thunderstorms produce hail[10] are shown in Fig. 7. The probability of encountering hail is

Table 3 Medium thunderstorm

(a)	9 miles in diameter
(b)	29.1 min in duration
(c)	speed of 18.6 mph

Table 4 Cloud and storm turbulence magnitude

Conditions	σ_{GW}
Cumulus clouds	6.36
Average thunderstorms	11.2
Severe thunderstorms	16.0

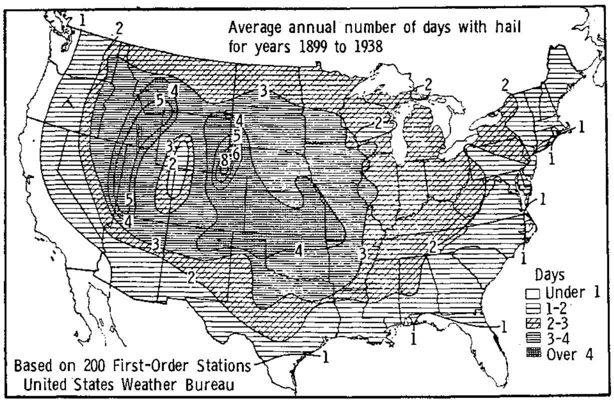

Fig. 7 Annual hail distribution over the U.S.

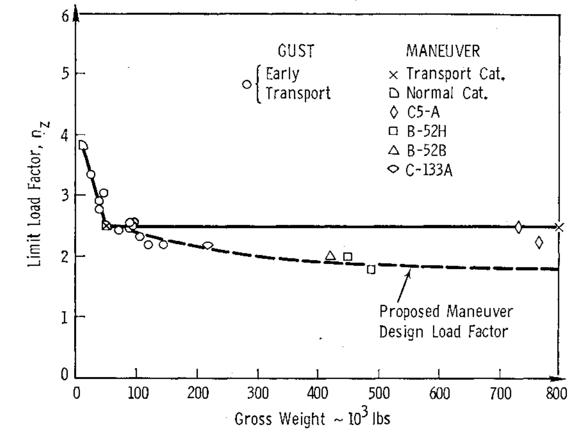

Fig. 8 Proposed maneuver limit design load factor vs gross weight.

quite low but can result in significant damage to aircraft. The proportion of time severe hail exists may be computed using Eq. (5)

$$P_3 = (0.000017) \text{ (numbers in Fig. 7)} \tag{5}$$

The average-sized hail storms,[10] as well as the duration and speed of a medium-sized thunderstorm of Table 3, were used in the derivation of Eq. (5). Highly sensitive ground radar may detect thunderstorm sections containing hail.

Aircraft flying through thunderstorms may be doing so at a very high risk. Hail, high-gust velocities, and tornadoes may be encountered in a thunderstorm; these conditions could cause severe damage or catastrophic structural failure to an aircraft.

Also, ice forming on an aircraft in flight is another weather condition which should be avoided. Mainly, atmospheric parameters which have an effect on aircraft design and operational risk are addressed in this paper.

Jet Stream Turbulence

Large, low-design load factor aircraft will continue to operate through cumulus clouds where the pilot expects turbulence. The surprise associated with encounters of lower magnitude jet stream clear air turbulence has resulted in several problems.

Wind shear is the basic source of turbulence near the jet-stream. The lower shear region is 25,000 to 30,000 ft and the upper altitude band is 35,000–40,000 ft. The lower region is felt mostly by commercial jet transport aircraft passengers at high-climb angles. This turbulence may result in discomfort and risk if the pilot initiates improper control input. The authors suggest lower climb angles be used in these potential turbulence regions to eliminate or minimize aircraft response. The magnitude of this type turbulence[12] for climb may be double that for descent through the same altitude band.

