NLR TP 89097 U

NATIONAAL LUCHT- EN RUIMTEVAARTLABORATORIUM

NATIONAL AEROSPACE LABORATORY NLR

THE NETHERLANDS

NLR TP 89097 U

ASSESSMENT OF SERVICE LOAD EXPERIENCE

by

J.B. de Jonge

NLR TECHNICAL PUBLICATION

TP 89097 U

12th PLANTEMA MEMORIAL LECTURE
ASSESSMENT OF SERVICE LOAD EXPERIENCE

by

J.B. de Jonge

This paper has been prepared for presentation at the 15th ICAF Symposium, Jerusalem, June 1989

(44 pages in total)

Division: Structures and Materials
Prepared: JBdJ/
Approved: JBdJ/

Completed : 890310
Ordernumber: 541.201
Typ. : AdV

12th Plantema Memorial Lecture

ASSESSMENT OF SERVICE LOAD EXPERIENCE

J.B. de Jonge

The paper starts with a review of the various types of loading acting on the aircraft structure and our ability to accurately predict their magnitude and frequency of occurrence for a given aircraft usage.
Next, attention is paid to the variation in load experience and its causes, with specific reference to the variation in aircraft usage. For transport type aircraft these variations are largely defined by the variation in flight length and payload. For combat type aircraft, on the other hand, the variability is considerably larger and consequently the prediction of load spectra considerably more difficult.
For the assessment of actual service load spectra, operational flight load measurements and/or service usage monitoring are required. The rapid development of electronics during the last decades has opened the possibility for advanced processor based service fatigue load monitoring systems at relatively low price. However, it will be argued that specifically for transport aircraft simple usage monitoring may already provide highly relevant information.

For combat type aircraft, the determination of average "mission type" spectra from in flight multiparameter recordings, in combination with mission usage monitoring for individual airplane tracking appears to be an adequate solution.

FOREWORD

Nearly thirty years ago I left the playgrounds of Delft University to enter into my first (and so far last) job as a young engineer in the Structures and Materials Division of what was then called the National Aeronautical Research Institute NLL, led by Dr. F.J. Plantema. Dr. Plantema was a quiet, modest person with a brilliant scientific mind and he was a very good chief. He paid much attention to the labours of his young co-workers. His well-founded criticism of their writings was always constructive, and his advice was positive and helpful. During the six years that I worked under his leadership until his early death in 1966, I learned a lot from him and I can say I owe him a great deal.

Therefore, it is for me not only a great honour but a sincere pleasure to present this paper in commemoration of Dr. Plantema, the founder of ICAF.

INTRODUCTION

As described by John Mann in the 9th Plantema Memorial lecture (Ref. 1) fatigue has been with Aviation starting from the first flight of the Wright flyer in 1903.

Since then, our knowledge and understanding of the fatigue phenomenon has greatly improved. We are able to design and build reliable structure that can withstand the expected spectrum of loads. However, the accuracy of fatigue performance predictions depends directly on the accuracy with which the loading environment has been predicted.

Service failures which are unexpected or which occur much earlier than expected often turn out to be due to unpredicted or unexpectedly severe service loads.

This may have two different reasons: the load experience for a given aircraft usage may be different or the aircraft usage, the way in which it is operated is different from what was expected.

This paper will start with the first aspect. A brief review will be given of the various types of loading acting on the aircraft structure and our ability to accurately predict their magnitude and frequency of occurrence for a given aircraft usage.

Next, the other aspect namely the variation in operational usage will be discussed. Specific attention will be paid to the differences in usage between different operators, and the changes in usage with time.
These variations turn out to be appreciable, both for civil transport as well as for combat aircraft, indicating the desirability of service load monitoring.
In the last chapter, various aspects of service load monitoring will be discussed. Such monitoring is generally accepted for military aircraft but has found very little systematic civil application.

The hope is expressed that this paper may contribute to a better appreciation of service load monitoring in civil aviation.

THE PREDICTION OF LOADS FOR A GIVEN USAGE

As said in the introduction, the loading experienced in service can differ from the assumed design spectra either because the aircraft is used in a different way or because the loading associated with the assumed usage is different. In this chapter we will review the latter aspect: how good are our predictions of the fatigue loading for various aircraft components for a given usage. In this review, as in this paper in general, we will restrict ourselves to two general types of aircraft namely the civil transport aircraft and the military combat aircraft respectively.

The design usage of the transport aircraft is defined by one or a mixture of more than one "design missions", each with a specific "mission profile", see e.g. figure 1.

As the task of a transport airplane is to move goods or people from A to B, such a "mission profile" is usually quite straightforward. The main variables are stretch length and pay load; all other parameters like climb and descent speed, cruise altitude and cruise speed and flap position are more or less defined by the aircraft performance characteristics.

Figure 2 gives a schematic representation of the loading history during one flight.

In our discussion of the various loading actions we will distinguish three "categories" of loads namely:
- Deterministic loads.
- Loads of a stochastic nature.
- Poorly predictable or unforeseen loads.

Deterministic loads are e.g.:
- steady state (n_z=1) loads in flight and on the ground,
- cabin pressurization load,
- loads on flaps and slats in take-off and descent,
- specific manoeuvres like rotation in take-off and flare before touchdown, causing relevant loads on the horizontal tail.

The magnitude of these deterministic loads is well predictable in a design phase, provided adequate windtunnel data are available. It should be realized that the variation in steady state loading per flight, indicated as Ground-Air-Ground Cycle, constitutes a main load cycle for the wing as well as for the horizontal tail. Also, the cabin pressurization cycle determines the fatigue loading of major parts of the fuselage.

Loads of a stochastic nature are:
- gust loads,
- manoeuvres,
- ground loads like taxiing etc,

their magnitude and frequency can only be predicted in a probabilistic sense, on the basis of statistical data.

For transport aircraft, gust loads are undoubtedly the most important.
We will have to distinguish between vertical gusts and lateral gust loads.

A relatively large amount of statistical data with regard to vertical gusts is available in the format of c.g. vertical acceleration data (Δn_z), obtained during routine commercial aircraft operation. Reference is made to the VGH-recordings and V.G.-records obtained by NACA, the RAE fatigue meter data and e.g. recent 747 ACMS data gathered by NLR (Ref. 3).

Recorded acceleration peaks were reduced to "derived gust velocities" U_{de} assuming a discrete gust of specific shape and length [e.g. a "1-cos" shape of 25 chords], or, more recently to "PSD-gust velocities" U_σ, on the basis of a continuous gustfield representation (see e.g. Ref. 4).

The resulting gust-exceedance curves as a function of altitude (see e.g. Fig. 3) are used in design to calculate gust load spectra.

The Δn_z spectra calculated using these data for a certain usage can be compared with measured acceleration data.

Figure 4 presents a typical result. C.g. acceleration spectra for the Boeiing 747 recorded with the ACMS system are compared with the spectra calculated using the gust data presented in NACA TN 4332 (Ref. 5) for the actual aircraft mission profile. The measured acceleration spectra are less severe or, in other words, the gust data presented in NACA TN4332 are conservative. This same trend towards conservatism has also been observed when using gust statistics presented in ESDU data sheets.

Reasons for this conservatism are:

- As shown by Card (Ref. 7), in the reduction of the NACA VGH.data in the early fifties, the response of the measuring aircraft was underestimated; this resulted in overestimated and hence conservative "derived gust velocity" statistics.
- Currently weather forecasts are more reliable than 40 years ago; today aircraft will be more successful in avoiding severe turbulence and hence will be subjected less frequently to turbulence than predicted on the basis of measurements made 40 years ago.

The fact that the predicted Δn_z spectrum due to vertical gusts is conservative does not automatically imply that the gust-induced loadspectra for the various structural components are also conservative.

The calculated structural load due to vertical gusts depends on the assumed gust model on the one hand and the assumed aircraft response characteristics on the other.

Figure 5 shows calculated structural loads "per g" due to gust for an aircraft model with different degrees of refinement, based on a discrete gust response calculation and a PSD-gust response calculation respectively (Ref. 8).

In the first place it may be noted that the loads obtained on a PSD-basis were always lower than those found using a discrete gust.

Inclusion of pitch freedom leads to a reduction in "load per g", specifically for the Stabilizer Bending Moment. Inclusion of flexibility resulted in higher loads in the Discrete Gust case, but to little or no increase in the PSD case. (It should be recalled that the above refers to the incremental structural loads "per g"; the load factor response itself, that is the "Δn_z per unit gust velocity" or, in the PSD case, $\bar{A}\Delta n_z$, decreases considerably due to elasticity for a swept wing aircraft like the one considered).

If we assume, in accordance with the author's opinion, that the PSD result for the fully flexible aircraft best represents the "truth", the figure 5 suggests that if the Δn_z spectrum is conservative, the structural load spectrum for wing and tail is also conservative, independent of the assumptions made by the designer with regard to gust and response-properties.

Lateral gusts are predominantly loading the empennage. Hardly any statistical data on lateral loads exist. Usually the vertical gust data are also used to calculate lateral gust loads. Again, the results obtained will depend on the assumed gust model and the aircraft response characteristics.

It may be noted that the simple "Pratt-type" expression for the vertical tail load L_t, given e.g. in FAR 25.351(b):

$$L_t = \frac{K_g\, U_{de} \cdot V \cdot a_t\, S_t}{498}$$

is based on a response calculation under the following assumptions:
- o the lateral gust U_{de} has a "1-cos" shape with a length of 25 vertical tail chords,
- o the airplane responds only in rotation around its top-axis (no side-ways motion, no elastic response, no rolling).

FAR 25.351(b) specifies that for static design loads the above expression <u>must</u> be used in the absence of a rational investigation. Probably, the above formula is quite often used by aircraft manufacturers to determine tailload spectra, which are then probably of a conservative nature. Again however, this possible conservatism has not been substantiated by long term flight load measurements.

Lateral gusts are of specific interest for tails in T-configuration because of the induced asymmetric loading of the stabilizer, see figure 6(a).

The induced asymmetric stabilizer load is quite substantial and causes major loads at the lugs attaching the stabilizer to the vertical tail (Fig. 6(b)). The induced bending moment at the stabilizer root due to a 50 fps lateral gust is typically of the same order of magnitude as the one due to a 50 fps vertical gust. With regard to static strength, the possible criticality of combinations of vertical and lateral gust have generally been recognized. The JAR-25 requirements include a so-called "Round-the Clock" gust case for the empennage structure (JAR-25.427(b)(3)).

For defining fatigue load spectra, the author is unaware of any generally accepted procedure. In full scale fatigue tests, the lateral gust and vertical gust load conditions appear to be usually applied separately: it should be realized that fatigue wise the simultaneous application of the lateral and vertical gust would mean a more severe loading of the stabilizer (see Fig. 6(c)).

Manoeuvres can be devided in symmetric manoeuvres (turns and pitching) and antisymmetric manoeuvres (yaw and roll). Symmetric manoeuvres result in load factor changes. A "typical" turning manoeuvre with 30 degrees bank angle results in an incremental load factor $\Delta n_z = 0.155$. Pitching manoeuvres can be associated with either positive (pull up) or negative (push down) Δn_z'S.

Statistical data on manoeuvre loads for transport aircraft are scarce and sometimes contradictory. Figure 7, derived from VGH-data, indicates manoeuvre loads to be comparable with gust loads in severity and, perhaps even more surprising, the "downward" manoeuvres spectrum to be nearly as severe as the upward part. Other sources indicate the contribution of manoeuvres to the Δn_z spectrum to be neglible in comparison with gusts.

Figure 7 suggests that loads due to gusts and due to manoeuvres can always be separated. In actual fact, these loads will often come together. Here, we can distinguish two different situations.

a In turbulent conditions, corrective manoeuvres involving both elevator an aileron deflections will be made to restore the aircraft attitude. We may consider this condition as a manoeuvre superimposed on a gust load. This manoeuvre may go without a noticeable Δn_z response, but can impose an additional load cycle on the control surface and tail plane.

probably of a conservative nature. Again however, this possible conservatism has not been substantiated by long term flight load measurements.

Lateral gusts are of specific interest for tails in T-configuration because of the induced asymmetric loading of the stabilizer, see figure 6(a).

The induced asymmetric stabilizer load is quite substantial and causes major loads at the lugs attaching the stabilizer to the vertical tail (Fig. 6(b)). The induced bending moment at the stabilizer root due to a 50 fps lateral gust is typically of the same order of magnitude as the one due to a 50 fps vertical gust. With regard to static strength, the possible criticality of combinations of vertical and lateral gust have generally been recognized. The JAR-25 requirements include a so-called "Round-the Clock" gust case for the empennage structure (JAR-25.427(b)(3)).

For defining fatigue load spectra, the author is unaware of any generally accepted procedure. In full scale fatigue tests, the lateral gust and vertical gust load conditions appear to be usually applied separately: it should be realized that fatigue wise the simultaneous application of the lateral and vertical gust would mean a more severe loading of the stabilizer (see Fig. 6(c)).

Manoeuvres can be devided in symmetric manoeuvres (turns and pitching) and antisymmetric manoeuvres (yaw and roll). Symmetric manoeuvres result in load factor changes. A "typical" turning manoeuvre with 30 degrees bank angle results in an incremental load factor $\Delta n_z = 0.155$. Pitching manoeuvres can be associated with either positive (pull up) or negative (push down) Δn_z'S.

Statistical data on manoeuvre loads for transport aircraft are scarce and sometimes contradictory. Figure 7, derived from VGH-data, indicates manoeuvre loads to be comparable with gust loads in severity and, perhaps even more surprising, the "downward" manoeuvres spectrum to be nearly as severe as the upward part. Other sources indicate the contribution of manoeuvres to the Δn_z spectrum to be neglible in comparison with gusts.

Figure 7 suggests that loads due to gusts and due to manoeuvres can always be separated. In actual fact, these loads will often come together. Here, we can distinguish two different situations.

a In turbulent conditions, corrective manoeuvres involving both elevator and aileron deflections will be made to restore the aircraft attitude. We may consider this condition as a manoeuvre superimposed on a gust load. This manoeuvre may go without a noticeable Δn_z response, but can impose an additional load cycle on the control surface and tail plane.

b Gust load may occur while the aircraft is carying out a steady turning manoeuvre. This situation can occur for example when the airplane is flying in a "holding" circuit at relatively low altitude. Here, gust loads are superimposed on a manoeuvre condition. Fatigue wise, the effect will be that the stress cycles due to gust will get a higher "mean " stress.

