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Monitoring Load Experience of Individual Aircraft

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The actual service load experience of aircraft may differ appreciably from design assumptions. The necessity to monitor service loads is generally recognized now for military aircraft. This article starts with a general review of the overall life management procedure commonly used today. Specific elements in this procedure are discussed in some detail. Specific attention is paid to the amount of scatter in severity between different flights and the required sample sizes of flight load measurements for obtaining reliable average load spectrum data. Possible causes for variation in load experience between different aircraft flying the same duty are analyzed. It is concluded that individual aircraft tracking (IAT), if necessary at all, can usually be adequately accomplished by administrative means, indicated as "usage monitoring."

I. Introduction

AIRCRAFT structures have a limited fatigue life. During design, a sufficient fatigue performance under the anticipated loading environment is certified. However, the actual usage and consequent loading may (and usually does), differ considerably from the design assumptions. Therefore, monitoring of the actual loading in service and an associated reassessment of fatigue performance is required.

The general introduction of damage tolerance (DT) concepts in structural design has not relaxed this requirement. On the contrary, the DT inspection periods, necessary to maintain airworthiness, are directly related to load experience, whereas for the calculations of durability lives, considerably smaller than formerly used safety margins are applied when calculating so-called safe service lives.

Hence, service load monitoring is even more desirable than before.

This article starts with a review of the general life management procedures applied by main Air Forces today.

Specific aspects of this procedure will be discussed in more detail, using experience obtained with Royal Netherlands Air Force tactical aircraft.

Finally, special attention will be paid to the desirability of so-called individual airplane tracking (IAT), and the most effective means of such IAT.

II. Review of Life Management Procedures

Fatigue load monitoring has become a generally accepted feature for military aircraft.

Although differences in philosophy and specifically the level of sophistication exist, the overall methodology adopted by all major air forces appears to be the same. In the following we will briefly review the successive elements of the life management process.

A. Fatigue Performance Determination

Fatigue/damage tolerance analyses and tests indicate the fatigue critical locations in the structure.

A number of these, usually the most critical ones, are selected as "control points."

Service fatigue experience may provide additional control points.

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B. Flight Load Survey

Test flights with a fully instrumented and strain-gauged aircraft provide relations between flight parameters (V, n_z, $\dot{p}$, etc.) and structural loads (M, T, S).

Analyses and/or structural load tests provide relations between structural loads and control point stresses.

C. Service Load Spectra Survey (SLSS)

A limited number of operational aircraft is equipped with multiparameter recording equipment.

Measurements are used to derive, for each control point, average stress spectra pertaining to each mission type or to a specific "mission mixture."

D. DT/Durability Reassessment

SLSS results are used to redetermine durability and damage tolerance lives on the basis of 1) analytical live/crack growth calculations; 2) (comparative) tests on coupons and detail components; and 3) additional full-scale tests.

E. Load Spectrum Change Monitoring

A limited number of operational aircraft are continuously equipped with relatively simple recording devices to monitor changes in operational usage and load experience.

If such changes are observed, a new SLSS program and consequent DT/durability reassessment may be required.

F. IAT

If systematic differences in load experience between aircraft within a fleet occur, IAT may be required.

IAT is usually accomplished by means of very simple recording devices (e.g. acceleration counters, mechanical strain recorders, etc.) and/or administrative date (usage monitoring).

In the next chapters, specific aspects and problems associated with the various elements of the above procedure will be discussed in more detail.

III. Required Batch Sizes in a Load Spectra Survey

The operational sorties of combat aircraft can be divided into a number of mission types, in accordance with the nature of the "main event" during that sortie.

The average load experience depends heavily on mission type, there are light and heavy missions. This does not imply, however, that the load experience per flight tends to be a constant for a specific mission type.

The mission type may define the type of maneuvering to be done in that flight, but the duration of the maneuvering period(s) and the magnitude of maneuvers may vary. As a consequence, there appears to exist a considerable scatter in load experience among flights of the same mission type.