Relative Risk with Current Design Gust and Maneuver Load Factors

Data[13] from early airline transport aircraft operating without radar indicate that these aircraft generally experienced higher gust than maneuver load factors during conditions where instrumentation was adequate to allow gust and maneuver to be separated. Gust and maneuver design limit load factor data are presented in Fig. 8.

It is true that these early reciprocating engine transport aircraft operated in a more severe turbulence environment than current airline transport aircraft. However, design stresses were normally lower for the same material. This may result in a higher equivalent safety factor than for current aircraft.

Current gust and maneuver criteria[14–16] for design limit loads are presented in Table 5. The gust design magnitude specified in Table 5 does not provide criteria as to where and how often such gusts may be expected. One purpose of this paper is to provide criteria that will allow gust design for the maximum gust to be encountered per one airplane life.

The severe turbulence parameters, P_2 and b_2, currently[8,17] in use are for the older propeller type and nonradar equipped transport versions. These parameters are not applicable to current operations of transport and large bomber aircraft. They are not applicable to any aircraft since even fighters seldom penetrate the hazardous domain of thunderstorms.

These background information for past and current design criteria need updating. New multichannel recorder data per airplane type needs to be collected to better establish probability load curves for all structural components. The data are needed primarily for maneuver and maneuver plus gust to even define the actual safety factor for normal operations.

The incremental angle of attack due to gust ($\Delta\alpha = U_{de}/V_e$) from vertical conditions for cruise airspeed may be considered to determine where more prudent turbulence avoidance procedures are desirable. Crosswind landings and low-airspeed conditions must be analyzed to establish the maximum rms turbulence for safe flight.

The atmospheric turbulence environments an airplane may encounter, if no turbulence avoidance procedures are used, are described in Fig. 9. Equation (2) was modified to approximate the dashed line of Fig. 4 and a standard day in order to compute the high mountains, plains, and water environments of Fig. 9. In addition, the cumulus cloud and thunderstorm data from Table 4 are presented. Most of the operational flight time for aircraft of Table 5 is logged in a small region covering the lower left-hand corner of Fig. 9.

Table 5 Gust and maneuver design data

Aircraft category	Maneuver design limit load factor	Design gust velocity (design gust limit load factor $n_z = 1. + U_{de}C$) U_{de}
Normal	$\left(2.1 + \dfrac{24000}{W + 10{,}000}\right)^a$	30
Transport	2.5	50
Bomber	2.0	50

^{a} Maximum 3.8 and minimum 2.5

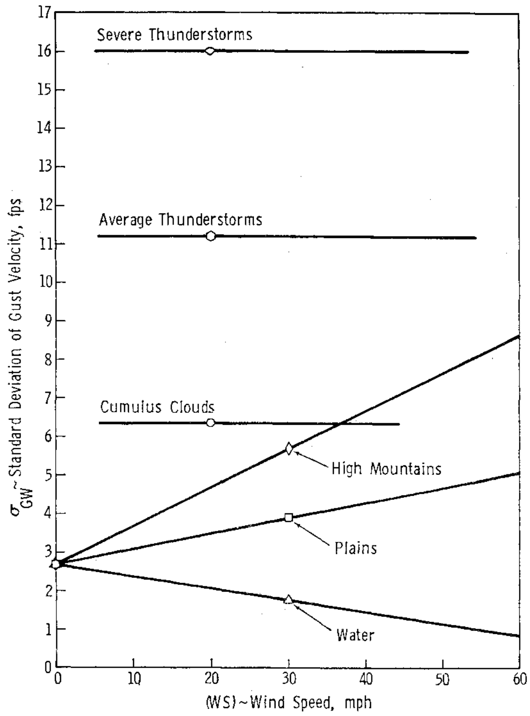

Fig. 9 Atmospheric turbulence environment.

The primary problems to be faced when attempting to expand the operating regions are loss of control, increased structural fatigue and structural overload.

