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IMPROVING THE ACCURACY OF FATIGUE DAMAGE CALCULATIONS FOR ARCHIVED DATA

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ABSTRACT

Historical operational usage data give a ground for fatigue damage estimation. Quality of sensors and recorders two or more decades ago were lower then modern one. Lack of resolution in *nz*-level measurement and recording leads to some errors in fatigue damage calculations. In this paper author propose a method to improve the accuracy of fatigue damage calculations for archived data. The method takes advantage of typical distribution of accumulated cycles for aircrafts. Small correction in representative *nz* value taken in calculations can reduce the error in fatigue damage assessment.

Keywords: Fatigue damage, nz, aircrafts, recorders, calculation, cycles, error.

INTRODUCTION

In order to estimate the current fatigue damage of the structure it is necessary to analyse information on the history of the alternating load acting on the structure. For fixed frequency and fixed amplitude loads, it is sufficient to determine the operating time of the unit. The situation becomes more complicated when the loads are random in terms of both amplitude and frequency. Random loads are typical for aircraft structures. In the case of an airline plane, it is wind gusts that are mainly responsible for the variation of loads. In the case of military aircraft and those used for training or aerobatics, aircraft manoeuvres are the main factor generating variable loads.

The problem of aircraft structure integrity was noticed in the 1950s. Crashes of the Comet aircraft [1] indicated the limited fatigue life of the structure. Given the necessity to minimize the aircraft mass, it is not possible to reduce the stress level in the structure to such a level that the material fatigue phenomenon is completely eliminated. Because of a high cost of new aircraft, there is a common need to extend the service life [2, 3]. Many countries undertake periodic modernization of their aircraft. Unfortunately, renovation does not remove the fatigue damage accumulated in the material. Therefore, in such a case it is necessary to estimate the degree of fatigue damage of a particular aircraft components and make an economically justified decision on the scope of the overhaul.

Currently manufactured aircraft are equipped at the production stage with sensors and recording equipment which enables automatic monitoring of loads of individual aircraft elements. Load history records are systemically collected and secured for future fatigue life calculations [4].

In aircraft manufactured in the second half of the 20th century, such solutions were not used. As the technology evolved, the first devices for counting the loads acting on the aircraft appeared in the late 20th century. It was commonly accepted to use a signal describing aircraft overload (*nz* signal) to describe load variations. This was mainly due to the fact that the *nz* sensor has been installed in airplanes for a long time and is relatively well correlated with the loads on the plane wing surfaces and thus with the wing-fuselage connection. For most aeroplanes the wing-fuselage connection is critical from the fatigue life's point of view. For other locations this compliance is worse and the use of the *nz* signal for estimating fatigue wear is characterised by high uncertainty.

Historically, the first attempts to monitor the fatigue consumption of aircraft involved the installation of load cycle recorders on board. An example is the fatigue-meter shown in Fig. 1.

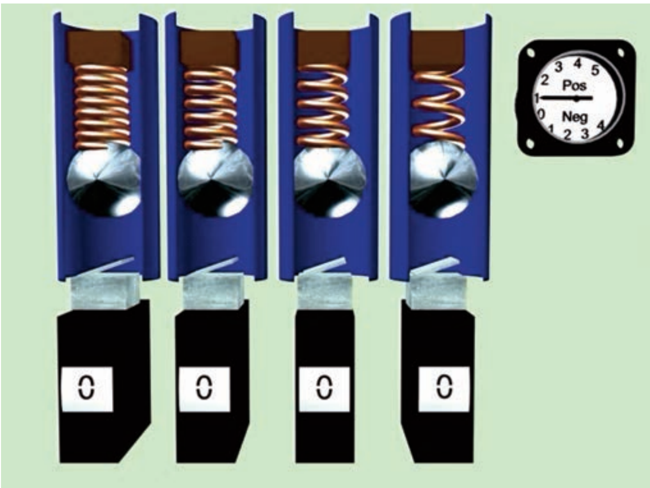

Figure 1. The principle of the mechanical fatigue-meter operation.

The aircraft overload acts on a set of masses placed on springs of different stiffness. Depending on the size of the overload, a different number of masses come into contact with the limiter, which causes the counter increment. In this way, it is possible to count load cycles with a specific overload value. Different types of Tables containing the multiplication factor of the defined *nz* levels are typical historical aircraft load data.

ACCURACY OF FATIGUE FAILURE CALCULATIONS FOR DATA IN THE FORM OF CYCLE MATRIXES

A typical cycle matrix defining the historical loading of the aircraft is shown in Fig. 2.