In Ref. 1, an extensive analysis was made of a relatively large batch of Royal Netherlands Air Force (RNLAF) F-104G flight load data.

In the following, we will present some of the obtained results to quantify our previous statements.

Counting accelerometer data of about 10,000 fully documented flights were available.

The accelerometer data for each flight was reduced to a "flight severity" z, on the basis of 1) an assumed "stress/g" as a function of takeoff configuration; 2) an assumed S-N curve; and 3) a fatigue damage calculation on the basis of Miner's rule.

Table 1 presents some of the results obtained for aircraft flying in the so-called "strike" duty.

A considerable variation in severity between the different mission types may be noted, e.g., the air-to-ground mission is on the average about 4 times as severe as the Combat Profile Mission/Navigation (CPM/Nav) mission.

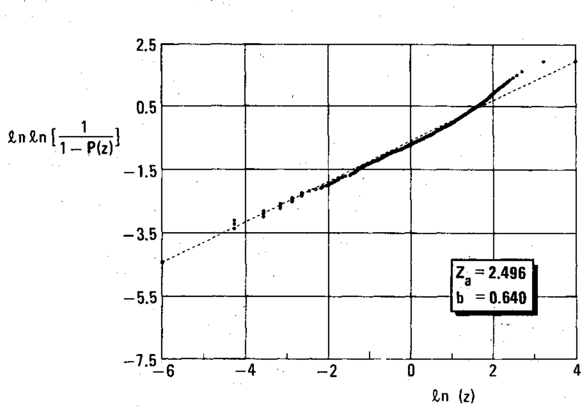

Fig. 1 Best-fit Weibull distribution. For all strike flights ($R = 0.984$).[1]

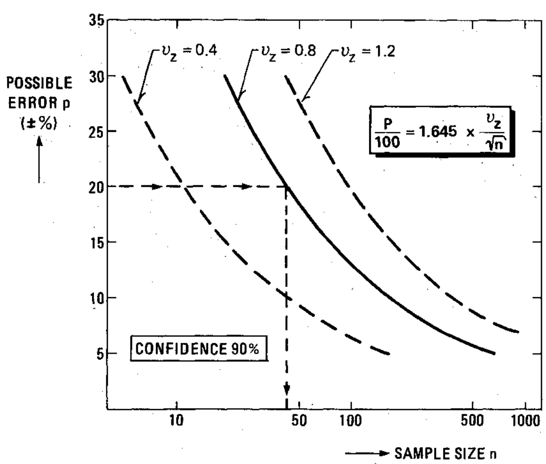

Fig. 2 Error in sample average as function of sample size n.

With regard to the variation in severity between individual flights, it was found that the data for the various data sets gave a good fit with a two-parameter Weibull distribution:

$$P(z) = 1 - \exp[-(z/z_a)^b]$$

In general, flights of more severe mission types showed less scatter and less variation in severity, resulting in higher values of the Weibull shape parameter b, and smaller values of the coefficient of variation $\nu_z = \sigma_z/\bar{z}$.

Figure 1 gives an example of the Weibull distribution fit obtained.

The data presented here refer to one specific aircraft type and operations 10 yr ago. However, recent analysis of flight load data for current RNLAF combat aircraft indicate that the F-104G scatter values might be fairly representative for combat aircraft operations in general.

Hence, these figures may give us an indication of the batch sizes, that is the number of flights to be recorded in a load spectra survey, in order to obtain reliable average load spectra.

If the load severity per flight z is a stochastic variable with mean $\bar{z} = \mu_z$ and coefficient of variation ν_z, then the average load severity of n flights z_n is also a stochastic variable with mean $\bar{z}_n = \mu_z$, and coefficient of variation $v_{z,n} = v_z/\sqrt{n}$. Also, according to the central limit theorem, the distribution of z_n will become Gaussian for larger values of n.

Hence, the following holds:

$$P\{\mu_z[1 - K_\alpha(\nu_z/\sqrt{n})] < z_n < \mu_z[1 + K_\alpha(v_z/\sqrt{n})]\} = \alpha$$

For $\alpha = 0.90$ (90% probability), the value of K_α is 1.645.