Proof for this latter superposition effect is presented in figure 8, showing 747 acceleration spectra "as recorded" plus spectra "corrected" for turning manoeuvre contributions.
Recorded acceleration peaks Δn_z were corrected according to:
$\Delta n_{z corr} = \Delta n_z - [(\cos \phi)^{-1} - 1]$ where ϕ is the bank angle at the time of the Δn_z-peak.

Looking at the positions of the squares and triangles it may be noted that the corrected spectrum is practically symmetric and that in the negative part of the spectrum the squares are positioned on the right side of the corresponding triangles: hence the negative part of the spectrum has become more severe.

With regard to asymmetric manoeuvres, again little or no service load statistics are available. Probably the most important loadings are associated with crosswind correction during take-off and landing and "decrabbing" just before landing.
Usually, manufacturers include conservatively assumed rudderloads in tail fatigue spectra. It may be noted that for t-tails rudder-loads also induce asymmetric stabiliser loads.

Summarizing our review of the stochastic flight loads we conclude that probably the prediction of wing loads is reasonably accurate but that the loading of the tailstructure includes a considerable amount of uncertainty.

Probably, the procedures applied by airplane designers lead to conservative tail load spectra but no long term service load measurements are available, at least in the open literature, to substantiate this.

For this reason, the Netherlands Aerospace Development Board contracted NLR to carry out a service-tail load recording programme. In this programme in which the Fokker company and KLM give important assistance measurements will be carried out during commercial operation of a Fokker F-100 over a period of at least one year. The tail load information, stored on a 4-channel "Spectrapot" recorder are complemented with flight profile data available from the standard ACMS system (Fig. 9).

It is hoped that this example of our possibilities for fatigue load measurements in this Electronic Era will be followed by others!.

Ground loads are obviously of predominant importance for the landing gear. Restricting ourselves in this paper to the airframe we should note that for the wing structure taxi loads usually determine the lowest load obtained in each flight and thus the size of the G.A.G.-cycle.

In the case of long slender fuselages, where fuselage bending may cause important fatigue stresses in certain areas one should note that taxi-load cycles, with a "typical" amplitude of $\Delta n_z = 0.3$ being exceeded once per flight are comparable with gusts in importance.

Fortunately, a reasonable amount of ground load data has become available. As an example of recent load measurements, the Airbus-data presented by Buxbaum (Ref. 10) should be recalled.

In general it is the authors impression that sufficient data is available to allow a reasonably accurate prediction of ground load spectra, in any case in so far as the airframe is concerned.

Poorly predictable in a quantitative sense during design are loads of a dynamic nature, involving structural resonance, like acoustic loads and buffeting. With regard to accoustic loads we should realize that an accuracy of 3dB in predicting sound pressure levels is generally considered as partly good. In terms of fatigue, however, 3dB may mean a difference from a few hours to infinite fatigue life.

Sometimes, dynamic loads occur that were fully unpredicted in the design phase.

For example the jet flow of the Fokker 100 turned out to contain a frequency component just coinciding with a resonance frequency of the empennage. Under certain conditions, application of the jet reverser after landing turned out to cause an important dynamic loading of the tailstructure.

For a qualitative and quantitative assessment of these dynamic loads flight tests with a properly instrumented prototype covering all conditions within the flight envelope as part of the certification programme are indispensable (see e.g. Ref. 11). If these flight tests are done and analysed properly, however, it is felt that the dynamic load spectra for a given operation can be predicted with fair accuracy.

We will now turn our attention to the Military Combat Aircraft

Also for fighter aircraft, a design usage is defined by means of a mixture of different missions, each with a specific mission profile. Contrary to transport aircraft, however, these mission

Ground loads are obviously of predominant importance for the landing gear. Restricting ourselves in this paper to the airframe we should note that for the wing structure taxi loads usually determine the lowest load obtained in each flight and thus the size of the G.A.G.-cycle.

In the case of long slender fuselages, where fuselage bending may cause important fatigue stresses in certain areas one should note that taxi-load cycles, with a "typical" amplitude of $\Delta n_z = 0.3$ being exceeded once per flight are comparable with gusts in importance.

Fortunately, a reasonable amount of ground load data has become available. As an example of recent load measurements, the Airbus-data presented by Buxbaum (Ref. 10) should be recalled.

In general it is the authors impression that sufficient data is available to allow a reasonably accurate prediction of ground load spectra, in any case in so far as the airframe is concerned.

Poorly predictable in a quantitative sense during design are loads of a dynamic nature, involving structural resonance, like acoustic loads and buffeting. With regard to accoustic loads we should realize that an accuracy of 3dB in predicting sound pressure levels is generally considered as pretty good. In terms of fatigue, however, 3dB may mean a difference from a few hours to infinite fatigue life.

Sometimes, dynamic loads occur that were fully unpredicted in the design phase.

For example the jet flow of the Fokker 100 turned out to contain a frequency component just coinciding with a resonance frequency of the empennage. Under certain conditions, application of the jet reverser after landing turned out to cause an important dynamic loading of the tailstructure.

For a qualitative and quantitative assessment of these dynamic loads flight tests with a properly instrumented prototype covering all conditions within the flight envelope as part of the certification programme are indispensable (see e.g. Ref. 11). If these flight tests are done and analysed properly, however, it is felt that the dynamic load spectra for a given operation can be predicted with fair accuracy.

We will now turn our attention to the Military Combat Aircraft

Also for fighter aircraft, a design usage is defined by means of a mixture of different missions, each with a specific mission profile. Contrary to transport aircraft, however, these mission

profiles are usually not simple and "straightforward" at all. Due to the usual "Multi Rôle Capability" of modern combat aircraft, the various missions may be very different with regard to mission content, take off store configuration etc.
Figure 10, reproduced from reference 12, presents as example the design profile for an Air-Combat mission, together with the main flight parameters for the various "mission segments".

The "main event" in this mission is obviously the Air-Combat segment, covering 17.9 % of the total mission time.

The values of 30.000 ft altitude and Ma 0.75 speed for this segment are obviously "mean" values: during the Air-Combat period tremendous variations in altitude and speed are expected to occur.

Manoeuvre loads are by far the most important contributions to fatigue damage for combat aircraft.
Manoeuvre load statistics, in the format of load factor exceedance curves per mission segment type (see e.g. Tab. 1) are available from measurements on previous aircraft types. However, such information is almost by definition not fully applicable for a new aircraft: the manoeuvre load spectra will depend on the aircraft performance characteristics and manoeuvrability, and one must expect the new design to have a "better" performance than previous ones!

Obviously, the load factor alone does not fully define the structural loading in a manoeuvre. Assumptions must be made with regard to manoeuvre build-up (control-time functions) and simultaneous asymmetric loading components ("rolling pull out" e.g.). A recent workshop of the AGARD Structures and Materials Panel was devoted to the difficulties in defining realistic static design loads conditions for advanced fighters (Ref. 13). There is no doubt that defining realistic manoeuvre load spectra for such aircraft in a design stage is at least as difficult.

With regard to the prediction of structural loads associated with specified manoeuvres it must be noted that the often very slender wing structures will show considerable deformation under load, influencing the load distributions and leading to nonlinear variations of load with g (Ref. 14).
Also, combat aircraft are operated at the boundaries of their flight envelope, where the occurrance of buffet loading is inevitable (Ref. 14). As said previously such loading is difficult to predict.
As a consequence, a complete flight load survey with a fully instrumented proto-type aircraft to check the structural loads within the operational envelope is undoubtedly indispensable.
In summary, we may say that accurate predictions of service load spectrum in the design stap is difficult as the actual manoeuvre load experience will depend on the flight performance of the new

profiles are usually not simple and "straightforward" at all. Due to the usual "Multi Rôle Capability" of modern combat aircraft, the various missions may be very different with regard to mission content, take off store configuration etc.
Figure 10, reproduced from reference 12, presents as example the design profile for an Air-Combat mission, together with the main flight parameters for the various "mission segments".

The "main event" in this mission is obviously the Air-Combat segment, covering 17.9 % of the total mission time.

The values of 30.000 ft altitude and Ma 0.75 speed for this segment are obviously "mean" values: during the Air-Combat period tremendous variations in altitude and speed are expected to occur.

Manoeuvre loads are by far the most important contributions to fatigue damage for combat aircraft.
Manoeuvre load statistics, in the format of load factor exceedance curves per mission segment type (see e.g. Tab. 1) are available from measurements on previous aircraft types. However, such information is almost by definition not fully applicable for a new aircraft: the manoeuvre load spectra will depend on the aircraft performance characteristics and manoeuvrability, and one must expect the new design to have a "better" performance than previous ones!

Obviously, the load factor alone does not fully define the structural loading in a manoeuvre. Assumptions must be made with regard to manoeuvre build-up (control-time functions) and simultaneous asymmetric loading components ("rolling pull out" e.g.). A recent workshop of the AGARD Structures and Materials Panel was devoted to the difficulties in defining realistic static design loads conditions for advanced fighters (Ref. 13). There is no doubt that defining realistic manoeuvre load spectra for such aircraft in a design stage is at least as difficult.

With regard to the prediction of structural loads associated with specified manoeuvres it must be noted that the often very slender wing structures will show considerable deformation under load, influencing the load distributions and leading to nonlinear variations of load with g (Ref. 14).
Also, combat aircraft are operated at the boundaries of their flight envelope, where the occurrance of buffet loading is inevitable (Ref. 14). As said previously such loading is difficult to predict.
As a consequence, a complete flight load survey with a fully instrumented proto-type aircraft to check the structural loads within the operational envelope is undoubtedly indispensable.
In summary, we may say that accurate predictions of service load spectrum in the design step is difficult as the actual manoeuvre load experience will depend on the flight performance of the new

aircraft and the way in which "real" operational pilots make use of this performance. Flight load verification is indispensable.

The main conclusions of this chapter are that for transport aircraft means are available to make reasonably accurate predictions of the fatigue loading associated with a given utilization. An exception must be made for tail structures, especially in T-configuration. Long term measurements to substantiate tail-load spectra should be promoted.

For combat aircraft, on the other hand, the accuracy of fatigue load spectra prediction is much more questionable.

This is due to the complexity of the military mission on the one hand and on the other the fact that the manoeuvre load experience depends on the performance characteristics of the aircraft and the way operational pilots will use this performance.

VARIATIONS IN OPERATIONAL USAGE

The "design usage" of an aircraft usually represents an expected "average" usage or an estimated relatively severe usage. The actual usage may show considerable variations from operator to operator depending on the network served, or, for combat aircraft, the rôle they are used for. Also, the utilization by a specific operator may change with time for various reasons.

In the following, we will try to quantitatively review the amount of variation observed in practice, again for transport aircraft on the one hand and combat airplanes on the other.

Transport aircraft are usually designed or at least optimized for a specific stage length, ranging from the short haul to the typical long distance mission. Yet, considerable differences in usage of the same aircraft type between different operators are observed.

Figure 11 shows average flight times recorded for different operators of the F-28 short haul transport aircraft. A factor 3 difference in flight time between the "shortest" and the "longest" operator may be noted. (For the F-28, a conservative design mission of 30 min. duration has been assumed). The relatively large variation in usage between the different F-28 operators and the conservatism of the design assumptions is also reflected in the result of the fatigue meter readings shown in figure 12 (Ref. 16).

Another example relates to the Boeiing 747 as typical long range aircraft.

Figure 13 shows the design usage, consisting of a mixture of 3 commercial flights with 1 hour, 3 hours and 7 hours duration respectively plus a training flight. The "overall" flight time average is 3.03 hours.

During the last decade, usage statistics for 747, operated by KLM, Swissair and SAS have been obtained from ACMS-recorded data (Ref. 18, 6).

Fig 14 shows the recorded flighttime distributions for Swissair and KLM respectively. The "overall" averages for both companies are 4.93 hours for KLM and 5.10 hours for Swissair respectively and hence nearly the same and considerably longer than the design value of 3.03 hours.
Looking more closely at figure 14, important differences in utilisation between the two operators may be observed.

The KLM fleet consists of "full pax" (purely passengers) and "Combi" (passengers plus freight) aircraft. The KLM-network includes the transatlantic stretch plus flights to the middle and far east, resulting in a wide band of flight lengths. The "combi" is predominantly used on the long transatlantic route, resulting in an average flight time of 5.71 hours, compared to 4.5 hours for the full Pax aircraft.

The recorded average landing weight of the full pax aircraft was 219.5 tons and for the Combi aircraft 231.0 tons, while the design value is 233 tons. Thus, nominally the same aircraft within one operators fleet may have a noticeably different usage.

Swissair's aircrafts are nearly solely used on the stretch from Zürich to New Yorks and back, but in a certain percentage of flights a stop at Geneva is made, resulting in a considerable batch of short flights (appr. 25 min.) between Geneva and Zürich.

Figure 15 shows the distribution of recorded maximum cabin pressure differentials for the two airlines. We may note that in nearly all flights the actual maximum cabine pressure remained well below the design value of 9.0 PSI. In the short duration flights of Swissair the altitude remains low. Hence, in 30 percent of Swissair flights the cabin pressure differential remains below 8.2 PSI.

The usage of transport aircraft has often changed in the past over longer periods of time towards shorter flight durations: many of us will remember how e.g. early DC.8 aircraft, originally used on long distances were eventually only used on relatively short stretches because of the high fuel consumption of their engines. But also over shorter periods usage may change, due to changes in an operators network or introduction of other aircraft.
Figure 16 shows recorded variations in average flight durations over a period of 5 years for KLM and Swissair 747. The Swissair

average remained virtually constant, but the KLM averages did show considerable variations.

Turning now our attention to the combat aircraft, we will see that the variability in load experience in this category is even larger than for transport aircraft. Firstly, the multirôle capability of modern combat aircraft leads to a utilization by different operators (different air forces or different units within one air force) in different rôles and associated mission mixtures.

This rôle may change with time due to increased emphasis on a specific task.

Secondly, the "mission content" changes with time due to changes in flying procedures, manoeuvring patterns etc., quite often associated with changes in "threat".

Utilization appears to tend to become more severe: in the authors experience, design load spectra for combat aircraft have always been too optimistic and the aircraft always remained longer in service than expected, invariably leading to some fatigue problem and some Service Life Extension program being set-up during the aircraft lifetime.
To get a quantitative insight into the amount of loading variability of fighters we will consider some results of a recent analysis of available load data of Lockheed F-104 G aircraft operated by the Royal Netherlands Airforce (Ref. 19). The available data included c.g. acceleration recordings plus detailed mission information (mission type, configuration, T.O. weight etc.) of about 10000 flights.

Although the F-104 G does not have the agility of more recent fighter designs it is felt that the results of the analysis are representative for fighter operations in general.

