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THE MONITORING OF FATIGUE LOADS

by

J. B. de Jonge, Research Engineer
Structures and Materials Department
National Aerospace Laboratory NLR
Amsterdam, The Netherlands

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J.B. de Jonge
Research Engineer, Structures
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National Aerospace Laboratory NLR,
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Abstract

To assess the consumed fatigue life of an aircraft structure, knowledge of the actual load experience of that structure is essential. Methods and techniques for monitoring structural loads are analysed and discussed. An accurate measure of structural loads can be obtained by means of strain gages installed in critical areas of the aircraft structure. At the NLR, a strain-gage monitoring system is being developed of such simplicity that it can be installed in all aircraft of a fleet. A description of this system is given, and special reference is made to the "counting technique" applied to evaluate the recorded loads.

1. Introduction

It is generally recognized nowadays that the structures of modern aircraft have become critical with regard to fatigue. This knowledge is reflected by a careful "fatigue-conscious" detail design and by the basic principle of the types of structures used; the concept of fail-safety is widely accepted, at least for civil aircraft, as a mandatory property of the aircraft structure. Moreover, the fatigue properties of new aircraft are extensively checked by either component testing or a full-scale fatigue test. Summarizing, it can be said that aircraft designers and operators have learned how to cope with fatigue. This does not mean, however, that the fatigue problem has been overcome. Every day, aviation pays a penalty to fatigue by laborious and costly inspections, modifications and unscheduled repair or, in the case of safe-life structures, by early replacement of major components or even complete aircraft.(1)
For a large extent, this is caused by our insufficient knowledge of the actual loads encountered by aircraft during operational use. Apart from the geographical variations in "loading environment" it should be mentioned that one operator may use a certain aircraft type as a rule on stretches of say 1000 n.m., whereas another operator will use the same type to cover distances of only 100 n.m. In other words, the average load experience per hour for aircraft of the same type may show considerable variations. For military aircraft, these variations may even be larger. Modern fighter aircraft are often designed to have multi-rôle capability and are consequently used for a wide variety of tasks, ranging e.g. from reconnaissance to air-to-ground attack missions. When no information is available about the specific load experience of individual aircraft it will be clear that, in order to guarantee safe flying, inspection periods and safe service lives must be based more or less on the "worst case". In other words, relatively conservative assumptions with regard to load experience have to be made. This conservatism can be reduced when information is available about the structural loads encountered by individual aircraft. Such information can be obtained from load-monitoring equipment installed in operational aircraft.

The present paper discusses different methods and techniques for monitoring fatigue loads and their associated problems and merits. At this stage the existence of so-called fatigue-gages should be mentioned. Although these devices eventually serve the same purpose as load monitoring, namely the assessment of fatigue damage, their basic principle is different as they are intended to monitor the accumulated fatigue damage directly rather than the fatigue loads. For this reason, the problems associated with these devices are of a different nature. They will not be discussed in this paper.

2. Definition of monitoring systems

Systems for monitoring operational aircraft loads can be devided into two basically different types, namely: (see fig.1)

a Systems, in which loads are monitored on a limited number of aircraft of the fleet. These systems will be indicated as: "Sample monitoring systems".

b Systems in which loads are monitored on each individual aircraft of the fleet. These systems will be indicated as "Individual monitoring systems".

The load data obtained from sample monitoring can be used to derive a statistical estimate of the load experience of an individual aircraft. In other words, the information obtained is basically of a statistical nature and the loading encountered by a specific aircraft can only be expressed with limited accuracy.

In the case of individual monitoring, on the other hand, the loading history of each individual aircraft is recorded throughout its life; the information obtained with regard to the load experience of that particular aircraft is of a deterministic nature.

It will be clear that in principle the consumed fatigue life of a specific aircraft may be calculated with a much better accuracy from individually monitored loads than it could be done on the basis of sample records. However, to reach this high accuracy it will be necessary that the individual load monitoring system complies with the following requirements:

a The loading of the aircraft structure should be monitored with a relatively high accuracy.
b The loading should be monitored in such a way that a relatively accurate calculation of fatigue damage can be made.

On the other hand, the application of individual monitoring systems is only operationally and economically feasible if
a Relatively simple, small sized and inexpensive recorder equipment can be used, that needs only little maintenance.
b The load data are presented in such a way to allow fully automatic processing and evaluation.