Figure 2, based on the above elementary statistics, gives the required sample size n as a function of the desired accuracy, and the coefficient of variation ν_z at a confidence level of 90%.

Referring to the data of Table 1, one may assume that a coefficient of variation $\nu_z \approx 0.8$ is fairly representative for relatively severe mission types. Figure 2 shows that in that case, to get an average spectrum estimate which does not differ more than 20% from the true average with a confidence of 90%, a sample size of 43 flights of that particular mission type is required!

The above figures show that, especially if the usage includes a number of different mission types, a valid flight load survey requires a considerable number of flights to be recorded, i.e., up to a few hundred.

IV. Life Reassessment by Comparative Tests

The DT inspection periods and durability lives established during the certification process were based on assumed design load spectra. If the service load spectra survey reveals a load experience difference from design assumptions, a reassessment of the fatigue performance is required.

Usually, such reassessment is largely based on analysis, both with regard to crack growth (damage tolerance) and fatigue life. However, if the service loading differs substan-

Table 1 Statistics of RNLAF F-104G aircraft in strike role[1]

		Flight severity, z		Best-fit Weibull parameters		
Mission type	Percentage	Average, $\bar{z}$	Coefficient of variation, v_z	z_a	b	Correlation, r
CPM/Nav	42	1.189	1.36	0.982	0.61	0.958
Air-to-ground	39	4.139	0.84	4.479	1.02	0.990
Air combat	15	4.016	0.74	4.864	0.91	0.951
Night flying	3	0.580	2.50	0.345	0.57	0.970
Miscellaneous	1	1.036	1.27	0.757	0.42	0.962
All	100	2.742	1.11	2.496	0.64	0.984

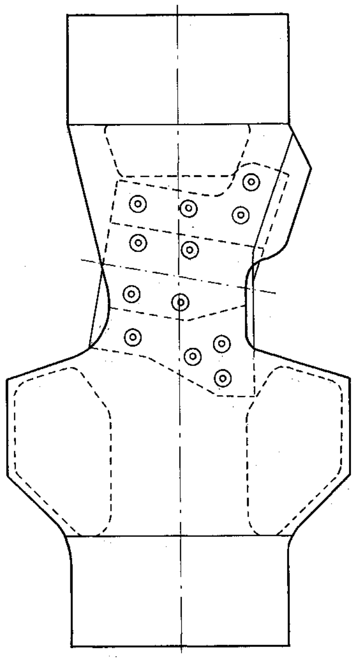

Fig. 3 Fatigue test specimen representing critical wing root lower skin area of NF-5A/B aircraft.[2]

tially from design spectra, the accuracy of such an analytical reassessment becomes doubtful, especially if the structure under consideration includes fatigue enhancing means as cold-worked holes, interference fit fasteners, etc. Sometimes, it is decided to carry out a complete new full-scale DT/durability test, especially when structural changes and modifications of the aircraft type have undermined the validity of the original certification test done on a prototype or early production structure.

This rigorous reassessment is attractive, but costly, and also time-consuming.

An attractive alternative may be the carrying out of comparative fatigue tests on specimens representing fatigue critical structural areas.

For such tests to yield valid results, a careful design of the specimen is of utmost importance.

Reference 2 describes the development of a test specimen to be used in a normal fatigue testing machine, which represents the critical wing root lower wing skin area of the NF-5A/B aircraft (see Fig. 3).

Criteria for design and production were 1) same stress distribution as in real structure; 2) same fastener pattern, fastener system, and same installation procedures; 3) same material, heat treatment, and rolling direction as in real wing; and 4) same surface treatments (anodizing, primer, etc).

The specimen was successfully used to evaluate variations in loading between different RNLAF duties and also foreign airforces.

In addition, it was found that the specimen could be used successfully to investigate changes in surface treatments, fastening techniques etc., which would hardly have been amenable for analytical evaluation.

