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Gust load conditions for fatigue tests based on a continuous gust concept

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ABSTRACT
Newly designed aircraft structures must be subjected to full scale fatigue/damage tolerance testing. The present paper describes an automated procedure for the generation of fatigue test load sequences, with specific reference to gust loads. The procedure uses a continuous gust concept. A statistical gust model, based on gust data recently published by FAA, is proposed. Specific attention is paid to the determination of the incremental load distributions due to gust on PSD basis.

Contents

(14 pages in total)

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Abstract

Newly designed aircraft structures must be subjected to full scale fatigue/damage tolerance testing. The present paper describes an automated procedure for the generation of fatigue test load sequences, with specific reference to gust loads. The procedure uses a continuous gust concept. A statistical gust model, based on gust data recently published by FAA, is proposed. Specific attention is paid to the determination of the incremental load distributions due to gust on PSD basis.

Introduction

Newly designed transport aircraft structures must be subjected to extensive full scale fatigue/damage tolerance testing as part of the certification process. It has become standard practice to carry out these tests as so-called "flight simulation tests"; that means the test articles are subjected to a series of successive loads simulating as realistically as possible the load histories occurring in actual service.

The determination of representative test load sequences is an important element in the test definition. Recently, the National Aerospace Laboratory NLR completed the development of a fully automated procedure for the test load generation for major structural components.

This procedure includes several elements that have become accepted as "standard practice" throughout the Aerospace Industry. A "new" aspect is the use of a continuous gust model for determining gust loads, and specifically the solutions that have been chosen for specific questions associated with the use of PSD techniques when determining gust test loads.

The present paper will start with a general overview of the test load sequence generation process. Next, specific attention will be paid to the procedure for definition of gust load conditions on PSD basis, and its background.

The paper terminates with a general discussion.

Overview of Load Sequence Generation Procedure

We will assume that a full scale fatigue test will be carried out on a "major structural component". This may be for example the wing, a front fuselage or a stabilizer. The loading of the test specimens will consist of a series of successive discrete "loading conditions", simulating the often very complex loading history occurring in service. Each "loading condition" is associated with a specific "Internal Load Distribution" (bending moment M, torsion moment T and shear force S for each section).

It cannot be stressed enough that even the most complex full scale fatigue test is only a very simplified representation of the real service loading: it is the task of the test designer to set up a test that is as simple as possible but still provides a realistic simulation of the fatigue loading and associated damage accumulation in service.

The first step in the definition of the fatigue loading environment is the Mission Analysis: For the new aircraft one or more "design missions" with regard to flight length and payload are specified and their expected relative frequency of occurrence estimated.

For each of these missions, a detailed "mission profile" with regard to speed, altitude, weight and (flap-)configuration is determined. Next, each mission is split up in a finite number of "mission segments". In each segment, speed, altitude, weight etc. are thought to remain constant. As an example, figure 1 and table 1 show the design mission profile and the associated mission segments for a short haul transport aircraft.

Fatigue test load sequences usually refer to a certain "repeat" period, typically in the order of 5000 flights for transport aircraft. We will call this our "test block". As will be explained later on, the block length must be sufficiently long in order to include rarely occurring high loads.

To summarize, in the mission analysis we have split up the usage in a block of 5000 flights over a number of flight segments in each of which the flight and configuration parameters of the aircraft remain constant. The total time spent, distance flown etc., in each segment are known.
With regard to the number of segments to be distinguished in a flight, NLR procedures foresee a not too fine mesh: typically, depending on flight length between 7 and 12 segments will be needed for an appropriate mission description (see eg. table 1).

For each mission segment the spectrum of loads expected to occur in that segment must now be determined.

Some of these loads are of a relatively simple and deterministic nature, for example the loads on the flap structure when the flap is extended, or the manoeuvre loading in the rotation during take-off.

The majority of loads, and specifically the loading due to gustiness, are not of a deterministic nature but can only be described in a probabilistic sense. In the next chapter the choice of the atmospheric turbulence model will be discussed in more detail; at this stage we will only note that all existing models allow the calculation of a "load exceedance curve" for each load quantity per mission segment.

This gust load exceedance curve must be "translated" in a set of discrete loading cases; the continuous exceedance curve must be approximated by a "stepped" spectrum, as indicated in figure 2.

In this stepping, decisions with regard to three aspects must be made:

- The highest load to be applied (truncation or clipping level)
  Rarely occurring high loads tend to have a beneficial effect, particularly on crack growth. The highest load applied in the test should not be taken too high. A widely accepted level is the load level being exceeded on the average 10 to 20 times per aircraft life, or the level being exceeded on the average a few times per major inspection period. A reasonable choice might be the level occurring once in a "block" of 5000 flights.
- The lowest load simulated in test (omission or low load truncation level)
  The choice of this level is very important as it has a major influence on the total duration of the fatigue test. For transport aircraft, this level is usually chosen in such a way that the total number of cycles to be applied is in the order of 100 per simulated flight. In case of a design life of 100,000 flights and a scatter factor of 2 this still results in 20 million load cycles to be applied in the test. This seems a quite adequate figure, considering that the fatigue limit of usual aluminium alloys is normally taken at 10^6 to 10^7 cycles.
  The choice of 100 cycles per flight as a whole implies that for a specific flight segment the number of cycles of a specific load type is lower, say e.g 10 gust cycles on the average per "cruise" segment.
- The number of load steps. (step width)
  In order to avoid having an excessively high number of different "loading conditions", it is advisable to restrict the number of steps.