Aircraft Design Criteria and Operational Change Considerations

The ground rule used by the authors was to consider the design limit load (gust or maneuver) as the maximum load to be experienced in one airplane life under average usage. Also, the shape (type, normal, or exponential) of load distribution curves must be considered in defining a safety factor. The maneuver limit load should not be ultra conservative when compared to the probability of structural overload due to gust.

Since the pilot can usually control the magnitude of the maneuver load factor, it is suggested that the gust design should over-ride maneuver design. This is true unless the gust design limit load factor is less than the dashed line for maneuver on Fig. 8. More operational recorded maneuver data is needed to define load probability curves by structural component for the aircraft of Table 5.

The suggested maximum design load factor for maneuver vs gross weight for normal category, transport category, and bomber aircraft is shown in Fig. 8. The logic in the use of this curve is that the pilot has control of the maneuver magnitude. This proposed maneuver design load factor criteria is based on past designs. However, the design criteria philosophy that past designs were successful and the designer of new aircraft should use the same load environment is questionable in the case of turbulence.

This paper addresses the high-risk domain for these aircraft which are believed to be gust sensitive in moderate to severe turbulence. For loss of control problems the cruise condition may need to be studied for various turbulence magnitudes. Crosswind landing conditions should also be studied.

Figure 9 may be used in conjunction with the criteria of the following sections to meet this objective. Thus, the maximum angle of attack and side slip may be computed for a given time in severe turbulence and airplane airspeed. This detailed information for aircraft operational changes can decrease the risk of structural overload and lower the rate of structural fatigue damage accumulation.

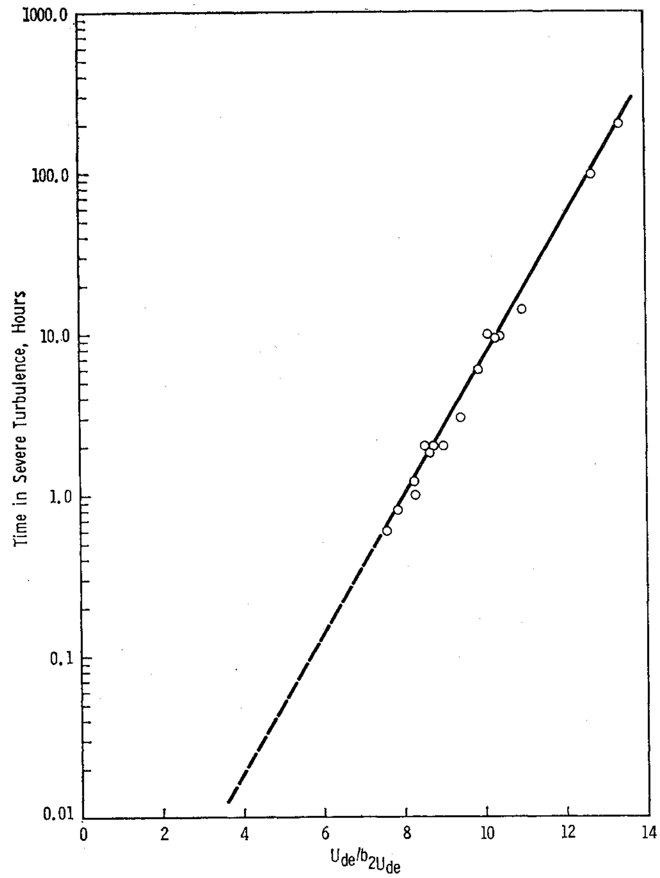

Fig. 10 Relation of time in severe turbulence to the gust velocity and gust rms representation.

The P and b turbulence parameters for computing fatigue damage should be defined with an analysis of the expected missions. The refined prediction methods of this paper may be used in this analysis.

The P_2 and b_2 values of the referenced reports[6,8,17] should not be used since they were derived from aircraft penetrating thunderstorms. All thunderstorms and severe mountain turbulence should be avoided.