An important feature of the matrix is the number of nz levels for which cycles are counted. This has a large impact on the accuracy of the fatigue life calculation because all cycles in a certain range are treated equally. Most often the historical data include cycle counting with an accuracy of $\Delta nz = 1$.

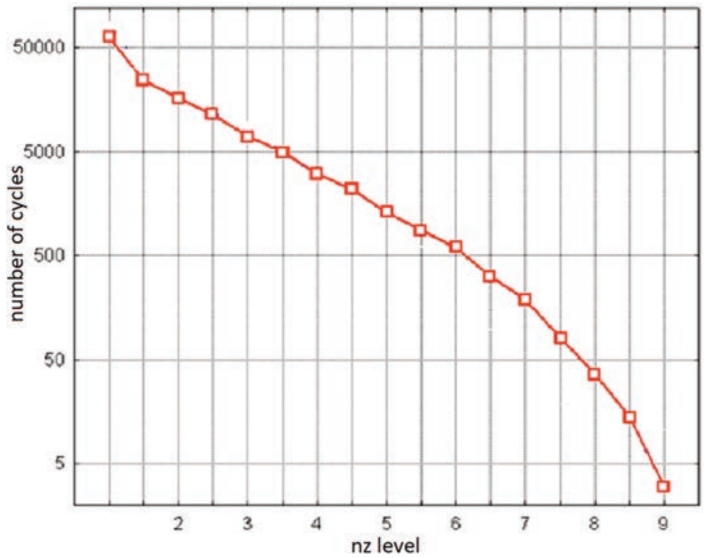

Figure 2. The example of cycle matrix for MiG-29 aircraft [6].

More accurate calculations are possible for $\Delta nz = 0.5$ or $\Delta nz = 0.25$.

An example showing the influence of the size of the cycle counting interval on the fatigue damage calculations is presented below. The calculations were carried out for the PZL-130 Orlik trainer using the following assumptions described below.

Fatigue damage calculations were performed for the S-N curve plotted from the [5] whose equation has the form of:

$$\sigma_a [MPa] = 1023 N^{-0.12} \tag{1}$$

$$N = \left(\frac{\sigma_a [MPa]}{1023} \right)^{-8.33} \tag{2}$$

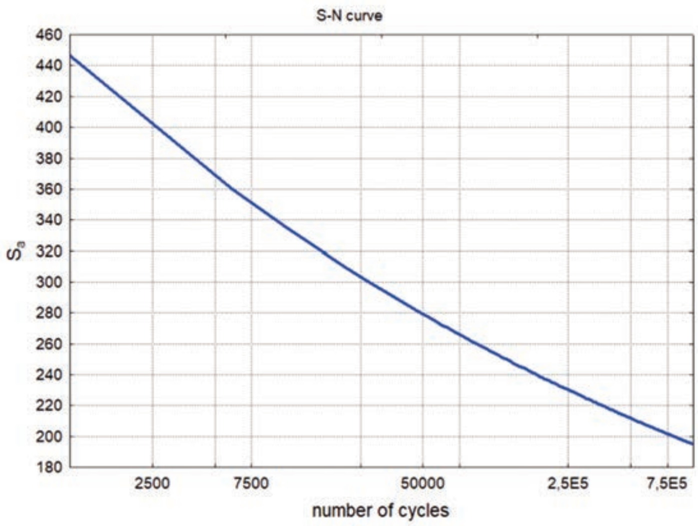

Figure 3. S-N curve accepted for calculations.

The calculation was made for a series containing 1000 cycles, which approximately corresponds to 2 hours of flight time of this aircraft. All load strings were generated in a random way using the inverse distribution method. The basis for building the inverse distribution was the cycle matrix for the aircraft shown in Table 1.

Table 1. Cycle matrix used in calculations.

Nz level	Number of cycle	Distribution value
1	25000	0.87556
2	3000	0.98063
3	450	0.99639
4	90	0.99954
5	12	0.99995
6	1	1

For the discrete values of the distributions presented in Table 1, the function being the inverse distribution of the form was approximated:

$$nz_r = \ln\left(\frac{7.97}{1-x}\right)^{0.482} \tag{3}$$

Where:
nz_r – random *nz* value,
x – random number from the range <0.1.

Depending on the number of compartments into which the cycles were classified, different cycle matrices were obtained. Table 2 presents cycle matrices for $\Delta nz = 1$ and $\Delta nz = 0.5$.