The RNLAF used the F-104 G in three duties namely "Strike", "Air Defense" and "Recce". Average load factor spectra, pertaining to the 1972-1981 period, are shown in figure 17. The load factor spectrum of Air Defense is the most severe, but many A/A flights were carried out in a "clean" configuration, associated with low "stress per g" values, resulting in more severe wing stress spectra for the strike duty.

For each recorded flight, a "Load Severity"-value (LSF) was calculated, by

- o conversion of recorded acceleration spectra to stress-spectra.
- o Adoption of a representative K_t-value and associated S-n curve.
- o A damage calculation based on Miner's rule.

Figure 18 presents the average annual Load Severity over the 72-'81 period for the three duties. The Load Severity is expressed on a relative basis with LSF = 1 referring to a "fleet average" determined in an earlier Load Survey programme carried out in 1968.

Figure 18 shows a large difference in load Severity between de different duties: e.g. the "Recce"-flights are on the average more than two times less severe than strike-flights.

In addition, the continuous increase in Load Severity with time should be noted: in 1981 the fleet average was about 2.4 times higher than in 1968. It is interesting to know that the Load Severity recorded in 1968 was already considerably higher than the "original" design load spectra for the F-104 aircraft.

The variation in Load Severity between the different duties is caused by the different mission mixture. Table 2 gives the mission mixture for the "strike"-duty, with the LSF-values for the respective mission types.
Note a variation in average LSF between .580 for Night Flying and 4.139 for Air to Ground. The average LSF's for comparable missions of the different duties were approximately equal.
This does not mean, however, that the variation in Load Severity between different flights of the same mission type is small. In reference 19 the scatter in load experience between flights of the same mission type was extensively studied.
In general the scatter appeared to be the largest for relatively light mission types.
In all cases, the observed severities of flights of one mission type could be well approximated by a Weibull distribution

$$P(Z) = 1 - \exp \{(\frac{z}{z_a})^b\}$$

where z is the Load Severity of a flight and z_a are the socalled width parameter and b the socalled shape parameter of the Weibull distribution respectively. The value of the shape parameter varied from 0.6 for "light" missions to up to 1.4 for severe missions.

Figure 19 gives an example of an obtained data fit, for a relatively severe mission type with a high value of the shape parameter b (meaning small scatter).

It may be noted that even for this mission type with relatively small scatter, the observed LSF values of individual flights ranged from 0.05 to 33, at an average of 4.6!

Analysis of the data revealed that the increase in Load Severity with time was only very partly due to a change in mission mix: in general all missions tended to become more severe.
This increased mission severity was hardly or not reflected in a change in mission profile: the manoeuvres made became stronger and the number of manoeuvres became larger.

Summarizing this chapter we may conclude that for transport aircraft as well as for fighters considerable variations in usage from operator to operator and usage changes with time occur.

These variations are larger for fighter aircraft. For transport aircraft, the variations are defined by differences in relatively simple mission parameters like T.O.W., flight length etc.

This is not so for combat aircraft, where the average manoeuvre content of nominally the same mission type can change drastically with time.

SERVICE LOAD MONITORING

In the previous chapters we have seen that for combat aircraft but also for civil transport aircraft the actual load experience can be very different from design spectra. The service lives and inspection periods which were based on the design spectra must be re-determined to comply with the actual service conditions. This requires monitoring of the service load experience.

Fatigue Load Monitoring has become a generally accepted feature for military aircraft. The simple counting accelerometer devices that were used already thirty years ago have evolved to sophisticated recorder systems and complex procedures, for data processing and analysis.

The essential elements of the overall methodology adopted by major airforces are presented in table 3.

- Control Point Definition:
  Fatigue analysis and full scale test results are supposed to have indicated the fatigue critical locations in the structure. Usually the most critical ones are chosen as "control points". The aim of the fatigue load monitoring is to establish service stress spectra for these control points. Stress analysis and/or static tests provide relations between structural loads and control point stresses.

- Flight Load Survey:
  Flight load measurements are made with a fully straingaged and instrumented aircraft to establish relations between structural loads and various flight parameters for various aircraft configurations.

- Service Load Spectra Survey:
  A limited number of Aircraft is equipped with extensive recording equipment.

Continuous recordings of the "load determining" flight parameters during operational flights are made.
Purpose is to determine average load (= stress) spectra for each control point pertaining to a specific task (mission mixture) or for each mission type.
As the mission mixture and mission content may change, after some time a Load Spectra "Update" will be necessary. Lateron, we will come back on the latter aspect.

o Individual Aircraft Tracking:
Every aircraft in the fleet is monitored, either by means of a relatively simple recorder recording one or a few load quantities or by means of "Usage Monitoring" only, that is recording for each flight "administrative" parameters as Mission Type, T.O.W., flight duration etc.

Purpose of I.A.T. is to be aware of significant deviations in load experience from the fleet average for individual airplanes and, if this is the case to adapt maintenance schedules on the basis of individual aircraft usage.

A multitude of recording devices with various degrees of complexity are currently in use or proposed for I.A.T.
The OLMOS (Onboard Life Monitoring System) for the German Airforce Tornado may serve as an example for a relatively complex system (Refs. 20, 21). Here, Engine Life Cycle Monitoring, Structural Life Monitoring and event monitoring are integrated in one device. Structural Life Monitoring consists of determining "N_z*W"-spectra, subdivided in: 3 Wing Sweep Angles
4 Store Configurations
2 Flap Positions
2 Wing fuel conditions (wet/dry)

A simple I.A.T. device is undoubtedly the MSR (Mechanical Strain Recorder) used in the F-16. The MSR is expected to record a stress signal in the wing root area proportional to wing root B.M. (see Figs. 20 and 21).

The F-16 is an aircraft equipped with highly advanced avionics, computing and recording devices worth several millions of dollars.

To record stresses in this airplane by means of scratching with a needle in a tin strip is truly an anomaly in this Electronic Era!

In the following, we will discuss some aspects of the described methodology in some more detail.
In the first place, we will look into the necessity of Individual Airplane Tracking.

I.A.T. is useful or desirable _if_ a significant difference in average load experience of aircraft occurs. The average load experience per flight depends heavily on the aircraft duty: aircraft flying different duties will encounter different loads. On the other hand, aircraft serving the same duty must be expected to have the same average load experience, provided each aircraft flies a purely random selection out of the population of flights pertaining to that duty.

If the load experience per flight is described as a stochastic variable $\underline{z}$ with mean μ_z and variance σ_z^2, then the average load experience over n flights is also a stochastic $\underline{y}$ with mean $\mu_y = \mu_z$ and variance $\sigma_y^2 = \frac{1}{n}\sigma_z^2$. Moreover, for larger values of n $\underline{y}$ will become normally distributed.

We note that the value of σ_y, defining the "scatter" in average load experience decreases proportionally with the root of the number of flights, n, considered.

In other words, the "natural scatter" in average load experience decreases rapidly. The fatigue life consumption of an _individual_ aircraft can be estimated with reasonable accuracy if the average load experience pertaining to the specific _duty_, determining by sample load monitoring, is known.

On the other hand, _individual_ monitoring may be required _if_ the flights made by a specific aircraft are _not_ a random selection out of the total population, leading to a _systematic_ difference in load experience between aircraft.
In such systematic differences, two classes can be distinguised, namely:

_a_ The average load experience per _mission type_ differs from aircraft to aircraft.

_b_ Aircraft flying nominally the same duty experience a different _mission mixture_.

The first class of differences might occur if an aircraft is always flown by the same pilot: each pilot has his "own" aircraft like a knight his own horse and every pilot has his own "style" of flying. This is not the case in modern airforces. Also, one could imagine that one aircraft has a better performance and consequently flies more severely than the other. Performance variations, however, appear to be very limited and largely due to the engines, which are replaced relatively frequently. Hence, in the authors opinion the, first "class" of experience variation can be ignored.

Differences in _mission mixture_ will occur if specific aircraft are preferentially selected for specific missions.

This can easily happen if some missions require a specific configuration, either with regard to external stores or with regard to avionics, and if it is relatively difficult or impossible to change the aircraft configuration.

The F-104 G load data described earlier were used to study the scatter in individual load experience. As an example, figure 22, shows the scatter among aircraft flying the same "Air Defense" duty. The observed scatter was somewhat larger than might be expected in the case of a purely "random" flight selection, due to "clustering" of flights of the same mission type, pertaining to a specific aircraft configuration. This increased scatter fades out over longer periods of time and the F-104 G data confirmed that for the RNLAF Individual Airplane tracking is not waranted.

If differences in mission mixture between aircraft remain systematic and significant, there is a case for Individual Airplane Tracking.

An obvious way of I.A.T is then the tracking of individual mission mixture, usually indicated as Usage Monitoring.

For each sortie, a number of descriptive quantities like mission type, mission duration, store configuration T.O. weight etc. are stored.

Usually, such I.A.T. can be done without any additional effort as the above flight data are already acquired as part of existing operational or maintenance management programs.

In the authors opinion, I.A.T. by means of usage monitoring is cheaper, simpler and at least as reliable as I.A.T. by means of simple "one channel"-recording devices installed in each aircraft.

Another aspect to be discussed in some more detail is the possible change with time of loading severity, and the necessity of keeping track of these changes.

An obvious solution is a continuous "Service Load Spectra Survey", that means the measurements in extensively instrumented aircraft are continuous, and the Load Spectra are continuously updated.

Another simpler solution is a continuous severity tracking by means of a limited number of aircraft equipped with simple recording equipment.

If the tracking indicates a significant change in usage severity, a new "full scale" Load Spectra Survey should be initiated, resulting in updated Service Load Spectra.

The "severity tracking" may consist of the recording of one loading parameter, like the c.g. acceleration, or the loading history in one or a few control points which are indicative for the overall loading severity.

A typical example, described in more detail in Spiekhout's paper (Ref. 22) for "severity tracking" is the recording of wing root strain histories by means of a "Spectrapot recorder" in F-16A/B aircraft of the RNLAF.
The wing root strain history is considered to be a measure for the overall load experience of the F-16.
In each squadron of the RNLAF a few aircraft are equipped with the recording device. Recorded data are processed on a flight by flight basis, together with general mission data.

For an easy interpretation of recorded load data it is practical to have a simple procedure to quantify the severity of a recorded load history. The "classical" method, described earlier in this paper, made use of an assumed K_t-value, an assumed S-n curve and Miner's rule to calculate a relative fatigue damage.

The calculated relative damages depend very heavely on the assumed S-n curve. Moreover, in conjuction with damage tolerance criteria fatigue initiation life figures appear to be less relevant.

For the analysis or recorded F-16 strain histories, the NLR developed a method indicated as Crack Severity Index (CSI)-concept (Ref. 23).

The "Crack growth Potential" of a recorded stress history is calculated along the following lines:

- o Analysis of stress sequence according to Rain Flow method.
- o Crack growth of the i "upgoing" ranges defined by (σ_{max} , σ_{mini}) is calculated from:

  $$CSI = C \sum_i (\sigma_{max,i} - \sigma_{op,i})^m$$

  c = calibration constant
  m = materials constant, taken as 3 for 2xxx and 7xxx Al alloys.
- o The opening stress $\sigma_{op,i}$ is related to $\sigma_{max,i}$ and $_{min,i}$, using relations based on CA data, but has a lower boundary value $\overline{\sigma}_{op}$, defined by the peak stress and trough stress occurring once per thirty flights.
  In this way, retardation due to peak loads is included.

The CSI-procedure has been checked by means of comparative crack growth tests under widely varying stress sequences, showing remarkably good results.

<u>Civil Transport Aircraft</u>, as shown in chapter 3 are subjected as well to variations in load experience. Monitoring of the actual

history in one or a few control points which are indicative for the overall loading severity.

A typical example, described in more detail in Spiekhout's paper (Ref. 22) for "severity tracking" is the recording of wing root strain histories by means of a "Spectrapot recorder" in F-16A/B aircraft of the RNLAF.
The wing root strain history is considered to be a measure for the overall load experience of the F-16.
In each squadron of the RNLAF a few aircraft are equipped with the recording device. Recorded data are processed on a flight by flight basis, together with general mission data.

For an easy interpretation of recorded load data it is practical to have a simple procedure to quantify the severity of a recorded load history. The "classical" method, described earlier in this paper, made use of an assumed K_t-value, an assumed S-n curve and Miner's rule to calculate a relative fatigue damage.

The calculated relative damages depend very heavely on the assumed S-n curve. Moreover, in conjuction with damage tolerance criteria fatigue initiation life figures appear to be less relevant.

For the analysis or recorded F-16 strain histories, the NLR developed a method indicated as Crack Severity Index (CSI)-concept (Ref. 23).

The "Crack growth Potential" of a recorded stress history is calculated along the following lines:

- o Analysis of stress sequence according to Rain Flow method.
- o Crack growth of the i "upgoing" ranges defined by (σ_{max}, σ_{mini}) is calculated from:

  $$CSI = C \sum_i (\sigma_{max,i} - \sigma_{op,i})^m$$

  c = calibration constant
  m = materials constant, taken as 3 for 2xxx and 7xxx Al alloys.
- o The opening stress $\sigma_{op,i}$ is related to $\sigma_{max,i}$ and $\sigma_{min,i}$, using relations based on CA data, but has a lower boundary value $\overline{\sigma_{op}}$, defined by the peak stress and trough stress occurring once per thirty flights.
  In this way, retardation due to peak loads is included.

The CSI-procedure has been checked by means of comparative crack growth tests under widely varying stress sequences, showing remarkably good results.

Civil Transport Aircraft, as shown in chapter 3 are subjected as well to variations in load experience. Monitoring of the actual service loading appears to be desirable and potentially profitable also for transport. Yet, unfortunately service load monitoring has found very little response in Civil aviation although means and methods are available.

As an example of a highly sophisticated system the OLMS (Operational Load Monitoring System) being developed by MBB Bremen (Ref. 24) should be mentioned.

Figure 23, reproduced from reference 24 presents a functional diagram of OLMS.
Note that the system includes the "on-line" calculation of load time histories from measured "load relevant" parameters.

The OLM System is explicitly presented as a tool for Individual Aircraft Monitoring; it will be clear, however, that OLMS can also be used as a valuable tool for aircraft designers in checking design load definition procedures and in providing design load data for future aircraft.

Undoubtedly, OLMS is a modern system, fitting in our "Electronic Era", and its development should be commended.