In the next section, techniques for monitoring loads will be discussed. It will be argued that at the present time no system is available that is suitable for individual monitoring purposes.

3. Load monitoring techniques

Suppose that from fatigue tests and/or calculations, a number of areas in an aircraft structure can be indicated as the "most fatigue critical" ones. These may be e.g. the wing root section, a station in the main spar of the vertical tail, etc.

In order to monitor the fatigue loads imposed on the aircraft, it will be necessary to record one or more parameters from which the load history in these critical areas can be deduced. The first question that arises is which quantities or parameters should be measured for this purpose. Basically there are two different solutions to this problem:
a Measurement of movement parameters, such as c.g. accelerations, rotational velocities and speed. From these parameters the external loads imposed on the structure, and hence the internal structural loads can be deduced.
b Strain measurements within the critical areas, defining the internal load history in these areas.
The technique of measuring movement parameters will be discussed first.

It is current practice to express the loading of an aircraft in terms of "load factor" or c.g. vertical acceleration. In fact, this quantity is the basic load parameter in nearly all load monitoring systems which are currently in operation. Several simple and reliable accelerometer systems are commercially available, they can easily be maintained and calibrated and can be interchanged from aircraft to aircraft. A vast amount of very useful information has been and is being obtained from accelerometer data. However, the limitations of acceleration recording are obvious:
a The loading condition of several structural elements, such as vertical tail, landing gear, control surfaces etc. is not related at all to c.g. vertical acceleration. In fact, the load factor n_z can only be taken as a measure for the loading of wing and fuselage.
b The airload imposed on wing and fuselage is proportional to acceleration times aircraft mass rather than acceleration alone. The structural loads due to inertia depend heavily on mass distribution.
The aircraft mass and mass distribution may change considerably during one flight due to fuel consumption and possible store release. This is illustrated in fig.2 for a typical fighter-bomber mission. It can be noted that the "Wing Root Bending Moment per g" varies from 0.89 to 1.47 (arbitrary units) during one flight; obviously load factor alone is a poor measure for the wing bending moment with this type of aircraft.
c The distribution of the air load depends heavily on the aircraft speed, flap position and, in the case of variable geometry, wing sweep position.
d Loads due to structural resonances are not properly represented by the c.g. acceleration.

A number of these shortcomings can be eliminated or reduced by simultaneous recording of other parameters such as speed, altitude, control surface and wing sweep position etc. From such multi-parameter recordings the actual structural loads may be computed with fair accuracy. However, it will be clear that the amount of computational work involved, together with the complexity of the required recording equipment makes this technique suitable only for sample monitoring purposes.

It is our conviction that the combination of simplicity and accuracy, required for individual monitoring systems, can only be obtained by a more direct measurement of the internal loads in the structure. This may be done by measuring strains in the critical areas of the structure. To avoid misunderstanding it should be made clear that this does not imply the installation of strain gages exactly on the spot where a fatigue crack is expected to start. Suppose that during fatigue testing a failure occurred in a wing spar. A strain gage bridge should then be installed in such a way that its output is a measure for the bending moment in that area of the wing spar.

It has to be noted that in fatigue tests on large-scale aircraft components it is usual to install a number of strain gages in order to check the load distribution obtained in the test. Obviously, when the locations of monitoring gages coincide with those of gages installed during the fatigue test, the comparison of the test-load history and the loads encountered in actual service is greatly facilitated.

Strain measurements in flight have been carried out successfully for several years. As an example, strain monitoring programs carried out in Germany by the LBF on civil transport aircraft (2) should be mentioned. It has been shown that strain gages, when carefully installed and protected, can be used over long periods of time. However, the type of recorder equipment used and the associated techniques for processing the recorded data in these programs are too complicated to allow application on a large scale. In fact, it turns out that at present a suitable strain-monitoring system for individual load monitoring purposes is not available. For this reason the National Aerospace Laboratory NLR is presently developing such a system. It turns out that the basic problems of such a system are not associated with the electronic hardware; the present state of the art is such that the necessary electronic equipment such as small and reliable d.c. amplifiers, a-d converters etc. can be produced at relatively low cost. Simple magnetic tape recorders are becoming commercially available. The basic problem is to monitor the experienced loads in such a way that the necessary amount of data processing will be limited while still allowing sufficiently accurate damage calculations. In the next section possible techniques for reduction and evaluation of recorded load data will be briefly discussed. Finally, a description will be given on the NLR-monitoring system, with special reference to the method used for evaluation of the monitored loads.