V. Monitoring Changes in Load Spectra

The average load experience of fighter aircraft is not a constant but may (and usually does) change considerably with time. As an example Fig. 4 shows the change with time of the load severity for three RNLAF F-104G duties.

The average load severity of all duties together in 1968 was LSF = 1. For example, note that, for the Air Defence duty the load severity changed from 1.4 in 1972 to about 2.4 in 1980.

The change in severity may be due to 1) a change in mission mixture, due to a change in the aircraft role—for example the emphasis on air superiority may increase, leading to the introduction of more air combat training missions; or 2) a change of mission content, with regard to the frequency and severity of maneuvering—for example, the introduction of radar warning systems has resulted in a vast increase of evasive maneuvering during low altitude air/ground missions.

Obviously, if the operational usage changes drastically, a renewed load spectrum survey and associated life reassessment will be necessary.

To be aware of load experience changes, a continuous load monitoring activity is required.

For this spectrum change monitoring, use can be made of the equipment used in the load spectrum survey. However, this equipment is often rather extensive, requiring a relatively large effort for maintenance and data processing.

Hence, often simpler recording devices are applied, recording, e.g., the c.g. vertical acceleration or one of a few strain signals, representing the load history in significant pilot control points.

An example of this is the recording of a wing-root bending strain in RNLAF F-16 Aircraft (see Ref. 4).

A number of aircraft in each squadron are equipped with "spectrapot" recording devices, recording the values of successive peaks and troughs in a strain signal, proportional to the wing-root bending moment. Wing-root bending moment is a relevant measure for the loading of a large part of the structure, including the center fuselage. However, e.g., for outer wing sections, the relation between root bending moment and local stress will depend heavily on aircraft configuration.

For other structural areas (e.g., vertical tail) there is no direct relation at all with wing bending moment. The wing strain signal may serve for such areas as a general "maneuvering severity indicator": in a severe mission, leading to severe wing load spectra, one may expect that the vertical tail load spectrum is also relatively severe. In general, this may be true, but Fig. 5, taken from Ref. 4 shows that great caution is required.

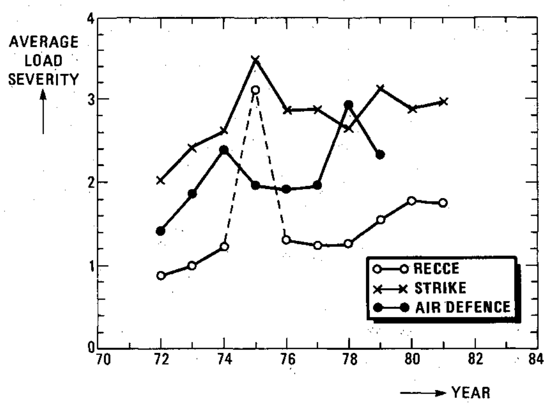

Fig. 4 Annually recorded load severity factor (LSF) for the three different duties of RNLAF F-104G.[3]

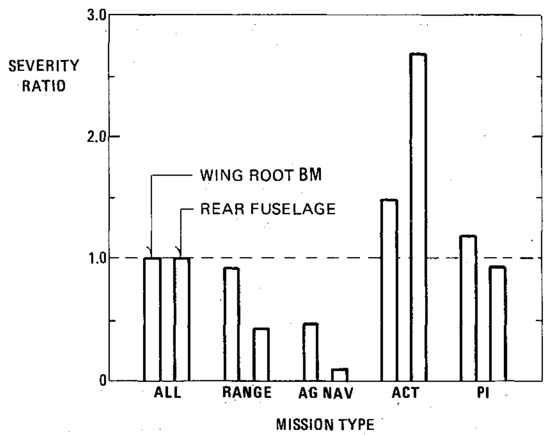

Fig. 5 Relative severities of different mission types.[4]