On the other hand, it should be realized that specifically for transport aircraft relatively easy means for service load monitoring are directly available. As shown in previous chapters, the variations in load experience for transport aircraft are largely defined by variations in usage; hence an informative service load monitoring can be obtained by adequate usage monitoring alone. In chapter 3 it was shown how highly relevant mission profile data could be obtained at very little cost from 747 ACMS data (Refs. 6, 18). The example given with regard to cabine pressure distributions illustrates the type of information that could be very beneficial for the owner of a ageing aircraft! The latter example required presence of an ACMS-recorder or an other recording device, but even simpler methods of monitoring can be proposed that may provide useful information.
For example the systematic "bookkeeping" of flight-duration, type of flight, T.O. weight and payload for each flight will already provide informative usage statistics.

Yet, as said before, most airline companies seem to remain unconvinced of the potential benefits of usage monitoring and the information about the airframe past is generally restricted to the total number of flights and the total number of flight hours.
Contributing factors to this negative attitude are:

- The outcome of usage monitoring can be that the actual usage is more severe or less severe than assumed. In the first case, the Airline fears for an increased maintenance burden imposed by authorities. On the other hand, they are not sure that in case of less severe usage they will be allowed to relax their maintenance schedule.

- So far, main aircraft manufacturers have usually shown a remarkable lack of enthousiasm. Hardly any active support for fatigue load monitoring projects from the manufacturers side has been observed in general. Probably, most manufacturers fear for the "extra work", associated with the translation of measured load experience into adapted inspection schedules.
- Airworthiness authorities seem to be hesitant to make any commitments with regard to possible adaption of maintenance on the basis of monitored service load data.

This present attitude is actually a luxury: we can afford, or at least we think so, to ignore service load monitoring and to cover scatter in load experience by means of conservative assumptions and large life factors. However, there are indications that with the growing age of our civil aircraft fleet our "reserves" are getting smaller and smaller.

The time may come soon that airlines would gratefully make use of the "extra life", obtained on the basis of measured service load experience. This economic advantage goes with another, at least equally important one. Monitoring of service loads means reducing an element of uncertainty. Reduction of uncertainty implies an increase in safety.

It is my sincere hope that this paper may stimulate the wider application of service load monitoring in transport aircraft, thus contributing to the economy and safety of civil aviation.

CONCLUSIONS

1. The fatigue load spectra pertaining to a given aircraft usage can be predicted with reasonable accuracy for civil transport aircraft. However, statistical data on tail loads are desirable.

2. Load spectra for Combat aircraft are difficult to accurately predict in the design phase, because the actual manoeuvring depends heavily on the aircraft performance and flight characteristics.

3. The service load experience for combat aircraft as well as for transport aircraft can differ appreciably from operator to operator due to differences in mission usage. For combat aircraft the manoeuvre content for a given mission type may drastically change with time.

4. Service fatigue load monitoring is generally accepted for military aircraft. The Methodology is well established and adequate recording systems are available or under development.

5. Individual Airplane Tracking (IAT) can be accomplished by monitoring of basic mission parameters for each flight and each aircraft.

6. For civil transport aircraft, systematic monitoring of service fatigue loading or mission usage has found very limited application sofar.

7. Systematic monitoring of a few relatively simple parameters can already provide relevant usage statistics.

8. Such monitoring could extent the service life of ageing aircraft and, by reducing the amount of loading uncertainty, contribute to the safety of civil aviation.

REFERENCES

(1) Mann, J.Y., Aircraft Fatigue - with particular emphasis on Australian operations and research.
9th Plantema Memorial Lecture Toulouse, May 25-27 1983 In.: Proceedings of 12th ICAF Symposium, ICAF Doc. 1336.

(2) Jongebreur, A.A., Louwaard, E.P. and Van de Velden, R.V., Damage Tolerance Test Program of the Fokker 100.
Paper, presented at the 13th ICAF Symposium, Pisa, May 1985.

(3) De Jonge, B., Van de Wekken, A.J.P. and Noback, R., Acquisition of gust statistics from AIDS-recorded Data. In: AGARD report nr. 734, 1987.
Also published as NLR MP-86048 U, issue 2.

(4) Kaynes, I.W., A summary of the analysis of Gust Loads Recorded by counting accelerometers on seventeen types of aircraft. AGARD Report no. 605, 1972.

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

(6) Spiekhout, D.J. and Van Lummel, C.W.J., Operational loads on B-747 aircraft: design assumptions, actual experience and maintenance aspects, NLR MP 83051 U, 1983.

(7) Card, V., A review of measured gust responses in the light of modern analysis methods. In: AGARD Report nr. 734, Addendum, June 1988.

(8) Van de Wekken, A.J.P., Calculations of tail loads due to vertical gusts for a flexible aircraft model.
NLR Report to be published.

(9) Coleman, T.L., Trends in repeated loads on transport airplanes. Paper presented at the 4th ICAF symposium, Munich June 1965 (ICAF Doc. Nr. 487).

(10) Buxbaum, O., Landing gear loads of civil transport airplanes. 8th Plantema Memorial Lecture.
Proceedings of the 11th ICAF Symposium, Noordwijkerhout, May 1981 (ICAF Doc. No. 1216).

(11) Birrenbach, R., Comparison of fatigue design load spectra with flight test measurement and service experience.
In: Proceedings of the 8th ICAF Symposium, Lausanne, June 1975 ICAF Doc. 801.

(12) Holpp, J.E. and Landy, M.A., the development of fatigue/crack growth analysis loading spectra.
In: AGARDograph no. 231 "Fatigue Design of Fighters".

(13) Workshop on design loads for advanced fighters.
AGARD Report no. 746, February 1988.

(14) Ward, A.P., Fatigue load spectra for combat aircraft: their derivation and data requirements.
In: Proceedings of the 8th ICAF symposium, Lausanne June 1975 ICAF doc. 801.

(15) Eskens, E.P.G., Fatiguemeter Data Report. Fokker report GO 28-463, 1969.

(16) Schijve, J., Editor, Review of Aeronautical fatigue investigation in the Netherlands during the period March 1971-March 1973.
NLR MP 73014 U, 1973.

(17) Spencer, Max, M., The Boeing 747 fatigue integrity program. Paper presented at 6th ICAF symposium, Miami, Florida, May 1971 (NASA sp-309).

(18) De Jonge, J.B. and Spiekhout, D.J., Assessment of service load experience using AIDS-recorded data.
Proceedings of the 9th ICAF Symposium, Darmstadt, may 1977 (ICAF-doc. nr. 960).

(19) De Jonge, J.B. and Van Lummel C.W.J., Review and analysis of service load data of RNLAF (R)F-104 G aircraft. NLR TR 85030 L, 1985.

(20) Kunz, L.T.C., OLMOS GE Airforce requirements for the onboard life monitoring system on Tornado.
14th International AIMS Symposium, Sept. 1987 Friedrichshafen.

(21) Neunaber, R., TORNADO Airframe fatigue life monitoring. 14th International AIMS Symposium Sept. 1987, Friedrichshafen.

(22) Spiekhout, D.J., Re-assessing the F-16 damage tolerance. Paper presented at 15th ICAF Symposium, Jerusalem, June 1989.

(23) De Jonge, J.B. and Van Lummel, C.W.J., Development of a crack severity index (CSI) for quantification of recorded stress spectra. NLR TR 86049 L.

(24) Schmücker, M., Meyer, H.J. and Ladda, V., New approaches in the field of inflight load evaluations. AIAA-87-0848-CP.

TABLE 1
Example of load factor spectra per mission segment
(reproduced from MIL-A-87221)

Maneuver-load-factor spectra for A, F, TF classes, cumulative occurrences per 1000 flight hours by mission segment

N_z	Ascent	Cruise	Descent	Loiter	Air-Grnd	Spec Wpn	Air-Air
Positive							
2.0	5000	10,000	20,000	15,000	175,000	70,000	300,000
3.0	90	2,500	5,500	2,200	100,000	25,000	150,000
4.0	1	400	500	250	40,000	7,500	50,000
5.0		1	1	25	10,000	2,000	13,000
6.0				1	1,500	250	3,300
7.0					200	15	900
8.0					15	1	220
9.0					1		60
10.0							15
Negative							
0.5					10,000		44,000
0					350		4,000
-0.5					30		1,200
-1.0					7		350
-1.5					3		60
-2.0					1		8
-2.5							1

TABLE 2

Mixture of missions for the RNLAF F-104 strike duty

Mission Category	Mission type	Percentage of flights	Average load severity LSF
Air/Ground	CPM/Nav Air to Ground	42 39	1.189 4.139
Air/Air	Air Combat/aero's	15	4.016
General	Nightflying Miscellaneous	3 1	.580 1.036
All sorties		100	2.742

Definition of the mission types pertaining to the Strike duty.

1. CPM/Navigation
   Low level navigation missions including one or more simulated weapon delivery patterns (conventional or strike) with or without formation flying, including tactical and close formation flying and aerobatics during a short period.

2. Air to Ground
   Strike and conventional weapon delivery patterns on an air to ground gunnery range or conventional, forward air controlled, simulated weapon delivery patterns. This mission type can be combined with formation flying, including tactical and close formation and aerobatics, during a short period.

3. Air Combat/Aero's
   Tactical and close formation practice, offensive and defensive arial combat manoeuvring practice and aerobatics.

4. Night Flying
   Night flying practice, including low level navigation and traffic patterns.

5. Miscellaneous
   Administrative flights, including instrument continuation training, cross aervicing, etc.

TABLE 3

Main Elements of fatigue load monitoring for combat aircraft

CONTROL POINT DEFINITION

- o Fatigue analysis and tests indicate critical locations.
- o The most critical ones are selected as control point.
- o Analysis or test provide relations between CP stress and structural load.

FLIGHT LOAD SURVEY

- o Test flights with fully straingaged aircraft provide relations between structural loads and flight parameters.

SERVICE LOAD SPECTRA SURVEY

- o Limited nr. of operational aircraft extensively instrumented.
- o Measurements provide for each control point average load spectra pertaining to a specific task (or mission type).

INDIVIDUAL AIRPLANE TRACKING

- o Each aircraft in the fleet involved.
- o Monitoring of one or a few parameters.
- o Possibility to adapt maintenance schedule to individual usage severity.

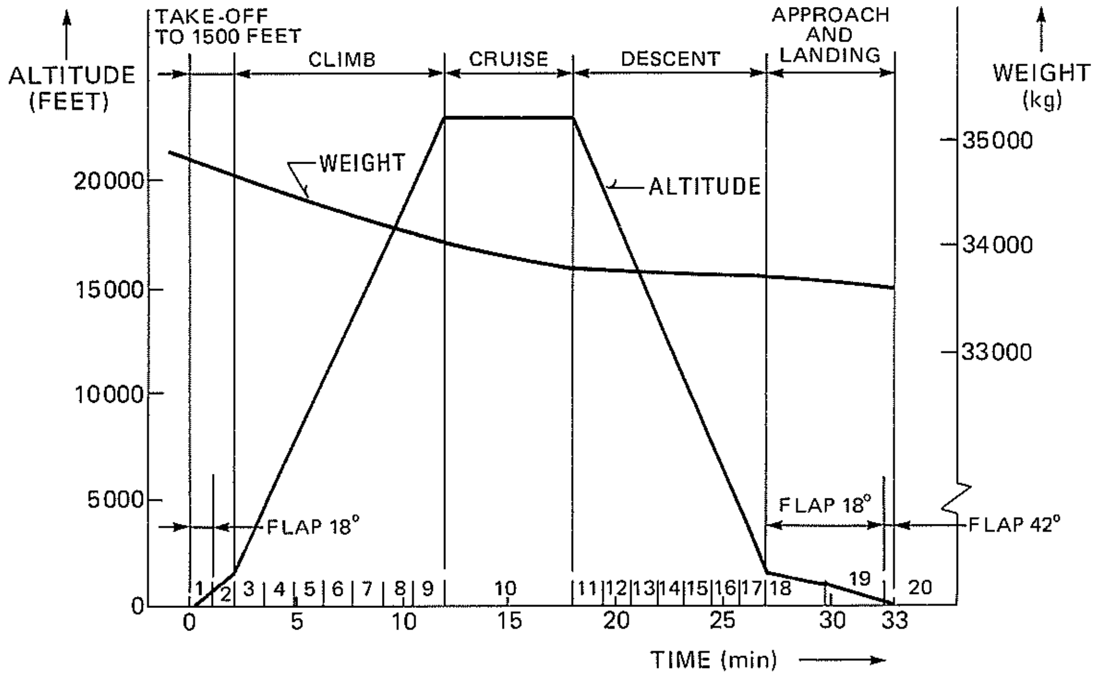


Fig. 1 Example of a design mission profile for a short haul transport (from ref. 2)