  A reasonable number of steps is in the order of ten.

Having established the set of loading conditions to be simulated in the test block, the sequence in which these loads must be applied must be determined. Standard procedure is to apply loads on a "flight by flight" basis, whereby in each simulated flight the proper segment sequence is maintained (Take-off, initial climb, climb,cruise, etc.).
As a number of the loading conditions to be simulated occur less frequently than once per flight, it will be clear that not all "test flights" can be equally severe. The NLR procedure defines flights of different "severity", using the rationale first described in ref. 1, and based on the analysis in ref. 2, indicating that flights of different severity have load spectra with the same shape but different severity scale, see fig. 3.

In principle, the gust load conditions for each flight segment will be applied in random order. However, one aspect needs some special attention.
Gust load conditions consist of "upward gust conditions" and "downward gust conditions". The following possibilities with regard to sequencing exist:

- An upward gust condition may be followed by either an upward or a downward gust condition (half cycle unrestrained).
- An upward gust condition is always followed by a downward gust condition, which is not necessarily of the same severity (full cycle unrestrained).
- An upward gust condition is always followed by a downward gust condition of equal severity (full cycle restrained).

All three solutions are defendable; as the structural loading of e.g. wings in turbulence has the appearance of a "narrow band response", the NLR procedure selected the third option, the "full cycle restrained" sequence.

To summarize, a test load sequence has been defined, representing the loading in a "block" of say 5000 flights. The sequence consists of a series of successive loading conditions grouped in successive "test flights". A number of test flight types exist, differing in severity. Within each flight the different flight segments are simulated in their proper order. The gust loads in each segment are applied in a random order, but an upward gust condition is always followed by a downward gust condition of equal magnitude.
In a fatigue test, the sequence of this test block will be repeated, until the desired test life has been simulated.

Turbulence Model

Two essentially different descriptions of gustiness are used to define the gust loading on aircraft, namely the "discrete" gust concept and the "continuous" gust concept. The first (and oldest) one considers the turbulence encountered by aircraft as a set of separate "bumps", either upward or downward, of specific shape and magnitude. With the growing size of aircraft and the associated increasing importance of elastic response, the physical inadequacy of the discrete gust model became apparent and in the early sixties the continuous turbulence model, using Power Spectral Density (PSD-) techniques was developed.[3] PSD-design load criteria have since then been included in the airworthiness requirements for transport aircraft (FAR25 and JAR25) in addition to the discrete gust criteria.

The structural load induced by a discrete gust will depend on the shape and the length of that gust; for many years, the airworthiness requirements specified a gust length that was proportional to the size of the aircraft (25 wing chords), based on the rationale that large aircraft will be sensitive for long gusts and small aircraft for short gusts; since recently, the JAR25 even specify a "tuned" gust length, that means the gust length causing highest loads must be considered. Thus, the discrete gust loading conditions are based on a "worst case" concept: the gust shape causing highest loads must be assumed.

The Power Spectral Density model, on the other hand, considers the gustiness as a continuous stochastic process with specified statistical properties: The structural response to this turbulence as calculated using PSD-techniques is a real average response, taking into account the sensitivity to specific gust length (through the aircraft transfer function) on the one hand and the relative frequency of occurrence of these gust lengths (defined by the shape of the spectrum of turbulence) on the other.

Specifically because of this averaging character, the PSD- model is considered as better suited for defining fatigue test spectra: the fatigue test spectrum should represent all gust wave lengths rather than only the worst ones! In the following, we will briefly summarize the main elements of the PSD techniques that are relevant in the context of this paper.

- The atmospheric turbulence is a continuous Gaussian process $\underline{w}$ with PSD shape spectrum

$$\phi_w^n(\Omega) = \frac{L}{\pi} \frac{1 + \frac{8}{3}(1.339\Omega L)^2}{\left\{1 + (1.339\Omega L)^2\right\}^{11/6}} \qquad \textbf{(1)}$$

  and standard deviation σ_w.
- A load quantity y induced by this turbulence will also be a gaussian process with standard deviation σ_y.
- This standard deviation of the structural load y is related to σ_w: $\sigma_y = \bar{A}_y * \sigma_w$, where

$$\bar{A}_y = \left[\int_0^\infty |H_{yw}(j\Omega)|^2 \, \phi_w^n(\Omega) d\Omega \right]^{½} \qquad \textbf{(2)}$$

- The number of positive zero crossings of load y is given by:

$$N(0)_y = \frac{1}{2\pi} \frac{1}{\bar{A}_y} \left[\int_0^\infty \Omega^2 |H_{yw}(j\Omega)|^2 \, \phi_w^n(\Omega) d\Omega \right]^{½} \qquad \textbf{(3)}$$

- The intensity σ_w is not a constant but a stochastic variable itself. The probability density function assumed for σ_w reads:

$$p(\sigma_w) = P_1 \frac{1}{b_1} \sqrt{\frac{2}{\pi}} \exp\left(\frac{-\sigma_w^2}{2b_1^2}\right) + P_2 \frac{1}{b_2} \sqrt{\frac{2}{\pi}} \exp\left(\frac{-\sigma_w^2}{2b_2^2}\right), \qquad \textbf{(4)}$$

  where the parameters b_1, b_2 and P_1, P_2 are a function of altitude.