4. Techniques for the evaluation of monitored fatigue loads

Normally, the fatigue strength of a structure is defined as the number of load cycles to failure under a cyclic load with amplitude S_a and mean value S_m. The fatigue damage due to a successive series of load cycles with different S_a and S_m may be calculated using a "cumulative damage rule".

Now, the time-history of an aircraft load will usually show a rather random picture, as indicated in fig.3. In order to calculate the associated fatigue damage, this load history has to be "translated" in a series of successive load cycles. This translation process can be divided in two phases. In the first phase, indicated as "reduction phase" the load-time trace is simplified or reduced but in such a way that the reduced record still contains all the information of the original record which is relevant to fatigue. In the second phase, which will be called the "counting phase" the reduced record is converted into a number of separate load cycles.

4.1 Reduction

The fatigue damage of a load cycle is defined by its mean and amplitude. This means, and tests have confirmed this, that the exact shape of the load variation, e.g. whether it is triangular or sinusoidal, has no influence. Moreover it turns out that within certain limits the duration of the load cycle has no influence on its damaging effect; for the type of loads considered here the so-called frequency effect may be ignored. As a consequence, the load-time history of fig.3 can be simplified to the reduced record indicated in fig.4. In a digital sense, the reduced record consists of a series of digital values, representing the magnitude of the successive extremes ("maxima and minima" or "peaks and troughs") contained in the load history. Considering the fact that very small load variations do not contribute to the fatigue damage, the record may be further reduced as indicated in fig.5 by eliminating the successive maxima and minima that differ less than a certain value. It should be noted that the reduction described here may be done with relatively simple electronic means within the airborne monitoring equipment.

4.2 Counting methods

In the previous sub-section, the reduction of the load record to a series of peak-values was discussed. The methods used to evaluate this reduced record can be roughly divided into two types, viz. a) peak-count methods and b) range count methods.

a) Peak-count methods

For a number of different load levels, the number of load extremes that have occurred above each level are counted. This is done both for load maxima and load minima. A variation of this method is the counting of level-crossings, as incorporated in the so-called counting accelerometers. As the number of exceedings of a certain load level is equal to the number of maxima minus the number of minima, above that level, it will be obvious that peak-counting and level-cross counting are directly related. A load cycle is defined by the values of a maximum and a successive load minimum. The result of a peak-counting gives the frequency and magnitude of the maxima and minima, but no information on their sequence of occurrance. In other words, a transfer of peak-count results into "load-cycles" requires assumptions with regard to the sequence of maxima and minima. For example, a maximum is often combined with a minimum that has the same frequency of occurrance. This is usually considered as conservative assumption. More sophisticated assumptions with regard to peak-sequence can be made on the basis of statistical information. Due to their simplicity, peak-count methods are very useful for the evaluation of load records that are used in a statistical sense. However, it is our conviction that when a relatively high accuracy is required, as in the case of individual monitoring, a more rational technique based on the counting of load ranges should be applied.

b) Range-count methods

The range-count method in its simplest form is sketched in fig.6. In the load trace x_1, x_2, x_3, x_4 three "load ranges" or "half load cycles" can be distinguished with respective amplitudes

$$S_{a_1} = \frac{|x_1 - x_2|}{2}, \quad S_{a_2} = \frac{|x_2 - x_3|}{2}, \quad S_{a_3} = \frac{|x_3 - x_4|}{2}$$

and mean $S_{m_1} = \dfrac{x_1 + x_2}{2}$, etc.

This procedure, however, has a serious shortcoming. Suppose that due to some filtering action the small load variation defined by x_2 and x_3 was not monitored; in that case the counting result would have yielded only one relatively large load variation $\dfrac{|x_1 - x_4|}{2}$ instead of three smaller ones.

In other words, the result of the counting depends heavily on the magnitude of the smallest load variation considered. In fact, the counting result is not well-defined.