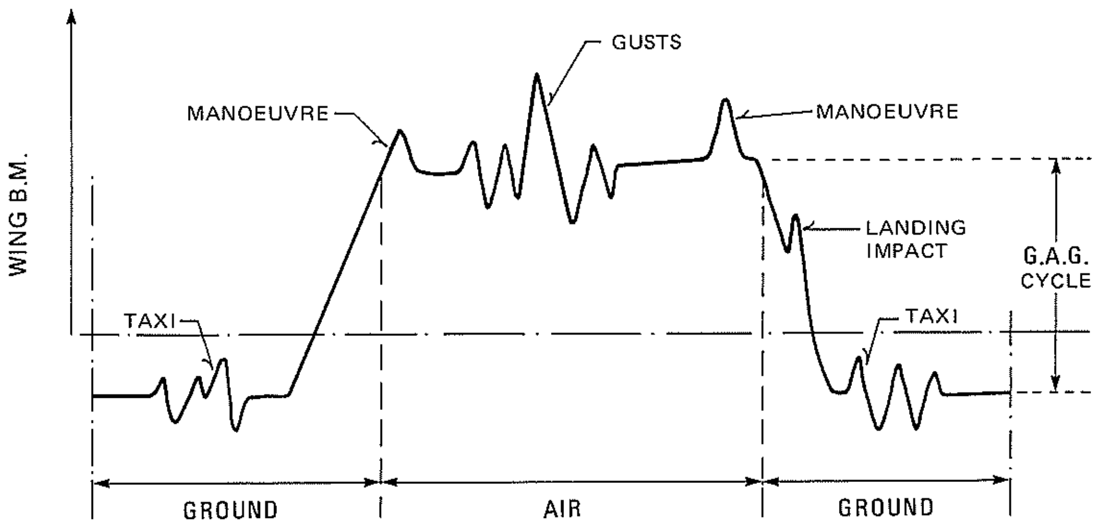


Fig. 2 Schematic representation of the load history during one flight

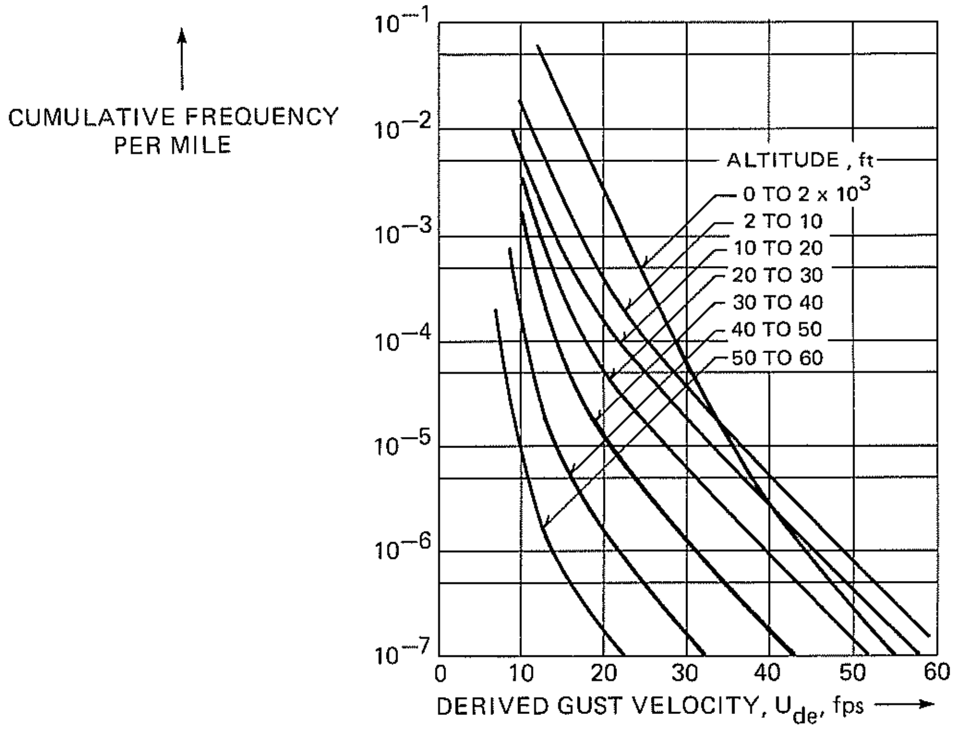


Fig. 3 Distribution of overall derived gust velocity $G(U_{de})$ for airplanes at various altitudes, derived from VGH and VG data (from ref. 5)

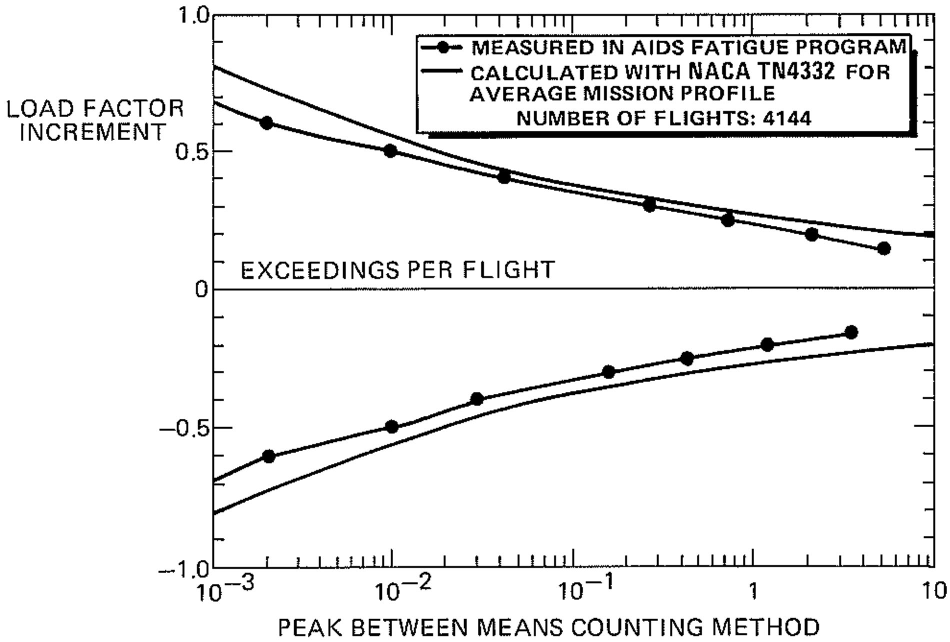
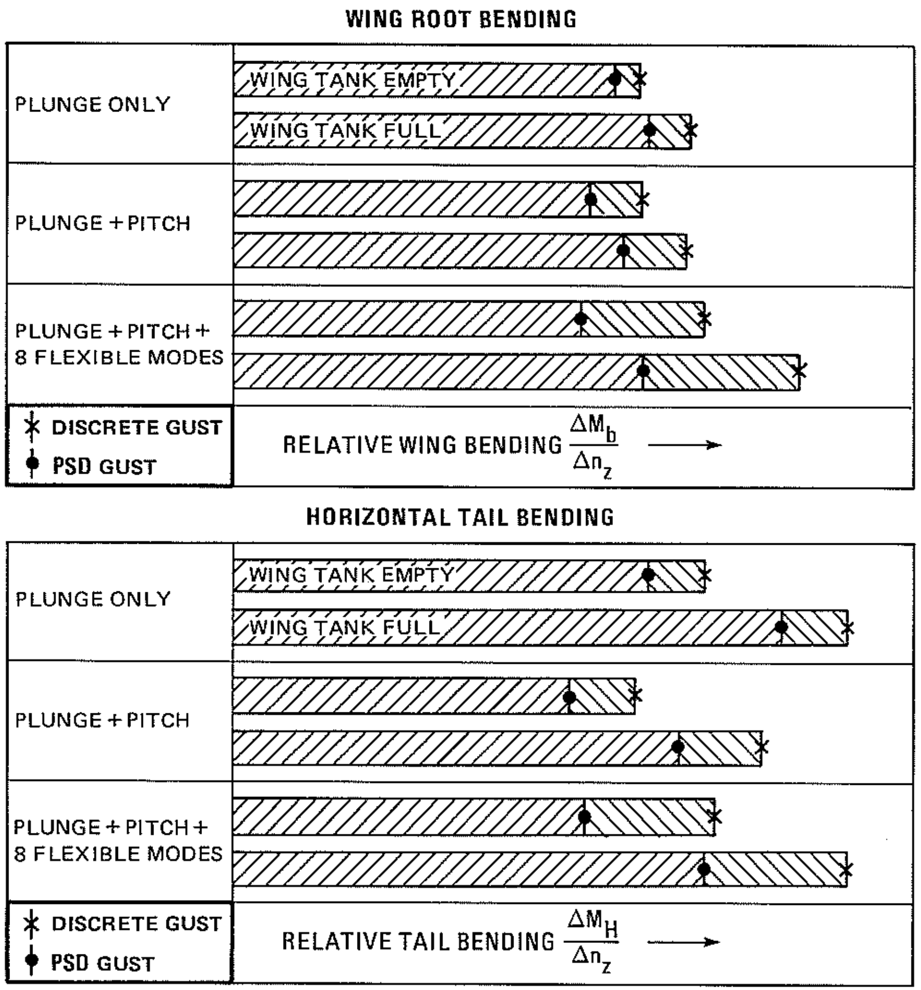
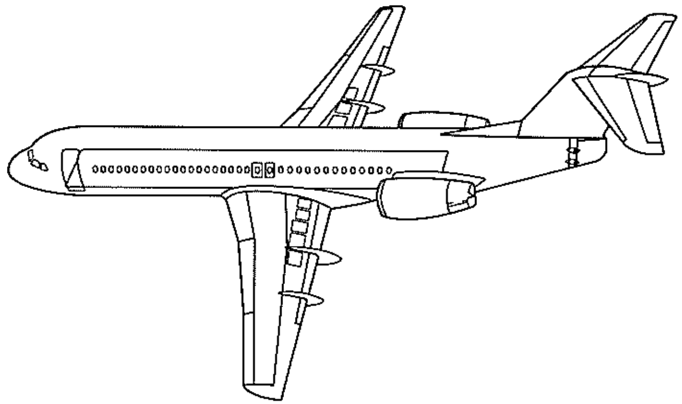


Fig. 4 Comparison of predicted and recorded c.g. acceleration spectra for Boeing 747 (from ref. 6)





AIRCRAFT

TWIN ENGINED SHORT HAUL TRANSPORT

CONFIGURATIONS

A) "LIGHT" → WING TANKS EMPTY
B) "HEAVY" → WING TANKS FULL

ALTITUDE 7000 m, SPEED 220 m/s TAS

CALCULATION MODEL:

- RESPONSE IN PLUNGE ONLY. AC STIFF
- PLUNGE AND PITCH, AC STIFF
- PLUNGE, PITCH AND 8 FLEXIBLE MODES

GUST MODELS:

DISCRETE GUST
"(1 – cos)" GUST, 25 CHORDS

PSD GUST:
VON KARMAN POWER SPECTRUM, L = 762.5 m

Fig. 5 Effect of aircraft response modelling and turbulence model on calculated "loads per g" due to gust

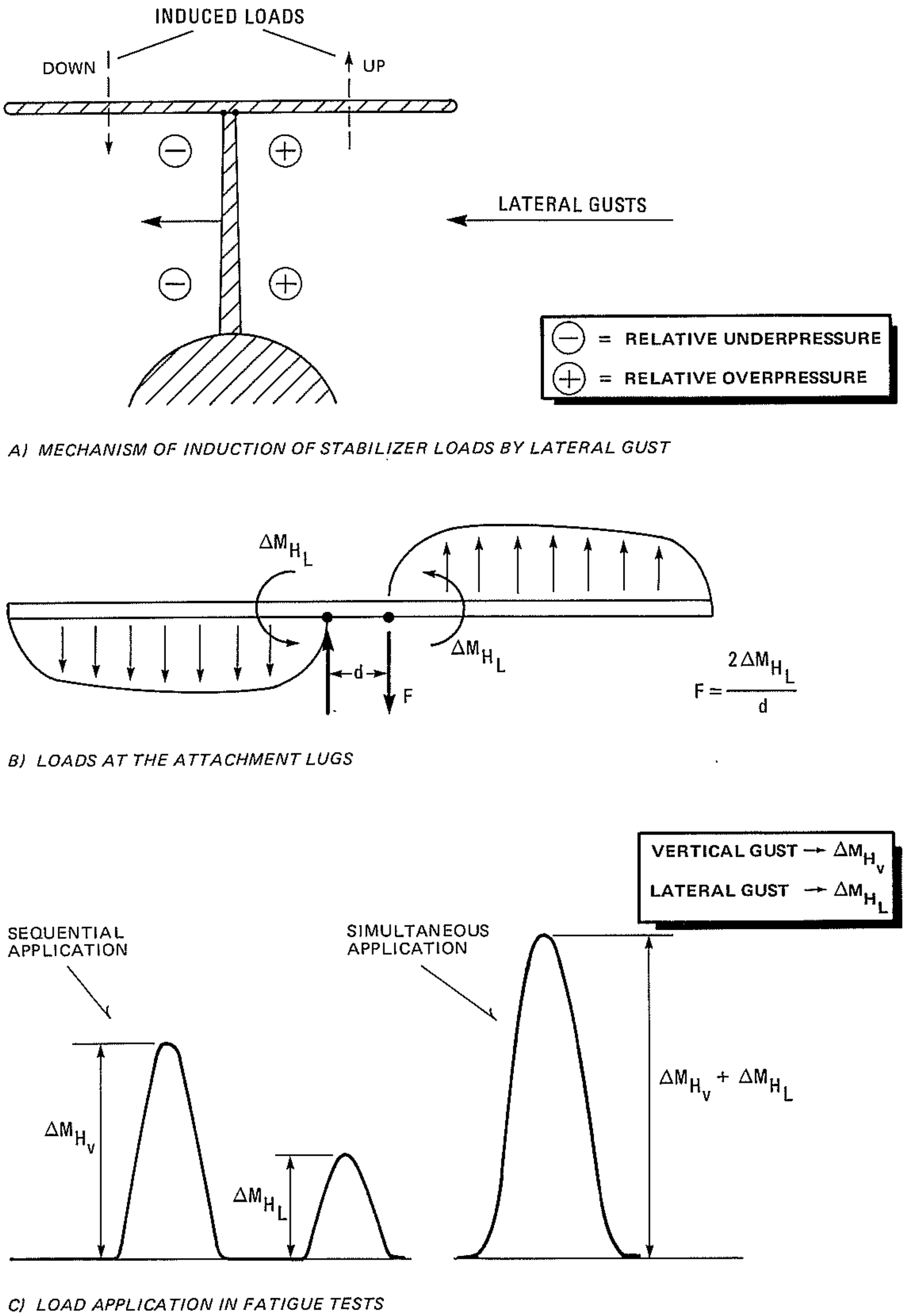


Fig. 6 Gust loading of the T-tail

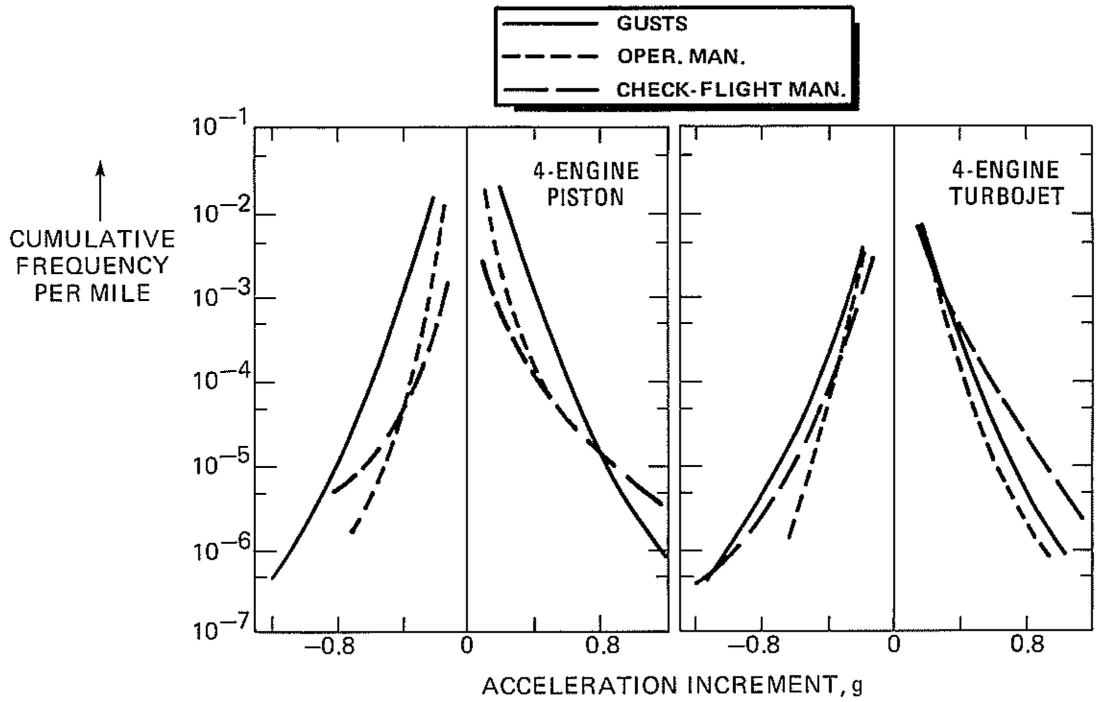


Fig. 7 Gust and manoeuvre accelerations for long-haul airplanes
Reproduced from ref. 9