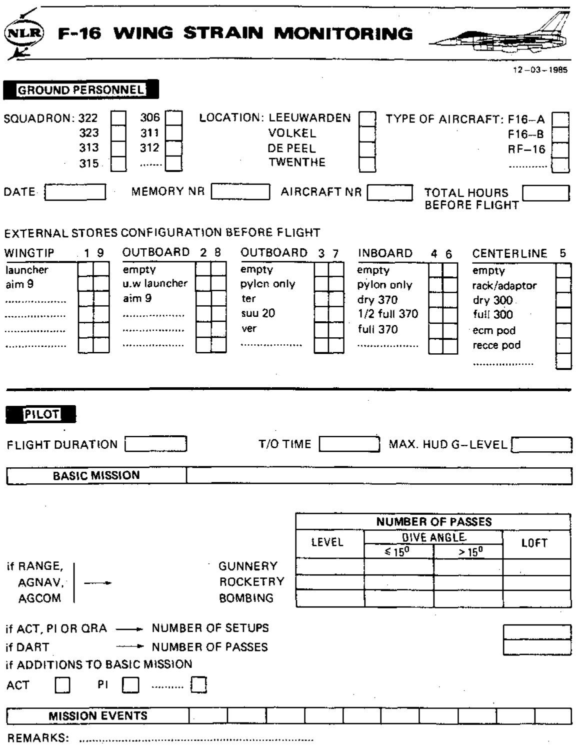

Fig. 6 Debriefing form used in spectrum change monitoring.[4]

The figure shows the relative severity of different mission types for two different control points located in the wing root and the rear fuselage, respectively. The rear fuselage location is also stressed by rudder loadings.

It appears that the "range" mission has an average severity for the wing, but is light for the rear fuselage. On the other hand, an air combat training mission appears very severe for the rear fuselage.

Hence, for a proper interpretation of recordings from one or a few channels, additional information about aircraft configuration and mission type is essential.

Therefore, the wing-root strain recordings of Ref. 4 are accompanied by documentary data and recorded on a debriefing form for each flight as shown in Fig. 6.

The spectrum change monitoring as a whole thus includes 1) monitoring mission mixtures; 2) monitoring configuration/mission distributions; and 3) monitoring stress spectra for one or a few pilot areas.

VI. Individual Airplane Tracking

So far, we considered the determination of average load experience pertaining to a specific duty or squadron.

Maintenance schedules and replacement times of all aircraft flying the same duty are based on the average duty load spectra.

If, for some reason, the load experience of individual aircraft differs appreciably from this average, this procedure may become unsafe or uneconomic and IAT may become attractive. In the following we will discuss in some detail the possible causes and magnitude of individual aircraft load variability, and the means of IAT.

A first aspect to be treated is the number of flights, and the flying period, for which the load experience (and its possible variation) should be determined.

The required service life of a fighter is at least several thousands of flights. Hence, with regard to durability we are interested in the load experience over long periods of time, at least 2000 h.

For damage tolerance control, quite different figures may prevail. Sometimes, crack growth characteristics of real structure are disappointingly poor and relatively short inspection periods may be required, specifically for repeat inspections. A typically low but not uncommon figure is a repeat inspection period of 200 flights.

In studying the possible variation in load experience over such periods, we will distinguish between 1) variation in load experience due to natural scatter, and 2) variations due to systematic differences in loading.

As discussed previously, the load experience per flight pertaining to a specific duty may be regarded as a stochastic z with mean μ_z and coefficient of variation ν_z. If the flights made by a particular aircraft in that duty are a purely random selection out of the set of possible flights, the average load experience over n flights will be a stochastic z_n with (for longer values of n) a normal distribution having a mean $\overline{z_n} = \mu_z$ and coefficient of variation $v_{z_n} = (v_z/\sqrt{n})$. This value v_{z_n}, defining the variation in load experience due to natural scatter, decreases rapidly with n, that is the inspection period of interest.

Taking $\nu_z = 1.20$ as a representative value for a relatively large scatter, and $n = 200$ as typical for a short inspection period, elementary statistics learn that, with a probability of 95%, the average load experience $\bar{z}_n$ will not exceed a value $\mu_z[1 + 1.645 \times (v_z/\sqrt{n})] = 1.14\ \mu_z$.