The so-called range pair count method, illustrated in fig.7, does not have this disadvantage. The load trace x_1, x_2, x_3, x_4 is considered here as a major load variation $x_1 - x_4$ on which is superimposed a small load cycle or "range pair " with amplitude $S_a = \frac{|x_2 - x_3|}{2}$ and mean $S_m = \frac{x_2 + x_3}{2}$.

The filtering previously mentioned will result in a neglect of this small load cycle; the counting result for bigger variations will not be influenced.

For a more rigorous description of counting principles, reference has to be made to the literature.[3] At this place it should be mentioned that the counting method applied in the NLR-monitoring system, which will be described in the next section, is basically a combination of the two range-count techniques discussed.

5. Description of the NLR-fatigue-load monitoring system

Fig.10 gives a diagram of the fatigue load monitoring system that is presently being developed at NLR. The different elements will be discussed here, starting with the part of the system that will be mounted in an aircraft.

a Load transmitters

In a number of critical areas, strains are measured using normal electrical resistance strain gages. The number of critical areas, and hence the number of strain channels needed, depends on the aircraft type involved. However, it is thought that a maximum of 6 channels will be sufficient in most practical cases.

b Conditioning, digitizing and reduction

The (analog) signal of each channel is amplified, digitized and reduced, using the reduction technique described in the previous section. A digital resolution of 32 (= 2^5) is thought to give sufficient accuracy.

c Recording

The reduced load records of each channel, which consist of a series of digital values representing the magnitudes of the successive peaks and troughs, are fed into a magnetic tape recorder. This may be a simple recorder which is used solely for fatigue-load monitoring purposes or a more complex so called AIDS-recorder. The required data-compatibility can be provided, when necessary, by relatively simple means. To restrict the amount of work associated with the system in operational aircraft use, it is thought that a minimum recording time of 20 hours is mandatory.

d Evaluation of recorded load data

The tapes with recorded loads, together with some written information (A.C. number, recording period) are sent to a central ground facility for further processing. For the evaluation of the load records a counting method has been developed at NLR. A flow diagram of this method is given in fig.9. The method consists of two phases. In the first phase, the reduced record is analysed in the following way.

Starting with i=1, four successive peaks x_i, x_{i+1}, x_{i+2}, x_{i+3} are considered. If the condition is met that both x_{i+1} and x_{i+2} fall within the interval bounded by x_i and x_{i+3} (see fig.8), a count is made of two half-cycles with amplitude

$$S_a = \frac{|x_{i+1} - x_{i+2}|}{2} \quad \text{and mean} \quad S_m = \frac{x_{i+1} + x_{i+2}}{2}$$

Next, the values x_{i+1} and x_{i+2} are deleted from the record, and the procedure is repeated for the four extremes x_{i-2} , x_{i-1} , x_i and x_{i+3}.
When the previously mentioned counting condition is not met, the value of i is simply increased with one, etc. It can easily be verified that, after the whole record has been analysed in this way, a "residue record" remains, which consists of a series of diverging numbers, followed by a series of converging numbers, as indicated in fig.11.

In the second phase, this residue record is analysed according to the simple range count method discussed in the previous section. That means, in the residue record x_1, x_2, $x_3 \ldots x_n$, a series of successive half-cycles with respective amplitudes $\frac{|x_1 - x_2|}{2}$, $\frac{|x_2 - x_3|}{3}$ etc. and means $\frac{x_1 + x_2}{2}$, $\frac{x_2 + x_3}{3}$ are counted.
These counts are added to the result of the first phase. It will be clear that the total result of the counting can be described as the number of cycles $n(S_a, S_m)$ with amplitude S_a and S_m, for each possible combination of S_a and S_m. However, it is thought that due to its two-dimensional character, such a presentation of the counting is difficult to survey.

Considering the well-known fact that fatigue damage is primarily defined by the amplitude of the load and to a lesser extent by its mean value, it was decided to calculate an average mean $\overline{S_m}(S_a)$, pertaining to each amplitude value, and to keep an information about the variations in the S_m-value, the standard deviation of the mean,

$$\sigma_m(S_a) = \sqrt{\overline{S_m^2}(S_a) - \left[\overline{S_m}(S_a)\right]^2}.$$

From fig.9 it can be seen that in fact this averaging technique is incorporated in the counting procedure.