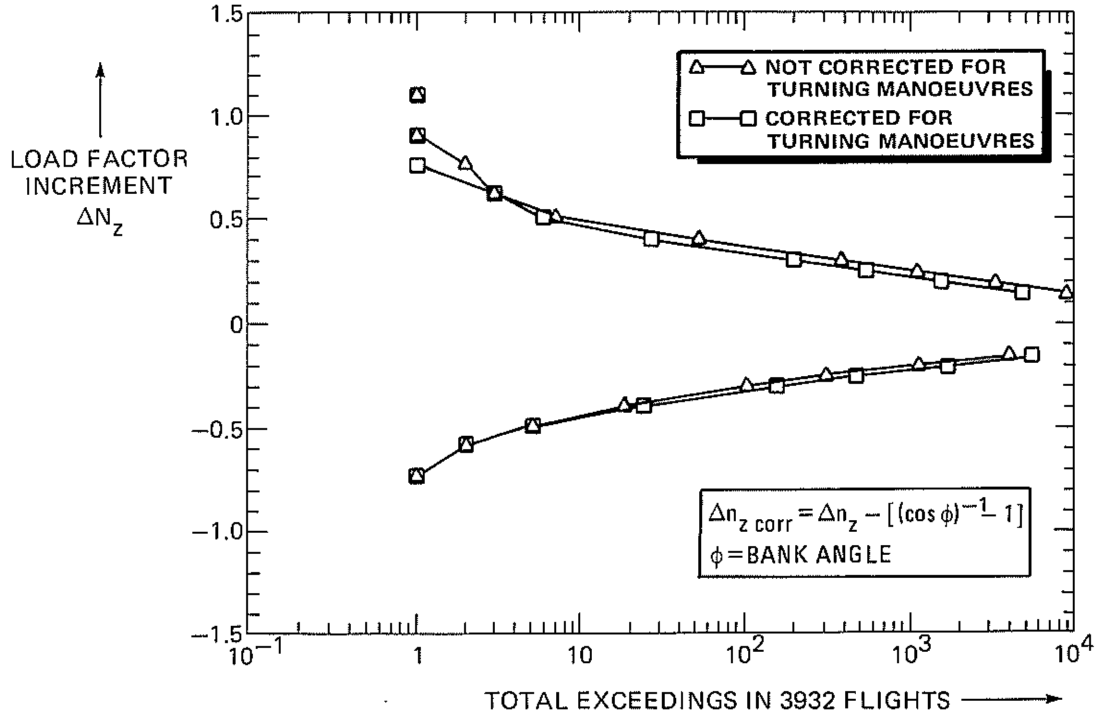
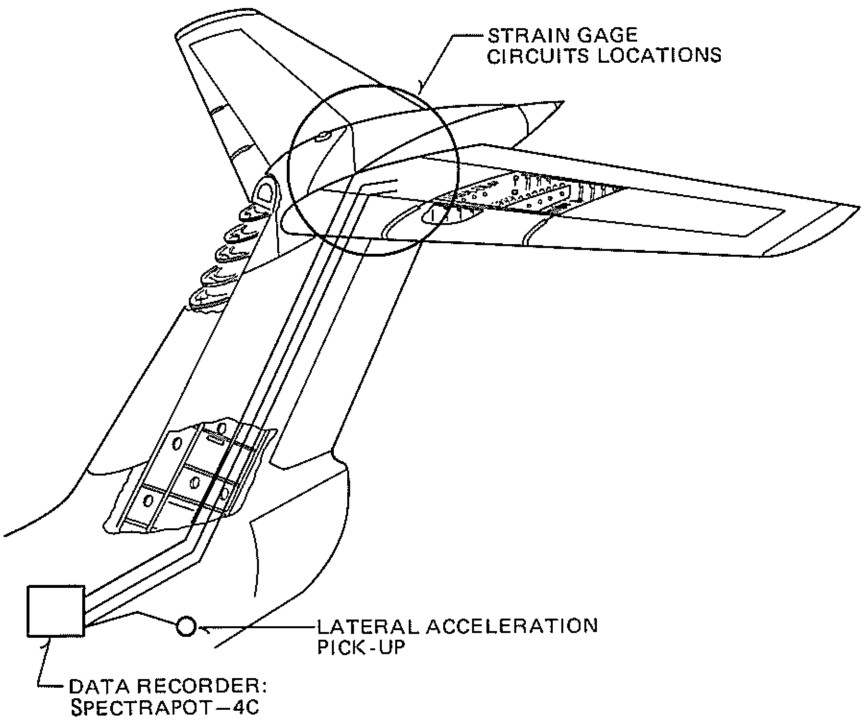


Fig. 8 Load factor spectra for Boeing 747 below 10000 ft, with and without "bank angle correction" (NLR ACMS Data)



MEASUREMENTS WITH SPECTRAPOT RECORDER:

- LATERAL ACCELERATION OF TAIL

FROM STRAIN GAGE BRIDGES:

- B.M. OF RIGHT STABILIZER
- SYMMETRIC COMPONENT STABILIZER B.M.
- ANTI SYMMETRIC COMPONENT STABILIZER B.M.

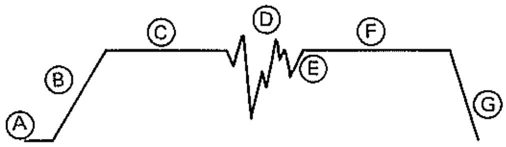
ADDITIONAL INFO FROM ACMS SYSTEM:

- ADMINISTRATIVE FLIGHT DATA
- C.G VERTICAL ACCELERATION
- SPEED
- ALTITUDE
- ELEVATOR POSITION

Fig. 9 Review of F-100 service-tailload measurements

AIR COMBAT MISSION PROFILE

1. Average flight time — 53.7 minutes
2. Configuration "A"
3. Take-off gross weight — 15,470 lb
4. Take-off fuel — 4360 lb
5. Mission radius — 153 nautical miles
6. Air-to-Air combat averages 9.6 minutes at various airspeeds, altidudes, and load factors
7. Mission segments



	POWER SETTING
(A) TAKE-OFF	MILITARY
(B) CLIMB	MILITARY
(C) CRUISE	OPTIMUM CRUISE
(D) AIR-TO-AIR COMBAT	MAXIMUM
(E) CLIMB	MILITARY
(F) CRUISE	OPTIMUM
(G) DESCENT	PENETRATION (80%)

MISSION SEGMENT FLIGHT PARAMETERS

	MISSION SEGMENT	SEGMENT TIME		AVERAGE FLIGHT PARAMETERS		
		(min)	% MISS	GW(LB)	ALT(ft)	MACH No.
A	TAKE-OFF	0.7	1.3	15,470	S.L.	0.28
B	CLIMB	6.5	12.1	14,933	18,500	0.73
C	CRUISE	12.9	24.0	14,464	37,300	0.82
D	COMBAT	9.6	17.9	13,420	30,000	0.75
E	CLIMB	2.3	4.3	12,525	35,200	0.89
F	CRUISE	17.1	31.8	12,246	40,750	0.82
G	DESCENT	4.6	8.6	12,025	20,550	0.59

Fig. 10 Example of a design mission profile for a fighter aircraft (from ref. 12)

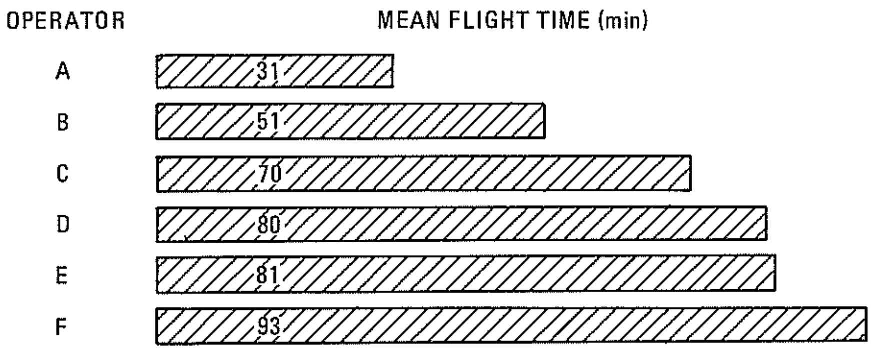


Fig. 11 Variation in mean flight times for various F-28 operators (from ref. 15)

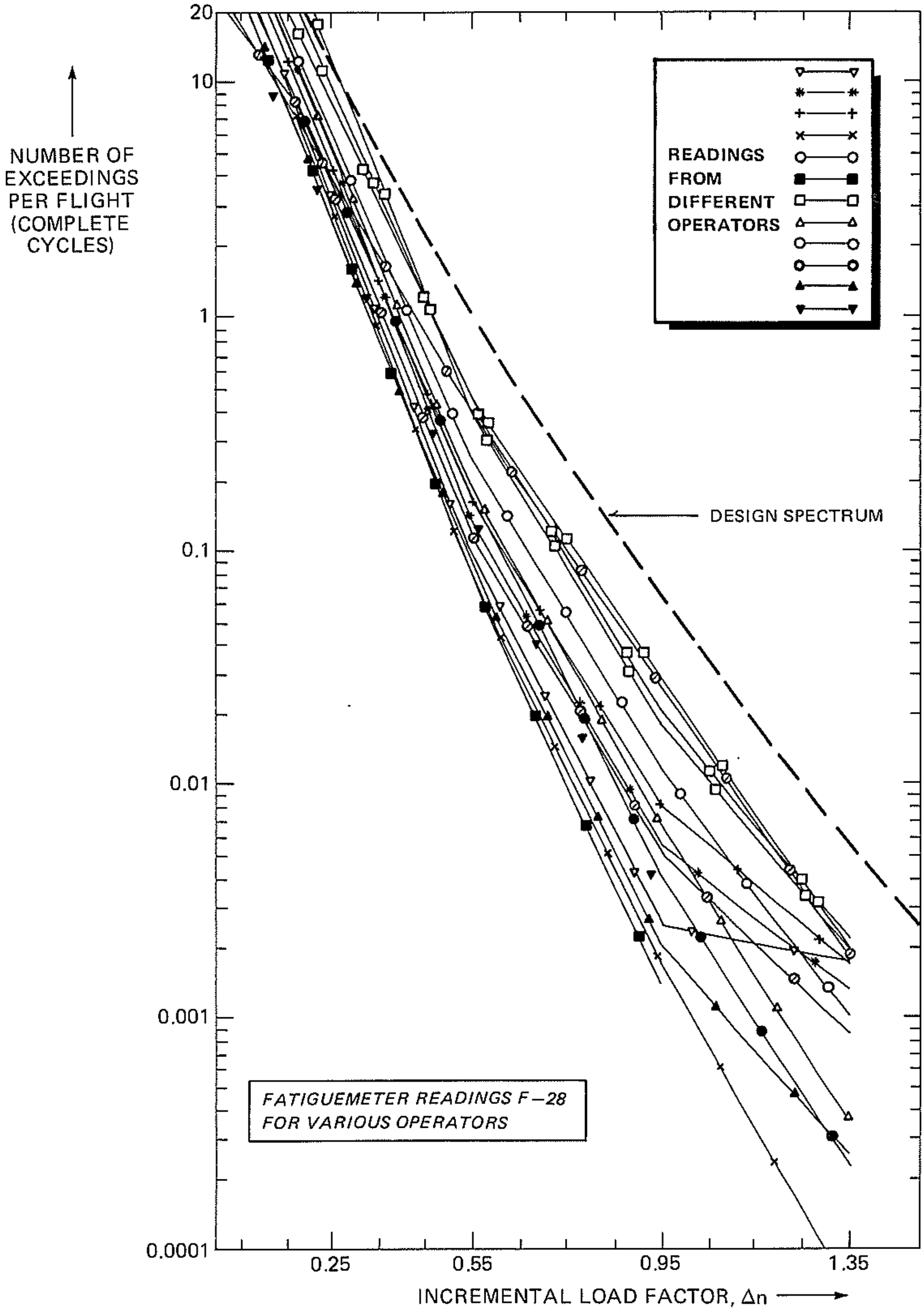


Fig. 12 Variation in load factor experience between F-28 operators (from ref. 16)