- Under the above assumption, the number of times per second that the load level y is exceeded while flying at a specific altitude is given by:

$$N(y) = N(0)_y \left[P_1 e^{-\frac{y}{b_1 \bar{A}_y}} + P_2 e^{-\frac{y}{b_2 \bar{A}_y}} \right] \quad \textbf{(5)}$$

Note that this equation contains <u>two</u> parameters depending on the load transfer function H_{yw}, namely $\bar{A}_y$ and $N(0)_y$.

In view of the subject discussed in the next chapter, it is necessary to also summarize some properties that are less generally known, associated with the <u>correlation</u> between different structural loads.

- Two load quantities y and z, both induced by the same random turbulence w, are correlated. The correlation coefficient ρ_{yz} may be calculated from:

$$\rho_{yz} = \frac{\int_0^\infty Re[H_{yw} \cdot H^*_{zw}]\Phi^n_w(\Omega)d\Omega}{\bar{A}_y \cdot \bar{A}_z} \quad \textbf{(6)}$$

The following relation holds: $-1 < \rho_{yz} < 1$. If $|\rho_{yz}|$ is close to one, y and z are highly correlated; if ρ_{yz} is close to zero, y and z are weakly correlated.

- In a Gaussian gust field with intensity σ_w, both y and z are Gaussian with intensities σ_y and σ_z respectively. It can be shown that <u>if</u> the load y has the value $y = k * \sigma_y$, <u>then</u> the <u>most probable</u> value for the load $z = k * \rho_{yz} * \sigma_z$ (see e.g. ref. 4).

The NLR procedure may be applied using any PSD-gust model, for example using the values for b_1, b_2 and P_1, P_2, originally derived in ref. 3 and currently included in FAR25 and JAR25. However, under contract with FAA recently a very large batch of operational c.g. acceleration data has been reanalysed and reduced to P- and b-values.
These data indicate less turbulence encounter at higher altitudes as the older data sets resulting in much lower P values, but equally severe to slightly more severe turbulence in lower regions.[5] Based on these Data, the NLR proposes the P- and b-values shown in the figures 4 and 5 and presented in table 2 for establishing fatigue load spectra.

<u>Determination of Test Load Distributions</u>

The structural loading of the test specimen for a specific gust loading condition will consist of a "basic" load distribution (the balancing load, associated with 1g steady flight) plus an incremental load due to gust. This incremental load may be described as a "Unit Incremental Load Distribution", multiplied with a "gust strength factor" fg.

For each mission segment, an Unit Incremental Load Distribution (M, T, S in each specimen section) must be determined.

The NLR procedure is based on the notion that a fatigue test can only be a simplified representation of the real environment and that it is <u>impossible</u> to simulate <u>all</u> loads in a proper manner: choices <u>must</u> be made!

We will assume that all stresses in a specific specimen section may be expressed as a linear function of the sectional loads M, T, S acting in that section: y= a*M + b*T + c*S. Usually, there will be one element in each section that can be indicated as probably the most sensitive to fatigue: the primary objective of the fatigue test must be to simulate the stress history in that element as realistically as possible. In a wing section, this is often the stress in the lower wing skin, but it could also be e.g. the shear flow in the rear spar web. This "most relevant" stress will be indicated as <u>"Master Load Quantity"</u>: its proper representation in the test is considered essential.
The combination of sectional loads M, T, S in a section must be such as to yield the proper value of the Master Load Quantity y. Taking into account the statistical nature of the PSD concept, it seems logical to associate specific values of the Master Load with those values of the sectional loads that are the "most probable" under the condition that the Master Load has that specific value. We may recall that these are the so-called "correlated loads".

The Unit Incremental Gust Load Distribution for a specific mission segment j will now be defined in the following manner:

a. For each section i, the Master Load Quantity y will be determined; the associated $\bar{A}$ value is $\bar{A}_y(i,j)$.
b. The Unit Incremental Gust Load Distribution for segment j is defined by the following M,S,T-values for each section i:

$$M = \tilde{A}_M(i,j) = \rho_{My}(i,j) * \bar{A}_M(i,j).$$
$$S = \tilde{A}_S(i,j) = \rho_{Sy}(i,j) * \bar{A}_S(i,j).$$
$$T = \tilde{A}_T(i,j) = \rho_{Ty}(i,j) * \bar{A}_T(i,j).$$

Note that the dimension of the above loads, expressed as "$\tilde{A}(i,j)$" is "Load per m/s" and the dimension of the gust strength factor fg is "m/s".