Hence, even for this very short inspection period, the deviation due to natural scatter from the fleet average will not exceed 15%, which is negligible in comparison with the other uncertainties in our life assessment procedures.

With regard to systematic variations. Two classes can be distinguished: 1) the average load experience per mission type differs from aircraft to aircraft; and 2) aircraft flying the same duty experience a different mission mixture.

Possible causes for the first category are systematic differences in performance and differences in piloting techniques.

With regard to differences in performance, it appears that for modern fighters these differences are very small indeed and are largely defined by the engines, which are exchanged rather frequently. Therefore, performance as a possible cause of differences between aircraft can be ignored.

Pilots are known to have a different style of flying, resulting in different load experience: one pilot flies rougher than the other. Analysis of RNLAF data by the author revealed that these differences can be appreciable. This fact may result in differences in aircraft load experience if pilots have their "own" aircraft, like a knight used to ride his own horse.

However, in many air forces, including the RNLAF, this is not so. Pilots booked out for a flight just get the airplane available; the "pilot-AC tailno." combination in each flight is fully random and differences in pilot performance cannot result in systematic load variation.

Differences in mission mixture can occur, if specific missions require specific aircraft configurations, and if the change in aircraft configuration is impossible or relatively tedious and time-consuming.

This may refer to external stores (e.g., wing fuel tanks, rocket/bomb dispenser, etc.) as well as to avionics configurations.

In Ref. 1, this effect was studied for RNLAF F-104G operations. Although the configurations of the F-104G could be changed very easily and in a few minutes it will be clear that not changing a configuration is easier.

Hence, aircraft when being brought in a configuration pertaining to a specific mission (e.g., rocket/bomb dispense for a "range" mission), tended to be kept for some time in that configuration, and to make a higher percentage of that mission during that period than according to the overall average mission mixture. For the RNLAF F-104G this effect was only of minor importance (the configurations were frequently changed) but as stated, if the change of configuration is difficult, it may lead to important variations in mission mixture, and therefore, in load experience between aircraft with nominally the same duty.

In summary, we can say that important differences in load experience between aircraft in one fleet, requiring a kind of

IAT, might have the following causes: 1) changes of aircraft duty (e.g., transfer to another squadron after depot level maintenance); 2) differences in mission mixture within the same duty (associated with configuration changes); and 3) differences in piloting technique, in case of fixed pilot/aircraft combinations.

IAT may take the form of so-called "usage monitoring" or "individual load monitoring."

Usage monitoring implies the recording, for each individual flight, of a number of administrative quantities like mission type, T.O. configuration, mission duration, etc.

Individual load monitoring implies the installation of (usually very simple) load recording devices like counting accelerometers or simple strain recorders (e.g., MSR recorder[3]) in each aircraft.

Note that usage monitoring, in combination with appropriate average load spectra per mission type, allows one to keep track of differences in load experience due to the first two causes in our list: only if differences in pilots has to be covered, then an individual load monitoring is required. However, as said before, in many air forces there is no pilot/aircraft relation and the third source of variation does not exist.

Usually, usage monitoring can be done without any additional effort as the necessary administrative data are already acquired as part of existing operational or maintenance management programs.

Individual load monitoring, on the other hand, goes with acquisition, installation, and maintenance of additional equipment.

It is felt that in many case variations in load experience between aircraft are too small to justify IAT; if IAT is desired, however, then in most cases usage monitoring should be preferred over individual load monitoring with simple recording devices.

VII. Conclusions

1) Monitoring of service load experience and assessment of the associated fatigue performance is necessary for military aircraft.

2) The variability in load experience for flights of the same mission type is large; relatively large samples are required to get reliable average mission load spectra.

3) The difference in load experience between aircraft flying the same duty is usually not very large.

4) An effective IAT can usually be obtained by means of usage monitoring.

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