Hence, the counting result can be described in a one-dimensional form, viz. for each possible value of S_a:

1. The number of cycles with amplitude S_a, $n(S_a)$
2. The "average mean" of these cycles , $\overline{S_m}(S_a)$
3. The standard deviation of the mean , $\sigma_m(S_a)$

e Damage calculations

Fig.2 gives a possible form in which the counting result can be presented. The load experience defined in such a way can be compared with

i) Load experience of other aircraft of the same type.
ii) The load spectrum applied in the full-scale fatigue test.

Moreover, although the discussion of fatigue damage calculations is beyond the scope of the present paper, it should be noted that the counting result is very well suited to be applied in a computerized damage calculation such as the one based on the Palmgren-Miner cumulative damage rule.

6. Conclusions

1 Modern aircraft structures may be critical with regard to fatigue. For reasons of both economy and servicability a fatigue load monitoring system is then highly desirable. Such a system should preferably be installed in all aircraft of a fleet.

2 Accurate information about the actual loads encountered in service may be obtained by means of strain gages located in critical areas of the aircraft structure.

3 At NLR a system for monitoring fatigue loads based on strain measurements is currently being developed.

4 This system will be sufficiently simple to allow instrumentation of large numbers of aircraft.

7. References

1 Morgan, R.C. — Some thoughts on the economics of fatigue. Paper presented at the 5th ICAF Symposium, Melbourne May 1967.

2 Buxbaum, O. Gassner, E. — Häufigkeitsverteilungen als Bestandteil der Lastannahmen für Verkehrsflugzeuge. Luftfahrttechnik-Raumfahrttechnik 13, Nr.4, April 1967.

3 Schijve, J. — The analysis of Random Load-Time Histories with Relation to Fatigue Tests and Life Calculations. 2nd ICAF-AGARD Symposium, Paris, 1961. NLR Report MP 201, May, 1961.

1 **SAMPLE MONITORING SYSTEMS**

ONLY A LIMITED NUMBER OF AIRCRAFT EQUIPED WITH LOAD MONITORING DEVICES.

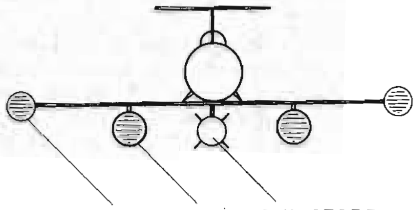
MEASURED LOADS CAN BE USED FOR STATISTICAL ESTIMATE OF LOAD EXPERIENCE OF INDIVIDUAL AIRCRAFT.

2 **INDIVIDUAL MONITORING SYSTEMS**

EACH INDIVIDUAL AIRCRAFT EQUIPED WITH LOAD MONITORING DEVICES.

DIRECT INFORMATION ABOUT LOAD EXPERIENCE OF EACH INDIVIDUAL AIRCRAFT IS OBTAINED.

FIG. 1 DEFINITION OF LOAD MONITORING SYSTEMS



CONFIGURATION	A.C. WEIGHT (1000 lbs)	ROOT B.M. PER g (ARBITRARY UNIT)
TAKE-OFF	29	1.00
P.T. EMPTY	26	1.04
T.T. EMPTY	24	1.47
C/L STORE DROPPED	22	1.32
5 % INT. FUEL	16	0.89