Table 2. Cycle matrices for $\Delta nz = 1$ and $\Delta nz = 0.5$.

Nz range	Number of cycles $\Delta nz = 1$	Number of cycles $\Delta nz = 0.5$
1 – 1.5	850	624
1.5 – 2		226
2 – 2.5	128	86
2.5 – 3		42
3 – 3.5	20	17
3.5 – 4		3
4 – 4.5	1	0
4.5 – 5		1
5 – 5.5	1	1
5.5 – 6		0

As a result of counting the cycles and qualifying them into ranges, information about the actual amplitude of the cycles is lost.

Fatigue damage calculations made for the same random population of cycles give different results. For the case presented above, fatigue damage calculations using the S-N curve (1 and 2) gave the results shown in Figure 3. The following relation between the value of *nz* and the amplitude of the stress cycle was used in the calculations:

$$\sigma a[MPa] = 25(nz)[MPa] \tag{4}$$

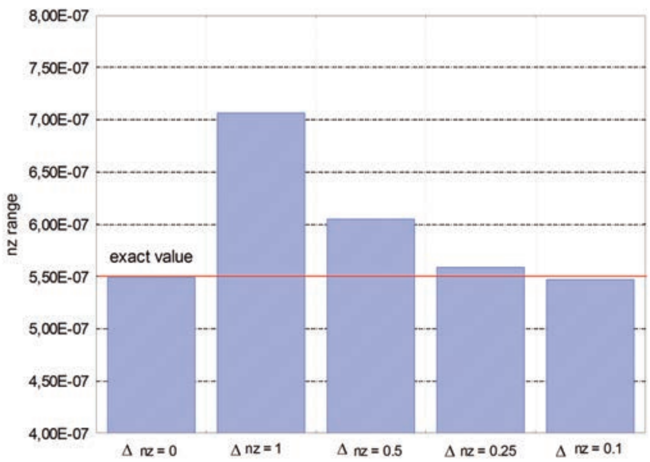

Figure 4. The results of fatigue calculations depending on Δ*nz*.

Figure 4 shows that reducing *nz* during cycle counting improves the accuracy of fatigue calculations. In the case of $\Delta nz = 1$, the error of the calculated fatigue damage was about 50%!

IMPROVEMENT OF CALCULATION ACCURACY

In the case of aircraft, the cycle matrix, although unique for each aircraft, shows a certain important common feature – the number of cycles at subsequent higher levels is much lower than the number of cycles at a lower level. This is a feature related to the operation of the aircraft.

As a result, the calculation of fatigue damage based on the cycle matrix gives an overestimated result in the vast majority of cases. This is because the middle value is taken as a representative value of the cycle amplitude for the range. It is therefore assumed that half of the cycles included in a given range have a value greater than the middle value. This is not true for actual cycle matrices obtained from monitoring *nz* values of aircraft. The distribution of the range amplitude values is not uniform.

This paper proposes to modify the method of fatigue damage calculation based on the cycle matrix in order to improve the accuracy of calculations.

The classic method of fatigue damage calculation involves summing up the defects calculated for each element of the cycle matrix, taking the middle value of the range as the representative value for the whole range of calculated cycles.

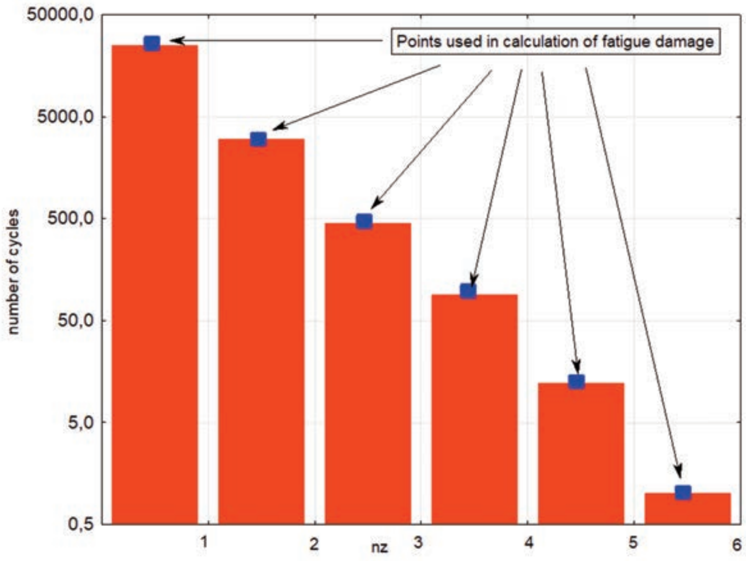

Figure 5. Points used in the classic method of calculating fatigue damage.