For any stress z in section i that is a linear function of M,S and T in that section, the above combination of M,S and T will give a stress z equal to $\tilde{A}(i,j)=\rho_z(i,j)*\bar{A}_z(i,j)$. As an example, table 3 presents the $\bar{A}$, ρ- and $\tilde{A}$- values for three sections of the wing of a short haul transport aircraft, pertaining to the "cruise" mission segment. The stress in the lower wing skin is taken as "Master Load Quantity".This stress is a function of bending Moment M only, hence the correlation between y and bending moment M is equal to 1. We may note that, as usual, bending moment and shear and hence master load y and shear are highly correlated, but that the correlation between bending moment and torsion is much weaker, with correlation coefficients in the order of 0.65. The reason is that high bending moments will occur when the wing bending modes are excited, while high torsion moments will occur when the wing torsion modes are excited. As the torsion modes are associated with higher frequencies, they "tune" with shorter gusts, that means with an other part of the gust spectrum. This is also reflected in the N(0)-values, that are substantially higher for the torsion moment, as shown in table 3.

Having established the Unit Incremental Gust Load Distribution, the number of variations of each load quantity must be determined. The number of load variations is proportional to N(0). In principle, the value of N(0) is different for each load quantity, as illustrated in table 3. In the NLR procedure this difference is ignored and one and the same N(0) value for all load quantities will be assumed. Usually, the value taken for this will be the N(0) of the Master Load Quantity in the section that is considered most relevant, for example the wing root section. This load quantity may be called "Head Master". For each mission segment j, the gust load exceedance curve of this Head Master Load is now divided by $\bar{A}$ of the head master, thus resulting in an exceedance curve for the gust strength factor fg. Fig. 6 shows the exceedance curve for fg pertaining to the cruise segment of our "example" short haul transport. The gust load conditions to be applied in the fatigue test are defined by the Unit Incremental Load Distribution on the one hand and the exceedance curve for fg on the other. The procedure of "stepping" the continuous exceedance curve as described in a previous chapter need only be performed on the exceedance curve of fg, to define the gust load conditions.

Discussion

In the previous chapters we briefly described various elements of the automated NLR procedure for the generation of fatigue test load sequences.
The procedure has been successfully tried out for some practical cases, including the wing and the tail structure of a short haul jet transport aircraft. The most important new elements in the procedure were the use of a PSD-based gust model and the definition of a unit load distribution on the basis of "master load quantities" per section, and the use of "most probable" or "correlated" sectional loads.

It must be realized that the applicability of the procedure as described has its limitations, largely defined by the amount of correlation between various loading components on the one hand and the degree of fatigue criticality of different structural elements on the other.

Returning to the example in the previous chapter, we may note that the torsional load that will be applied, defined by $\tilde{A}_T$, is only about 65 percent of $\bar{A}_T$ which is the desired amount of torsion if torsion would have been selected as the "Master Load Quantity". The average N(0)-value selected for our example structure is also much lower than the N(0)'s pertaining to the torsion T. In summary, we may say that the torsion moment will be "undertested" in our example.

In fact, all loads not selected as Master Loads will be undertested, the amount of undertesting depending on the correlation with the master load. This cannot be simply compensated by increasing one of the sectional loads above the "correlated" value, because this would probably result in "overtesting" of an other component.

The seriousness of undertesting a specific load depends on the question whether a specific component is "critically" loaded fatigue wise by this load. If this would be the case, e.g. if in our example wing structure a specific component would be fatigue-critical for torsional loads, our test loading would be inadequate. The solution then would be to apply additional loading conditions, whereby torsion moment (or the stress in the component critically loaded in torsion) is taken as Master Load Quantity.

It should be noted that the problem recognized above is not caused by the choice of a continuous gust model, but is associated with the flexible response properties of the structure and will also occur if a "discrete" gust model is used. If one uses a discrete gust approach, one must choose the length of the "gust bump" to be applied: a long gust will excite a bending mode and cause a high bending moment but little torsion; a short gust may give high torsional loads but relatively little bending. The ultimate solution also here would be to apply two sets of loading conditions: one associated with long gusts to test structure loaded in bending and one associated with short gusts to test structure loaded in torsion.

The procedure described is only applicable for aircraft systems with linear response behaviour to atmospheric turbulence. The way in which non linear effects must be accounted for will depend on the nature of the non-linearity. The nonlinearity due to limited maximum control surface deflection in case of gust alleviation systems will probably only be felt in very rare occasions when loads are at a high level; ignoring the nonlinear behaviour is probably on the safe side. On the other hand, load alleviation systems that only become active when the loads exceed a specific level (systems intended to reduce static design load levels) tend to have an adverse effect on fatigue life and crack growth behaviour ("truncation of high loads"). These effects should be properly accounted for!

To conclude this discussion, we may observe that, despite the availability of automated procedures for a proper determination of fatigue test loading sequences an understanding of fatigue, of aircraft loading and a sound engineering judgement will be required also in the future!

Conclusions

1. An automated procedure for the determination of fatigue test load sequences has been described.
2. This procedure makes use of a gust description on the basis of continuous turbulence.
3. A PSD-based gust model is proposed, based on statistical data recently published by FAA.
4. The procedure has been successfully applied for a short haul jet transport aircraft.
5. Understanding of the fatigue phenomenon, of aircraft loading and a sound engineering judgement will remain necessary for a proper definition of fatigue test sequences.