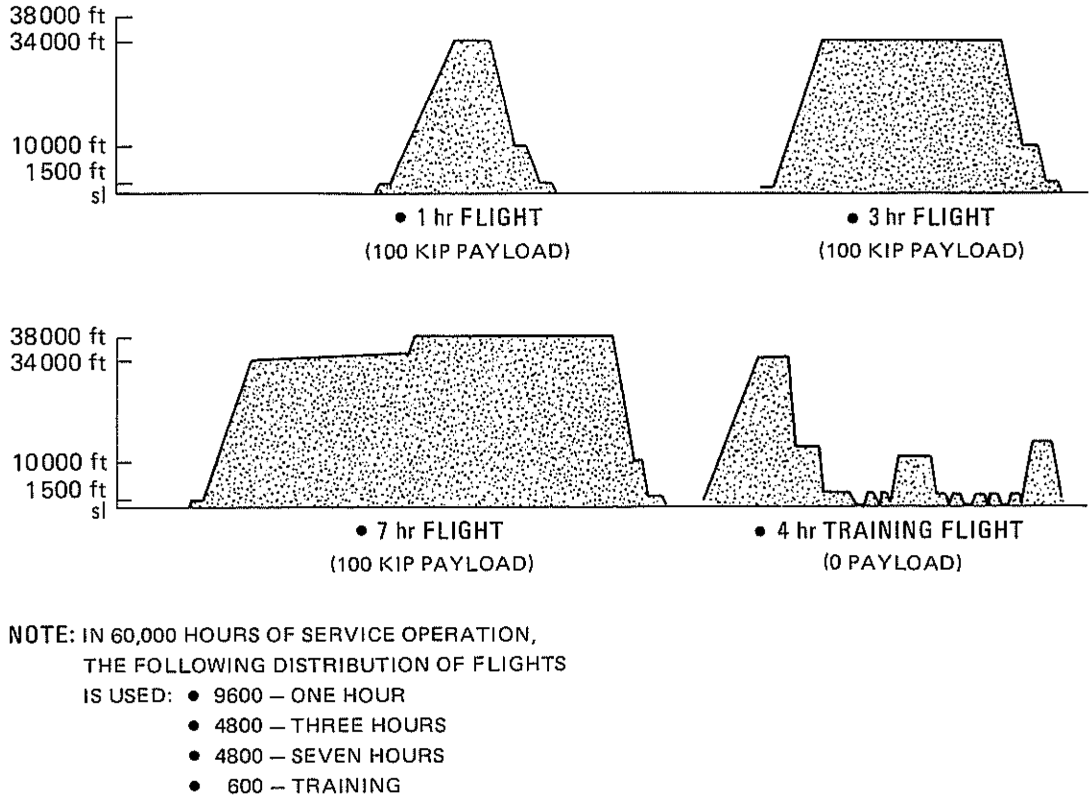


Fig. 13 Design mission mixture for the Boeiing 747 (from ref. 17)

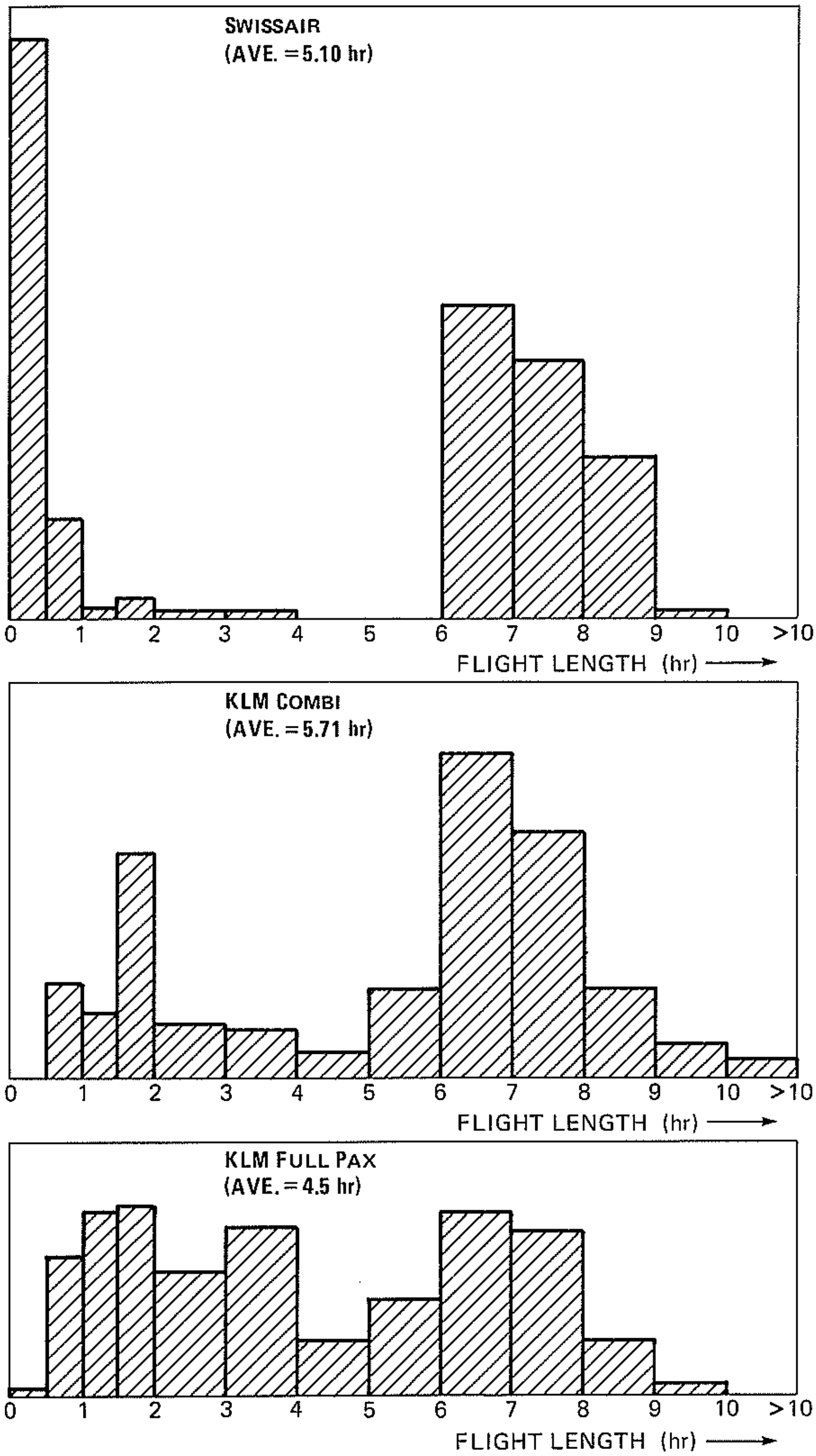


Fig. 14 Flight duration distributions for different 747 operators

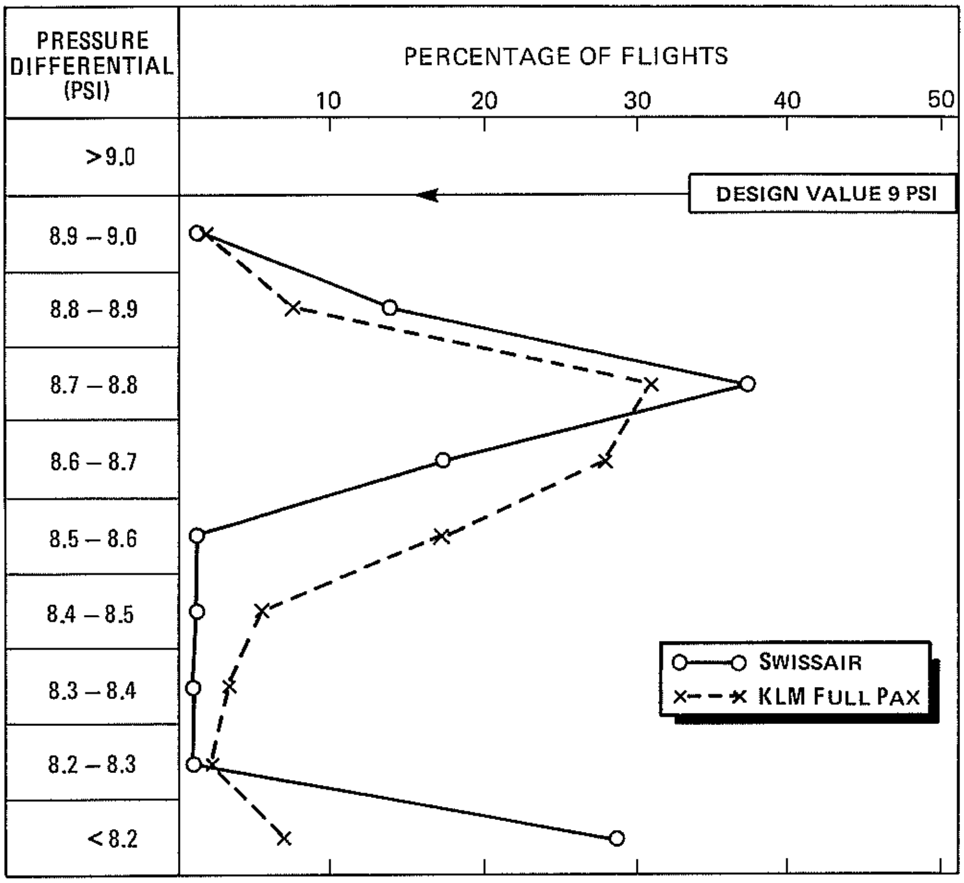


Fig. 15 Distribution of maximum cabin pressure differential for two 747 operators

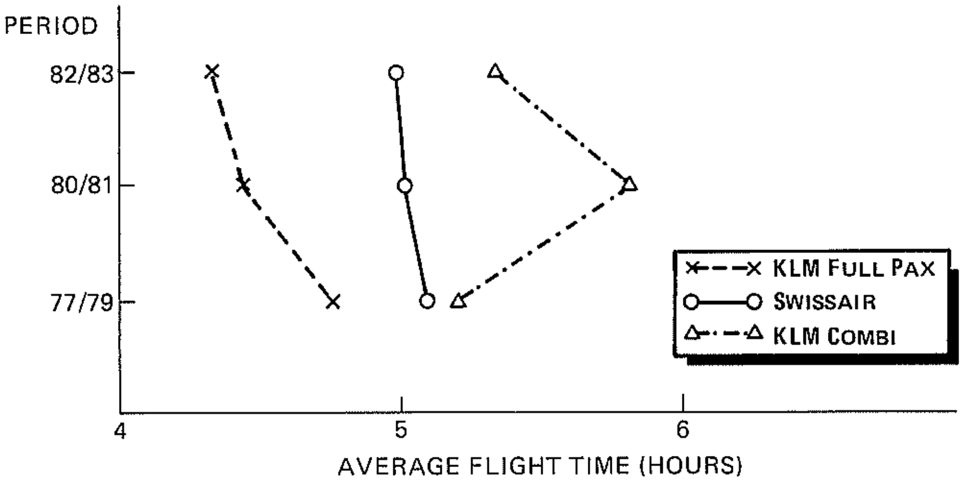


Fig. 16 Variation of average flight duration with time for two 747 operators

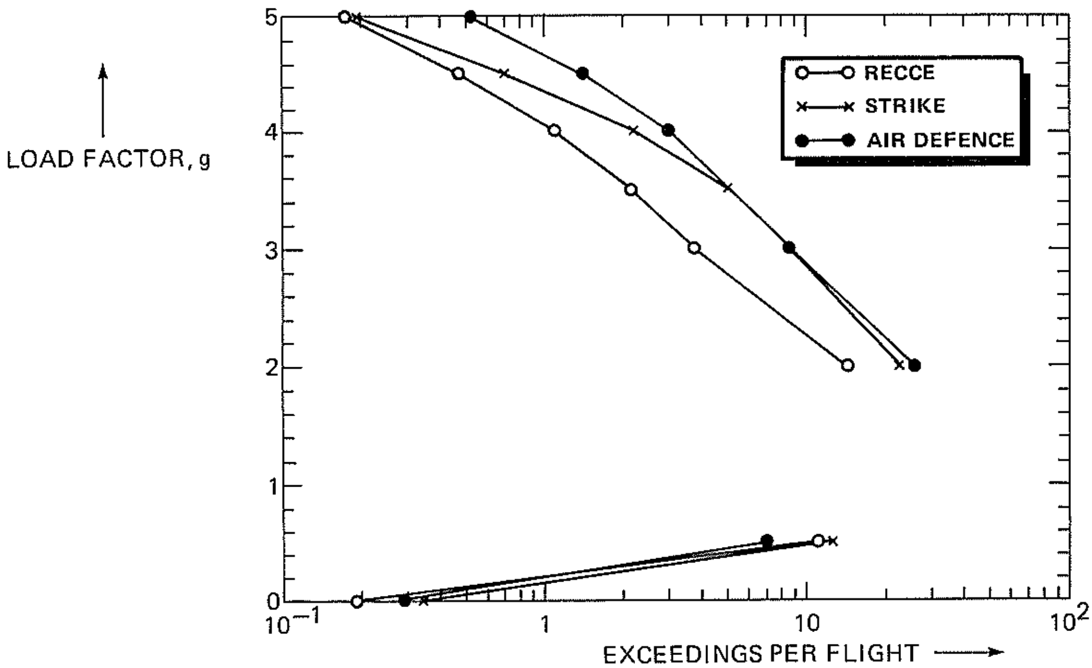


Fig. 17 Overall load factor spectra pertaining to the three duties of RNLAF F-104 aircraft (from ref. 19)

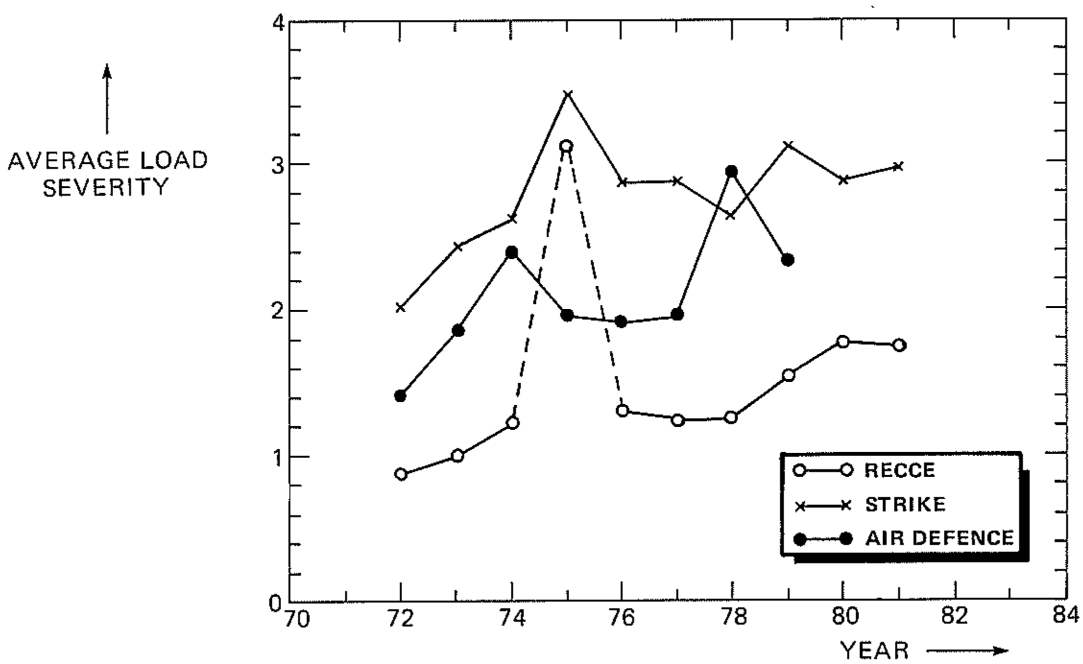
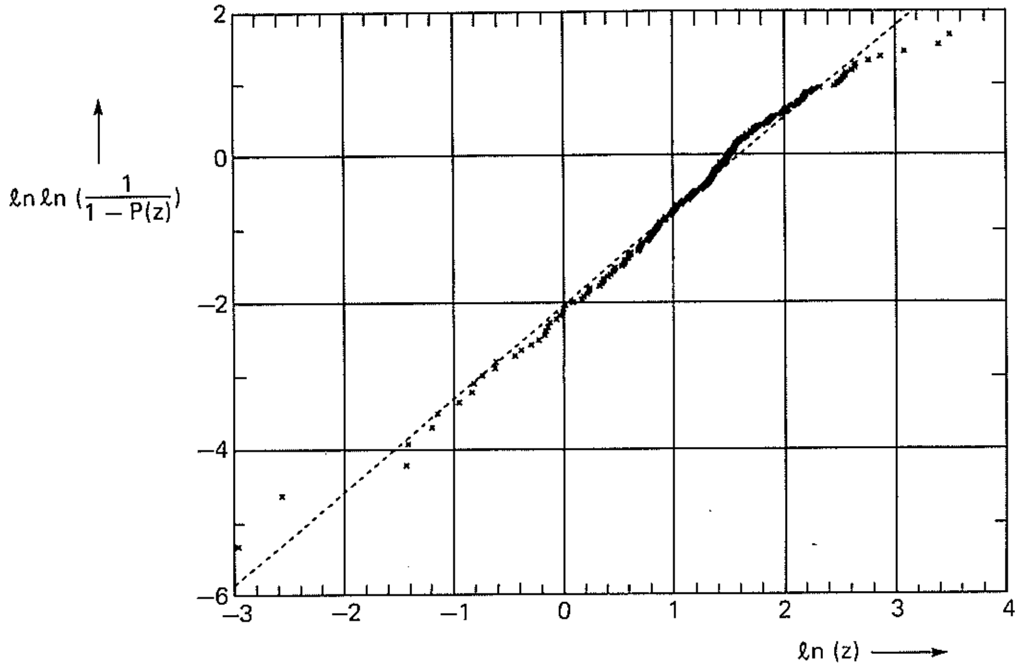