The fatigue damage calculated for the cycle matrix based on linear fault accumulation is determined by the relationship:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{5}$$

Where:
n_i – number of cycles for i *nz* level,
N_i – number of cycles to destruction for the i level (value determined from the S-N curve).

By substituting (2) to (5) we will get:

$$D = \sum_{i=1}^{k} \frac{n_i}{\left(\frac{\sigma_i}{1023}\right)^{-8.33}} \tag{6}$$

Where:
i – cycle amplitude for i *nz* level.

The classical calculation method assumes that the value σ_i corresponds to the middle of the range of the cycles to be counted. For example, if the interval includes cycles for which the relation:

$$1 < nz < 2 \tag{7}$$

For the calculation, the value σ_i corresponding to $nz = 1.5$ (centre of the range) is used.

Due to the actual distribution of cycle values for each interval, this counting method results in an overestimation of fatigue life. This is because most of the cycles in a given interval have the value lower than the average value.

The proposed method of improving the accuracy of calculations involves selecting a point other than the center of the range for calculation according to (6). It is proposed that this point should be the one defined by the equation:

$$\sigma_i = k\left(nz_i + x\Delta nz\right) \tag{8}$$

Where:
nz_i – lower nz value characterizing the counting interval nz,
Δnz – size of counting interval nz.

From the accepted determinations it follows that, for the classical method, $x=0.5$.
A change in the value of x may improve the accuracy of durability estimation according to (6). The optimum value of x depends on the form of the S-N curve and the actual distribution of cycle sizes in the population studied.
For the example described in this chapter, simulation tests were conducted.
The effect of the x-value on the fatigue damage calculation error is shown in Figure 6.

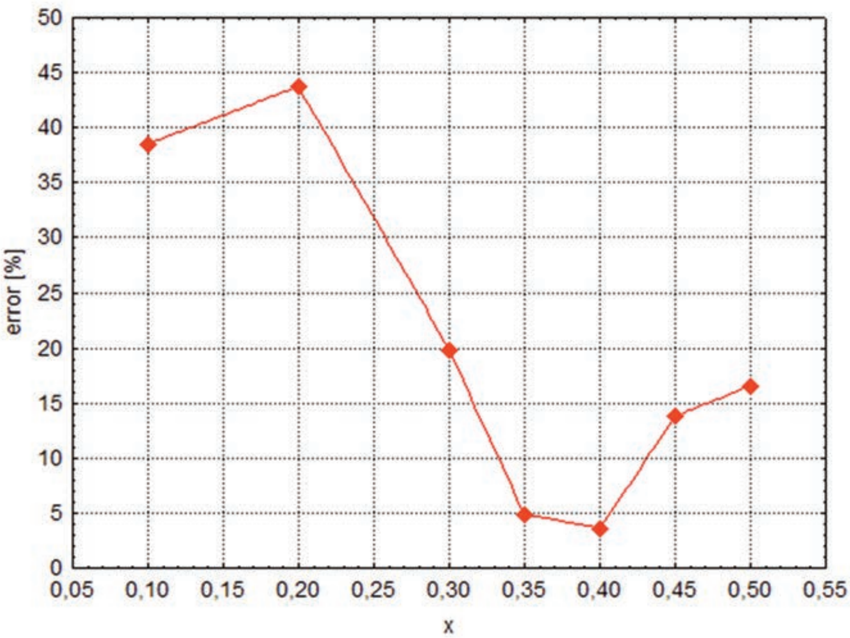

Figure 6. Effect of parameter *x* on calculation accuracy.

Accurate simulations made it possible to determine the optimal value for the examined case $x = 0.39$.

SUMMARY

This research study shows how the accuracy of aircraft durability calculations can be easily improved using historical data. A slight modification of calculations by adding a heuristic correction allows researchers to significantly reduce the calculation error.

The weakness of the presented method consists in the fact that the value of the parameter x was determined for the specific assumptions of the experiment. The change of these assumptions will affect the determined value of x. On the other hand, however, the simulation calculations were performed for the data corresponding to real data. Taking into account the general similarity between the cycle matrices for aircraft and the forms of S-N curves, it is reasonable to argue that the value of $x = 0.39$ will allow obtaining more accurate results than the classical approach ($x = 0.5$).

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