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Table 1 Mission segments for a short haul transport

Segment	Ave Speed (knts TAS)	Ave Alt. (ft)	Duration (min)	Distance (nm)	Ave flap (degr.)
take-off	200	750	2	6.7	18°
Climb 1	312	7500	5.6	29.1	-
Climb 2	364	18250	4.4	26.7	-
Cruise	425	23000	6.0	42.5	-
Descent 1	364	18250	4.0	24	-
Descent 2	313	7500	5.0	26	-
Appr./landing	175	750	6.0	9	30°
Total:			33.0	164	

Table 2 Proposed P- and b-values for turbulence model

- "Von Karman"-PSD function.
- L = 2500 ft for all altitudes

P-values:

- P_1: 0.5 at 0 ft, log-linearly decreasing to 9×10^{-3} at 12000 ft
  9×10^{-3} at 12000 ft, log-linearly decreasing to 1.3×10^{-3} at 30000 ft
  1.3×10^{-3} above 30,000 ft

- P_2: 4×10^{-3} at 0 ft, log-linearly decreasing to 2.3×10^{-4} at 12000 ft
  2.3×10^{-4} at 12000 ft, log-linearly decreasing to 2×10^{-4} at 30000 ft
  2×10^{-5} above 30,000 ft

b-values:

- b1: 1.55 m/s TAS for all altitudes.

- b2: 2 m/s TAS at 0 ft, linearly increasing to 2.9 m/s TAS at 20000 ft.
  2.9 m/s TAS above 20000 ft.

Table 3 Unit Incremental Gust Load Distribution for the wing of a short haul transport (Mission segment "Cruise")

Master Load quality y:

Lower wing skin stress
y = c.M for all sections

Master load y	Section I	Section II	Section III
$\bar{A}_y$ (MPa/ms^{-1}) $N(0)_y$ (m^{-1})	4.83 9.01×10^{-3}	4.80 8.78×10^{-3}	4.70 8.15×10^{-3}
Sectional Loads			
$\bar{A}_M$ (Nm/ms^{-1}) $\bar{A}_S$ (N /ms^{-1}) $\bar{A}_T$ (Nm/ms^{-1})	2.94 e + 4 5.69 e + 3 3.38 e + 3	1.59 e + 4 3.84 e + 3 1.57 e + 3	5.04 e + 3 2.04 e + 3 5.33 e + 2
ρ_{yM} (-) ρ_{yS} (-) ρ_{yT} (-)	1.00 0.982 0.712	1.00 0.992 0.627	1.00 0.989 0.597
$\tilde{A}_M$ (Nm/ms^{-1}) $\tilde{A}_S$ (N /ms^{-1}) $\tilde{A}_T$ (Nm/ms^{-1})	2.94 e + 4 5.58 e + 3 2.55 e + 3	1.59 e + 4 3.81 e + 3 9.85 e + 3	5.04 e + 3 2.02 e + 3 3.18 e + 2
$N(O)_M$ (m^{-1}) $N(O)_S$ (m^{-1}) $N(O)_T$ (m^{-1})	9.01 e - 3 8.03 e - 3 15.36 e - 3	8.78 e - 3 9.98 e - 3 17.28 e - 3	8.15 e - 3 8.05 e - 3 25.16 e - 3

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  1.3×10^{-3} above 30,000 ft

- P_2: 4×10^{-3} at 0 ft, log-linearly decreasing to 2.3×10^{-4} at 12000 ft
  2.3×10^{-4} at 12000 ft, log-linearly decreasing to 2×10^{-4} at 30000 ft
  2×10^{-5} above 30,000 ft

b-values:

- b1: 1.55 m/s TAS for all altitudes.

- b2: 2 m/s TAS at 0 ft, linearly increasing to 2.9 m/s TAS at 20000 ft.
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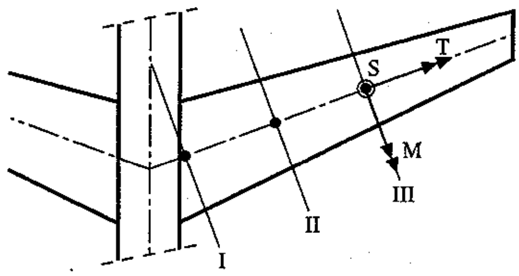

Master load y	Section I	Section II	Section III
$\bar{A}_y$ (MPa/ms^{-1})	4.83	4.80	4.70
$\bar{N}(0)_y$ (m^{-1})	9.01×10^{-3}	8.78×10^{-3}	8.15×10^{-3}
Sectional Loads			
$\bar{A}_M$ (Nm/ms^{-1})	2.94 e + 4	1.59 e + 4	5.04 e + 3
$\bar{A}_S$ (N /ms^{-1})	5.69 e + 3	3.84 e + 3	2.04 e + 3
$\bar{A}_T$ (Nm/ms^{-1})	3.38 e + 3	1.57 e + 3	5.33 e + 2
ρ_{yM} (-)	1.00	1.00	1.00
ρ_{yS} (-)	0.982	0.992	0.989
ρ_{yT} (-)	0.712	0.627	0.597
$\tilde{A}_M$ (Nm/ms^{-1})	2.94 e + 4	1.59 e + 4	5.04 e + 3
$\tilde{A}_S$ (N /ms^{-1})	5.58 e + 3	3.81 e + 3	2.02 e + 3
$\tilde{A}_T$ (Nm/ms^{-1})	2.55 e + 3	9.85 e + 3	3.18 e + 2
$N(O)_M$ (m^{-1})	9.01 e - 3	8.78 e - 3	8.15 e - 3
$N(O)_S$ (m^{-1})	8.03 e - 3	9.98 e - 3	8.05 e - 3
$N(O)_T$ (m^{-1})	15.36 e - 3	17.28 e - 3	25.16 e - 3