Fig. 18 The annually recorded load severity LSF for the three different duties of RNLAF F-104G (from ref. 19)



LOAD SEVERITY PER FLIGHT = $\underline{z}$

$\bar{z} = 4.596$

$\sigma_z = 4.360$

LIGHTEST FLIGHT OBSERVED : $z = 0.050$

SEVEREST FLIGHT OBSERVED: $z = 33$

WEIBULL DISTRIBUTION: $P_{(z)} = 1 - \left\{ \exp - \left(\frac{z}{z_a} \right)^b \right\}$

"BEST FIT": $z_a = 4.904$

$b = 1.276$

Fig. 19 Example of recorded LSF-values of flights of one mission type fitting a Weibull distribution (from ref. 19)

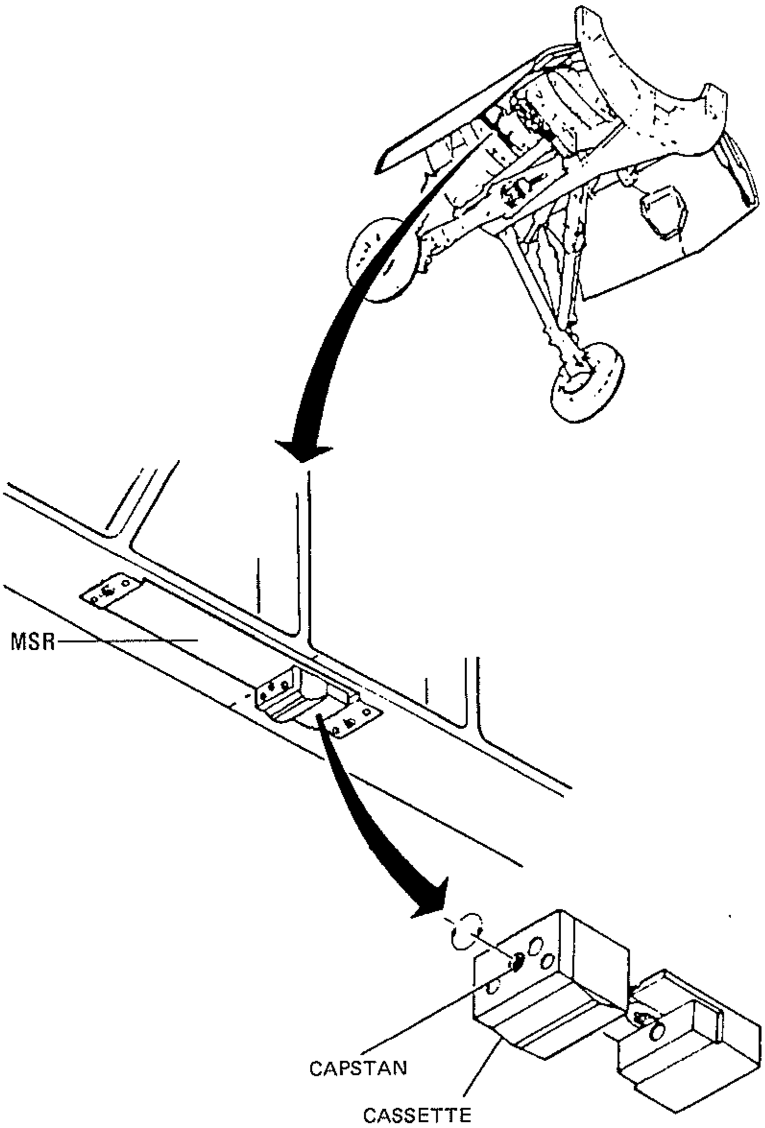


Fig. 20 Location of the MSR in the F-16

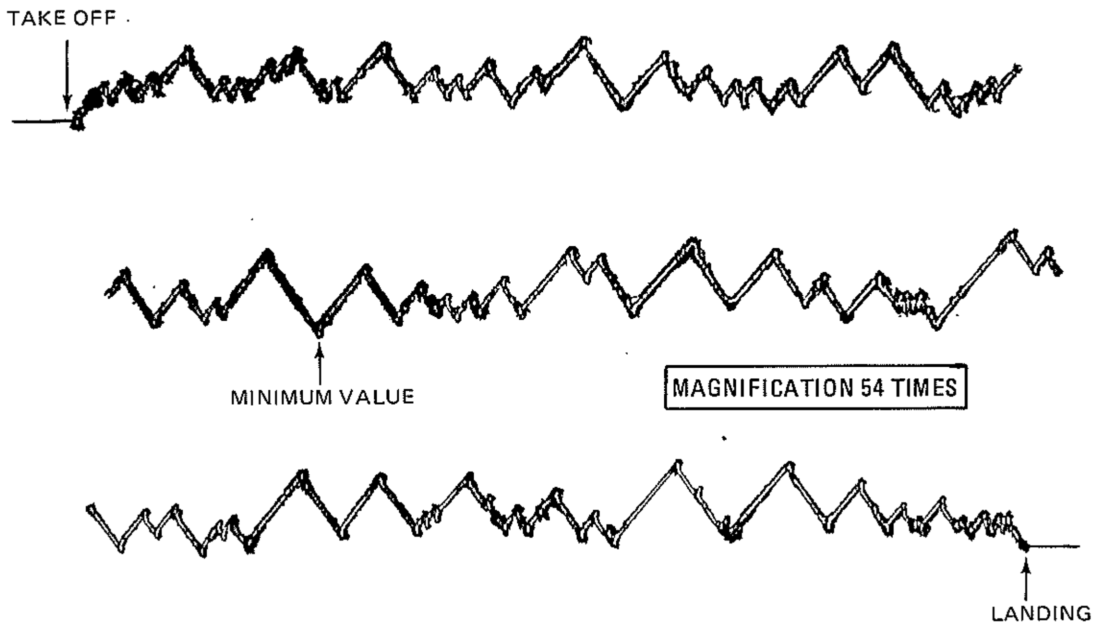


Fig. 21 Example of "strain" scratch on metallic tape of the MSR recorder,used in the F-16

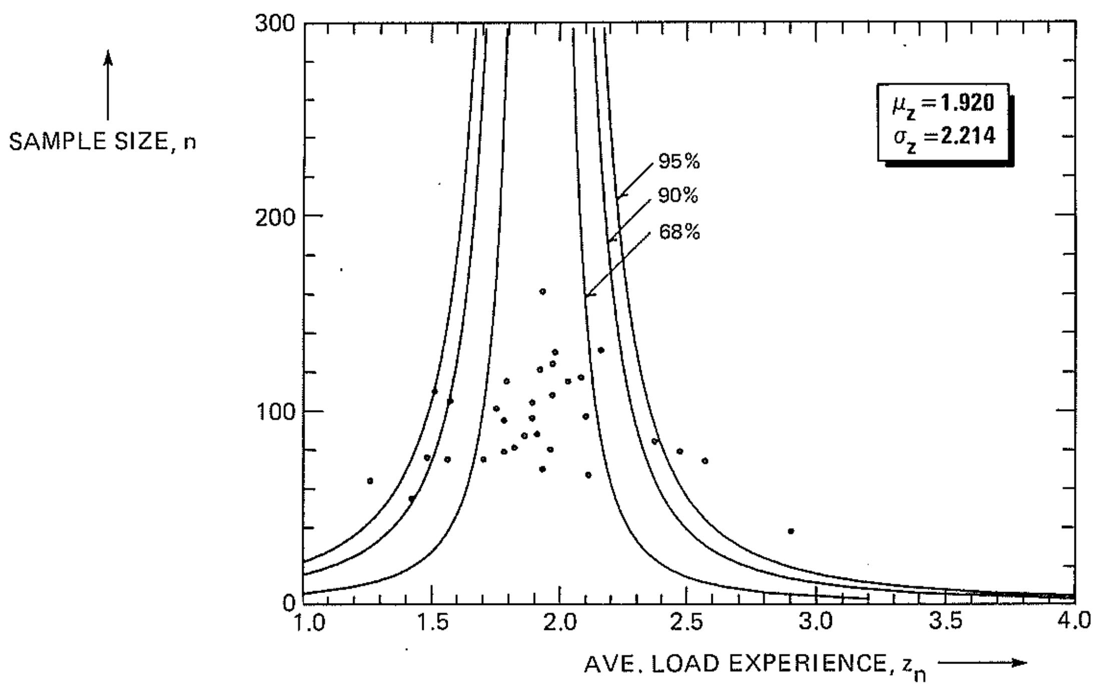
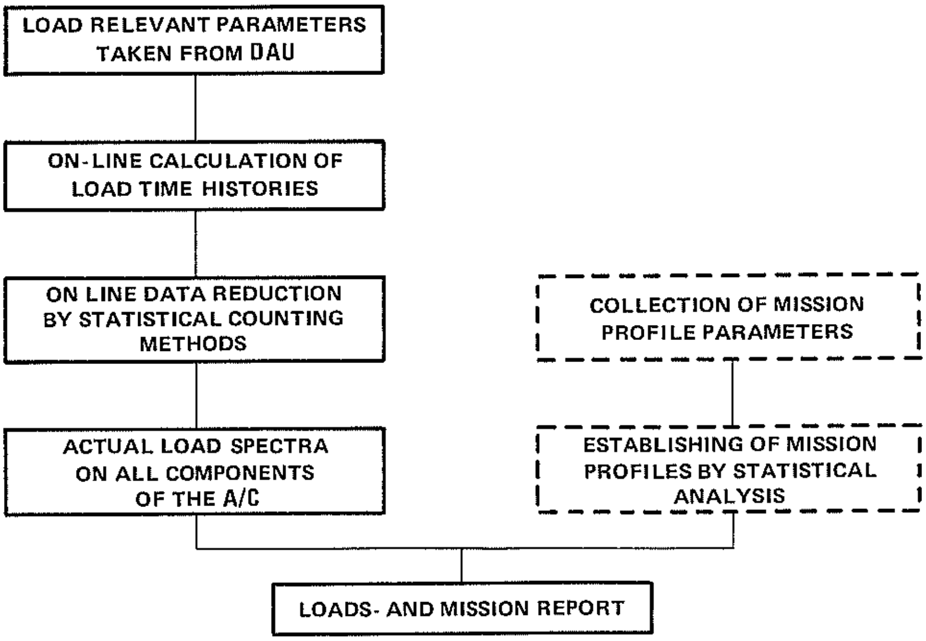
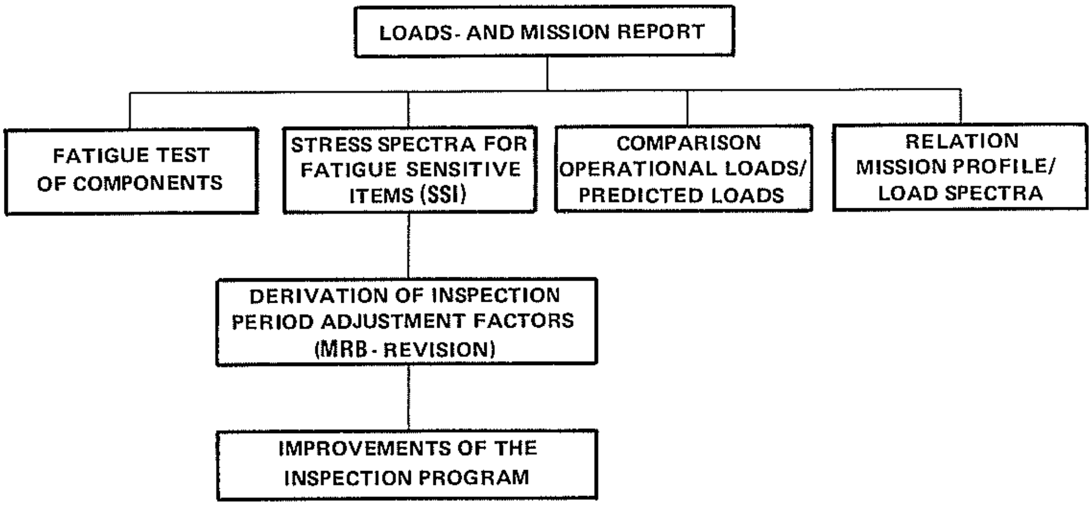


Fig. 22 Variation in load experience between Aircraft, flying the same duty (from ref. 19)



RESULTS OF LOAD MONITORING BY OLMS



OLMS FOLLOW-UP WORK

Fig. 23 Functional diagram of the OLMS-system (from ref. 24)