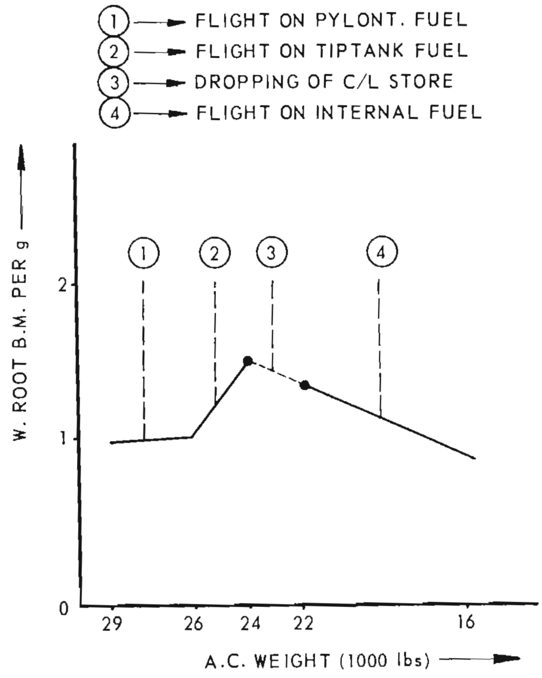


FIG. 2 VARIATION OF THE WING ROOT BENDING MOMENT PER g FOR A TYPICAL FIGHTER-BOMBER MISSION

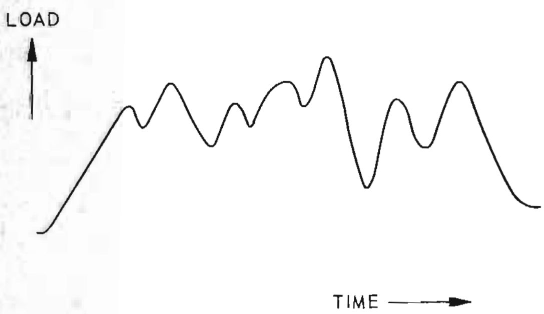


FIG. 3 LOAD-TIME HISTORY, SHOWING A RATHER RANDOMLY VARYING PICTURE

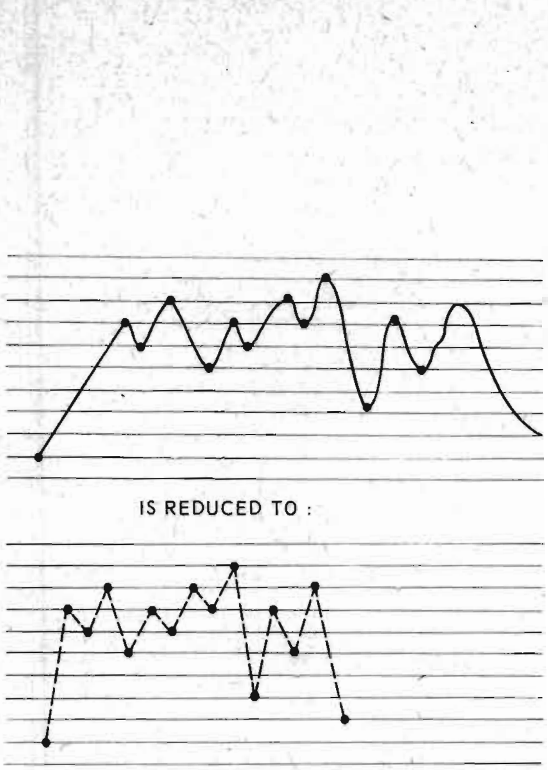


FIG. 4 REDUCTION OF THE LOAD–TIME TRACE OF FIG. 3

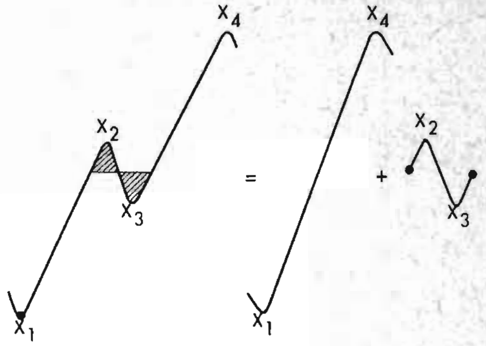


FIG. 7 PRINCIPLE OF THE RANGE–PAIR COUNT METHOD

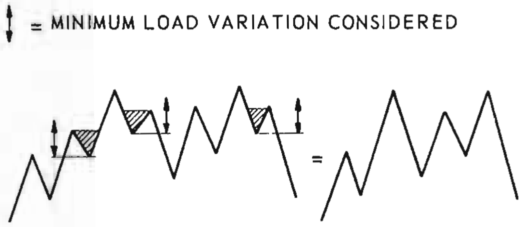
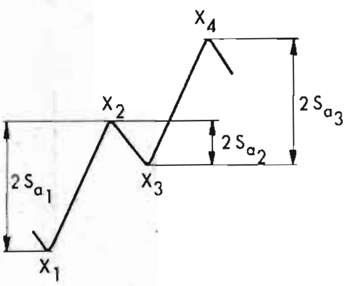