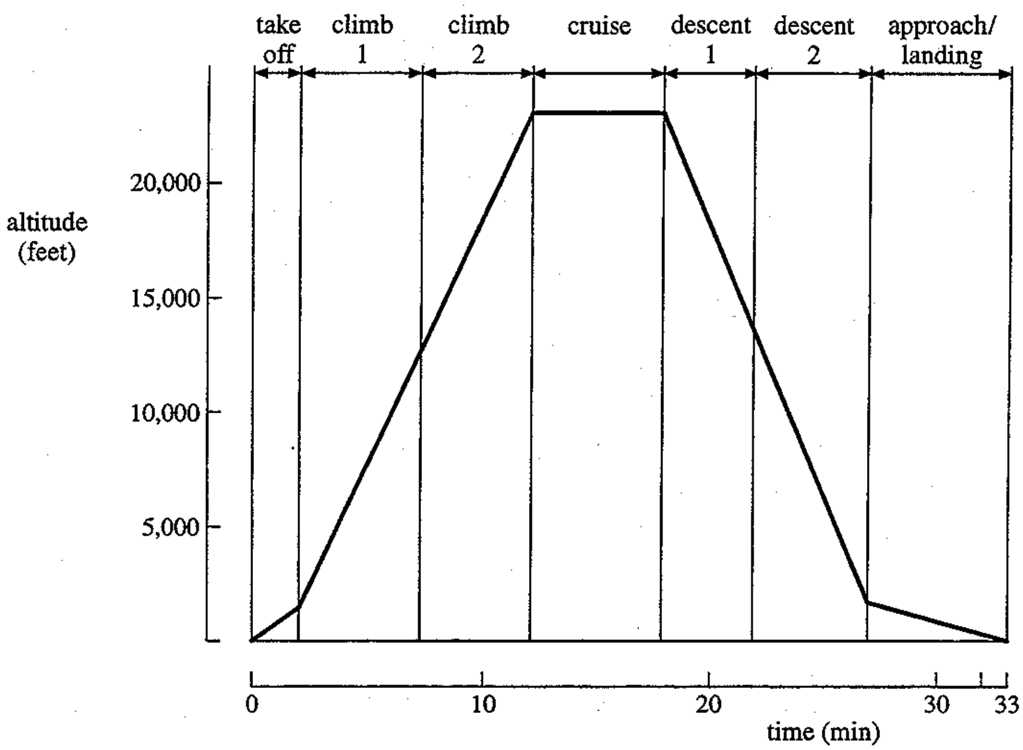

Fig. 1 Mission profile and segments for a short haul transport

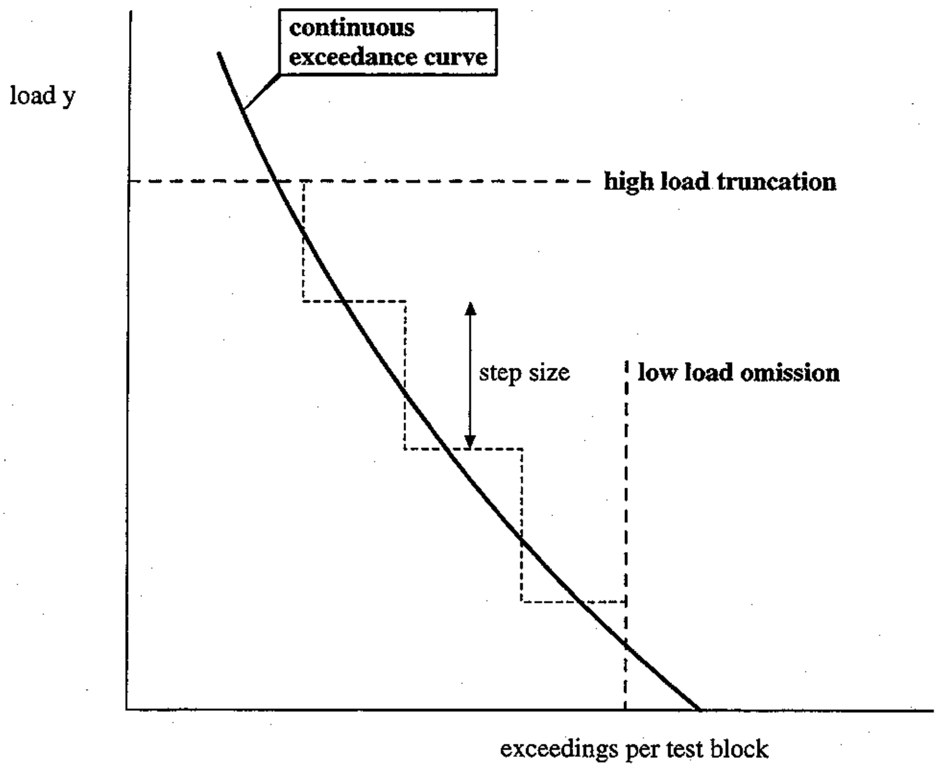

Fig. 2 Stepping of a continuous exceedance curve