The main objective of this section is to relate design rms turbulence magnitude, time in severe turbulence, and maximum gust per one airplane life. Contained in Fig. 10, are early airplane transport data normalized to 30,000 flight hr to represent one airplane life. Jones et al.[5] found that an average factor of five was good for maximum true gust velocity divided by the gust velocity standard deviation for 4.5 min turbulence samples. These findings (ratio of 5.0 for true gust velocity/σ_{GW}) agree well with the data in Fig. 10.

Equation (6) was derived to fit the data of Fig. 10. It is interesting to note that Eq. (6) may be used to determine the maximum turbulence for design when a time in severe turbulence for one life is selected

$$T = 0.00033e(U_{de}/b_{2U_{de}}) \tag{6}$$

Equation (6), then, is the link needed to close the loop on gust design to determine the maximum gust for one airplane life when a design turbulence magnitude has been selected. Also, Eq. (6) may be used in conjunction with the data in Fig. 9 to define turbulence avoidance procedures for a given aircraft. New design criteria must take into consideration the degree of avoidance of severe load environment conditions. Also, the maximum load environment and the amount of time an average airplane will be in this environment during its life

Table 6 Design turbulence magnitude

Aircraft type	Normal category	Transport category
P_2	0.0004	0.0004
Design U_{de} fps	30	50
Design airplane life (flt, hr)	10,000	30,000
Flight hours in severe turbulence	4	12
Design $b_{2U_{de}}$, fps	3.19	4.76

must be considered. Therefore, Eq. (6) may be used as the relation between time, maximum response, and rms response in the most severe environment.

An example application of Eq. (6) using the design gusts of Table 5 is presented in Table 6. The P_2 values of Table 6 were assumed to be applicable for all altitude bands. The design $b_{2U_{de}}$ values may be computed by flight segment in a more detailed form.

An empirical equation relating T, $b_{2U_{de}}$, and U_{de} has been provided. It is suggested that this equation is a key element for gust design criteria to allow identification of the maximum turbulence loads for one airplane life.

The logical design turbulence magnitude is cumulus clouds with an average true gust velocity standard deviation of 6.36. Thus, severe mountain turbulence exceeding this magnitude of 6.36 would be avoided.

The product $U_{de}/b_{2U_{de}} \approx Y/0.791\bar{A}\sigma_{GW}$ and Eq. (6) makes possible the computation of the power spectral density design ratio $Y/\bar{A}$. This is the only logical method known to the authors for defining this ratio. To demonstrate this ratio, we may select an $\bar{A}$ of $0.02g$/fps for a Boeing Model 720B,[18] $T = 12$ hr, $\sigma_{GW} = 6.36$ fps and $Y/\bar{A} = 52.8$ fps. Note that this value can be used to compute the limit load factor ($n_z = 1.0 + (Y/\bar{A})\,\bar{A} = 2.06g$).

Conclusions

The previous equations for predicting P_1 and σ_{GW} at low-terrain clearances may be used to reduce aircraft accidents for this flight domain as follows: 1) Avoidance of severe turbulence will decrease the probability of structural overload due to gust. 2) Marginal control conditions can be identified for revisions of flight plan. 3) Finer details on the load environment will allow a more definitive analysis of aircraft structural fatigue damage accumulation. 4) Those areas where crew and passenger discomfort or sickness may occur can be identified in advance and an alternate route selected. The portion of time that thunderstorms exist across the U.S. has considerable variation and an attempt has been made to provide P_2 coverage with an empirical equation.

Gust and maneuver design limit load factor data has been examined for a period when there were no restraints (no storm avoidance radar) on turbulence to be encountered. It was found that the gust load factors were normally higher than maneuver load factors; therefore, it is suggested that, in most cases, gust design should be the primary requirement.

We have provided an empirical equation relating T, $b_{2U_{de}}$, and U_{de}. It is felt that this equation is a key element for gust design criteria to allow identification of the maximum turbulence loads for one airplane life.

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