FIG. 5 FURTHER REDUCTION OF THE LOAD–TIME TRACE

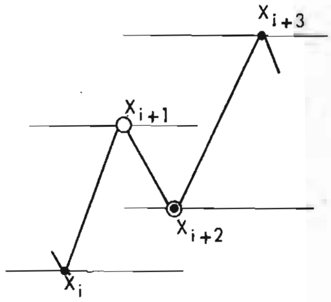


$$S_{a_1} = \frac{|X_1 - X_2|}{2}$$

$$S_{a_2} = \frac{|X_2 - X_3|}{2}$$

$$S_{a_3} = \frac{|X_3 - X_4|}{2}$$

FIG. 6 PRINCIPLE OF THE RANGE–COUNT METHOD



CONDITION FOR COUNTING A LOAD CYCLE WITH

$S_a = \frac{|X_{i+1} + X_{i+2}|}{2}$ AND

$S_m = \frac{|X_{i+1} + X_{i+2}|}{2}$:

IF $X_{i+3} \geqslant X_i$,

$X_{i+1} \leqslant X_{i+3}$ AND

$X_{i+2} \geqslant X_i$;

IF $X_{i+3} < X_i$,

$X_{i+1} \geqslant X_{i+3}$ AND

$X_{i+2} \leqslant X_i$

FIG. 8 COUNTING CONDITION IN PHASE I OF THE N L R – COUNTING METHOD

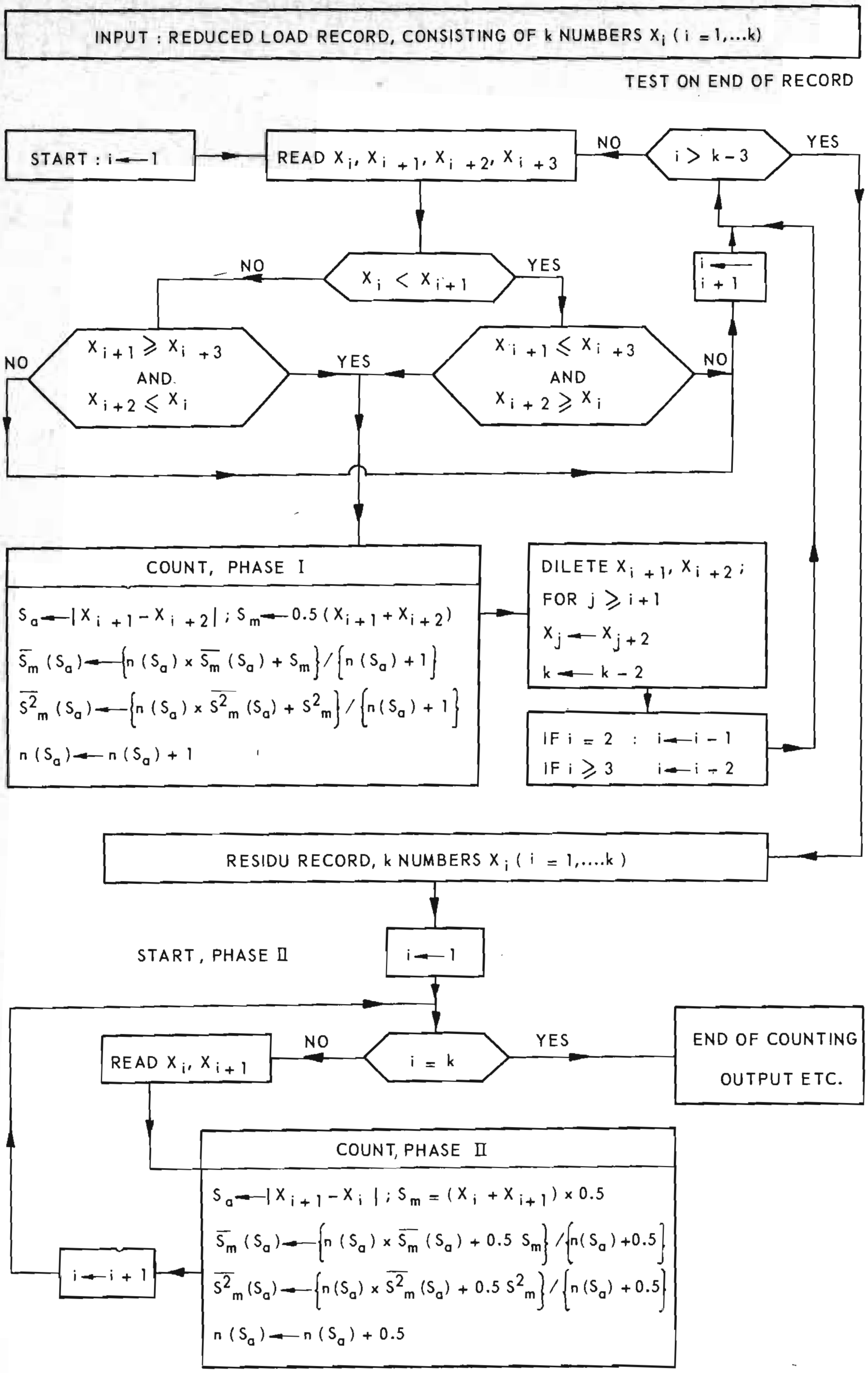