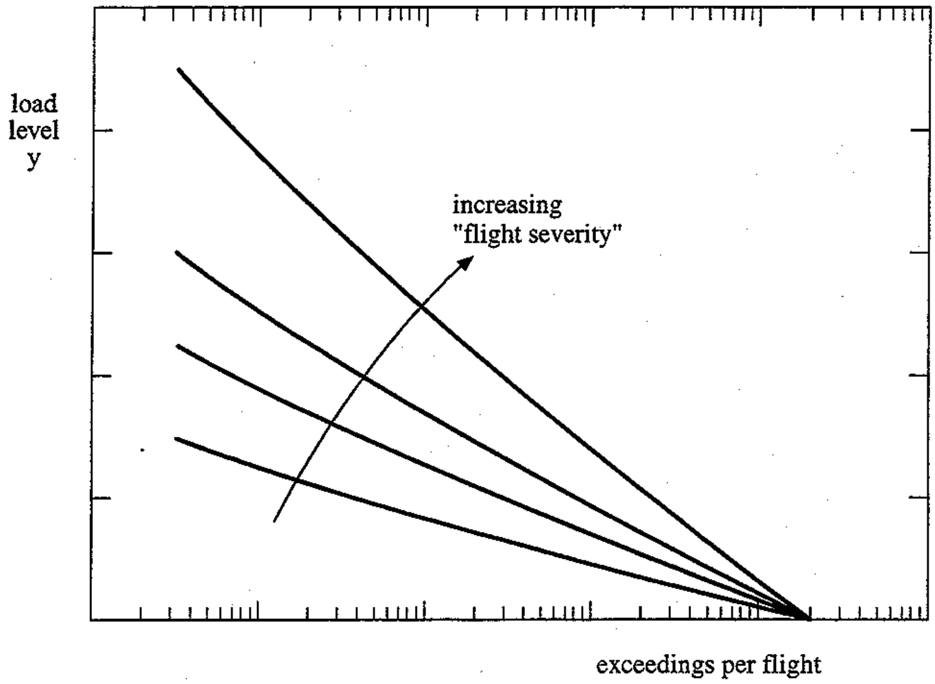

Fig. 3 Flight load spectra with equal shape but different severity

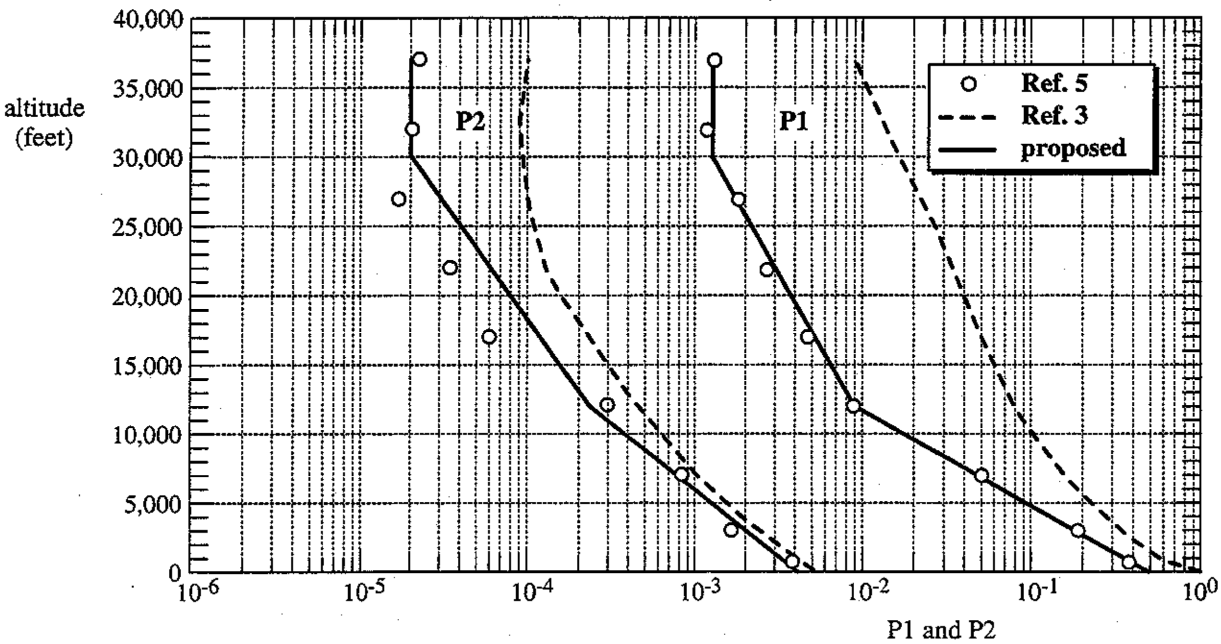

Fig. 4 Proposed P-values for turbulence model

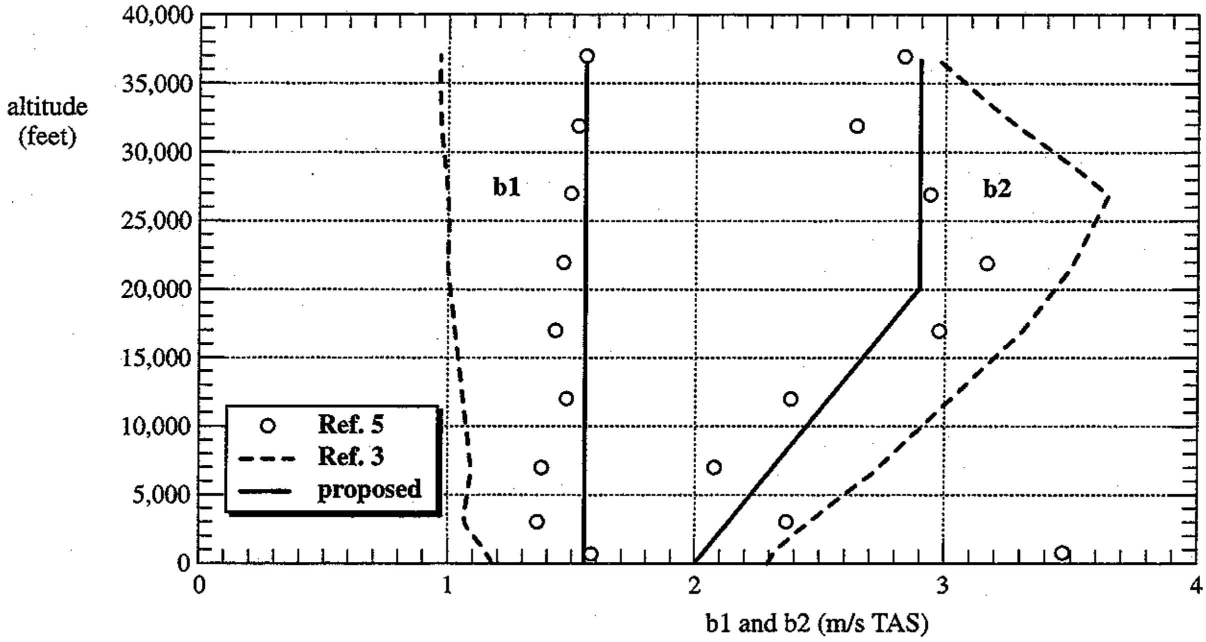

Fig. 5 Proposed b-values for turbulence model

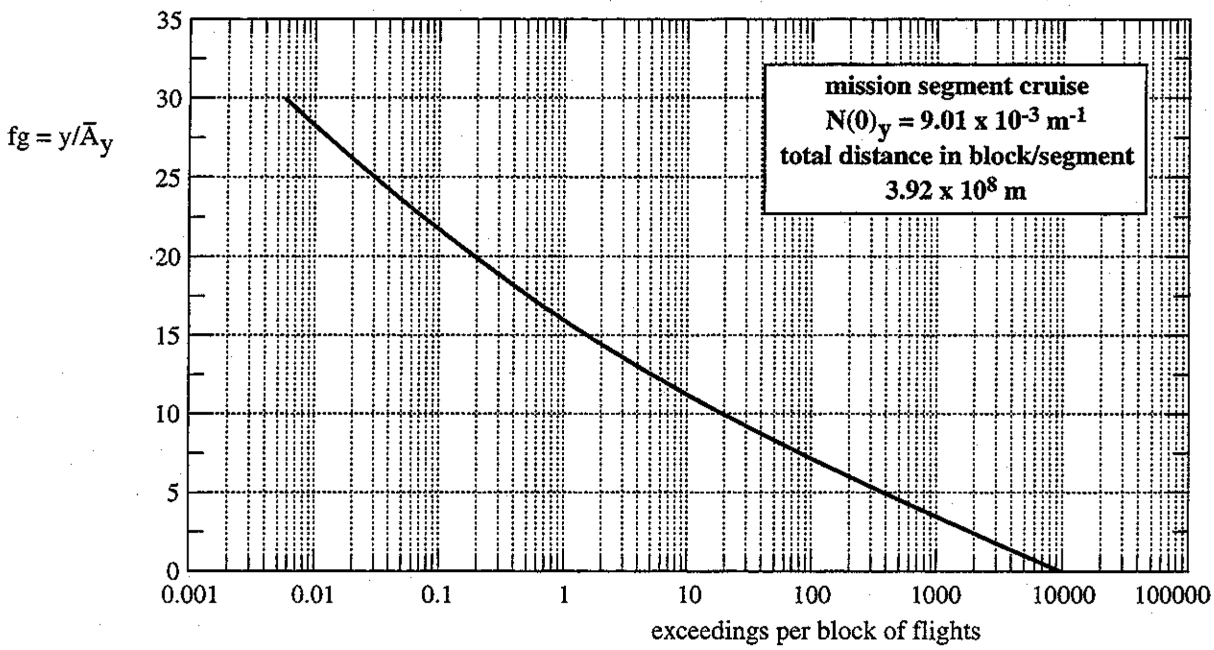

Fig. 6 Exceedance curve for gust strength factor fg