FIG. 9 FLOW DIAGRAM OF NLR COUNTING METHOD

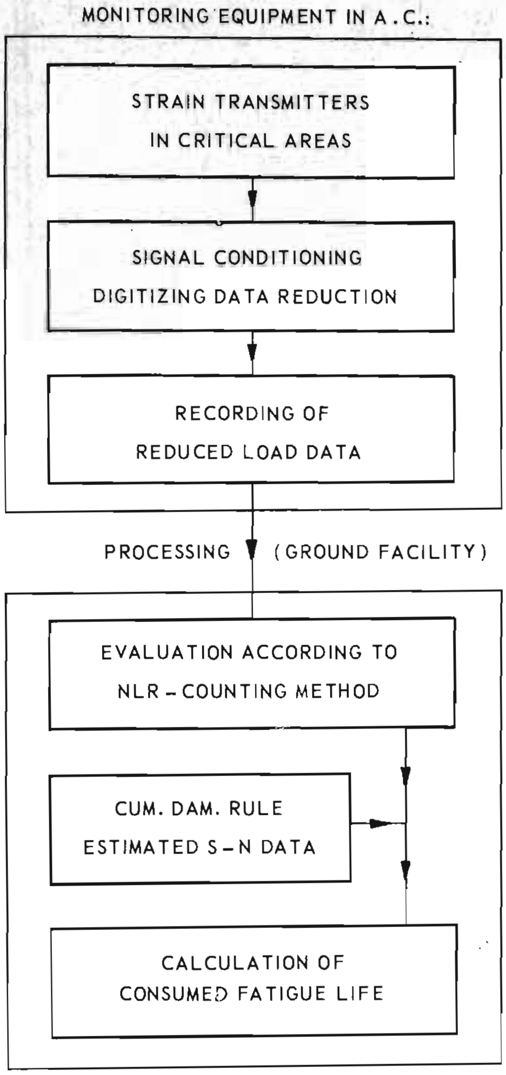


FIG. 10 DIAGRAM OF FATIGUE ASSESSMENT SYSTEM

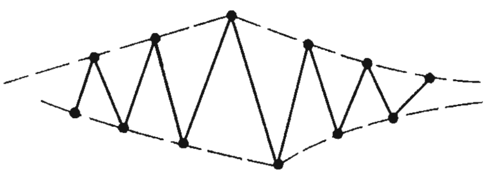


FIG. 11 SHAPE OF THE RESIDUE – RECORD AT THE END OF COUNTING PHASE I

AIRCRAFT SERIAL NR. :

RECORDING PERIOD :

FLYING HOURS :

FORMER TOTAL :
PRESENT RECORD :
NEW TOTAL :

LOAD COUNTS :

CHANNEL NR. :

S_a →		1	1.5			15.5	16
FORMER TOTAL	n						
	$\bar{S}_m$						
	σ_m						
PRESENT RECORD	n						
	$\bar{S}_m$						
	σ_m						
NEW TOTAL							

CHANNEL NR. :

S_a →		1	1.5			15.5	16
FORMER TOTAL							

FIG. 12 POSSIBLE PRESENTATION OF MONITORED FATIGUE LOADS