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Optimization of Fatigue Life of the PZL-130 Orlik's Structure

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Abstract

The paper has been intended to discuss the question of optimization of fatigue life of the PZL-130 Orlik structure. The PZL-130 Orlik is a light, two-seat, turboprop trainer to provide instruction and training in the flying skills. It is operated by the Polish Air Force.

The fatigue damage of an aircraft structures depend on histories of their usage. The operational usage can be analysed based on on-board flight recorder data. The collected data can be used to calculate and optimize the fatigue life of the aircraft.

A method of optimization of the process of selecting particular aircraft to perform various exercises in the course of pilot training has been presented in the paper. The optimal fleet management will allow of correcting the existing differences in the operational profiles of aircraft.

Keywords: aircraft structure, fatigue, usage profile

1. Introduction

Aircraft perfectly exemplify structures highly susceptible to fatigue. The major reasons are that, first, the aircraft structure is affected with dynamic variable loads, and second, limitations of aircraft gross weight do not allow of reduction of stresses down to the level, at which no material fatigue occurs. Back into the past, the problem of aircraft structure fatigue was approached and managed in a way for the first time based on scientific foundations, i.e. the safe-life concept. The idea underlying this approach is that any aircraft is taken out of service before any fatigue damages appear. In spite of many limitations, the safe-life concept continues to be applied to the operation of the whole aircraft structure or structural components thereof. One of the major problems that arise while using the safe-life concept is how to control the process of the structure's fatigue-life expiration throughout aircraft service life. Commonly accepted is the number of flight hours used as the structure's fatigue-wear rate. After reaching the manufacturer-defined total flying time, the aircraft structure is recognized as fatigue-worn and hence, further operation thereof is discontinued.

Since considerable differences in the scheme of operating particular aircraft may occur, the flying time is not an optimal rate of the structure's fatigue wear. If the aircraft structure's life is assumed to be limited first and foremost by the material fatigue, then the number of load cycles proves decisive to the structure's wear and tear [5-7, 13]. Variable loads affecting the aircraft result from many and various factors, among which the following ones prove to be of major importance:

- aircraft manoeuvres,
- gusts,
- ground-air-ground (GAG) cycles.

Flying time is not a good estimator of the number of cumulated fatigue cycles. This parameter being applied resulted from the level of engineering capabilities of that time. Much better is the number of cycles of changes in values of the vertical overload factor n_z (g-load). As analyses show, the n_z values are closely correlated with stresses in the airframe structure, in particular in the area of the wing-to-fuselage joint, i.e. one of the greatest fatigue-damage hazard (Fig. 1) [1-4,10-12]. The n_z factor can be used to estimate the fatigue-wear of an aircraft only if the aircraft is furnished with a flight data recorder that records the g-load sensor emitted signal, and historical data on the operational use of a given aircraft is available [8,9].

The load-monitoring systems of today represent more advanced technology as applied to count fatigue cycles in aircraft structural components. Two approaches can be distinguished:

- direct stress monitoring (e.g. with strain gauges), and
- indirect load monitoring by means of flight parameters **(**the n_z signal and other flight parameters are used**)**.

In both the instances the structure's fatigue wear is found basing on the course of flight/flights. The first stage of analysis resolves itself into finding the number of fatigue cycles and parameters thereof (amplitude and mean value) for the location recognised as critical. At the second stage, the fracture mechanics or the materials-fatigue theory is used to determine the destructive effect of the cycles upon the material.

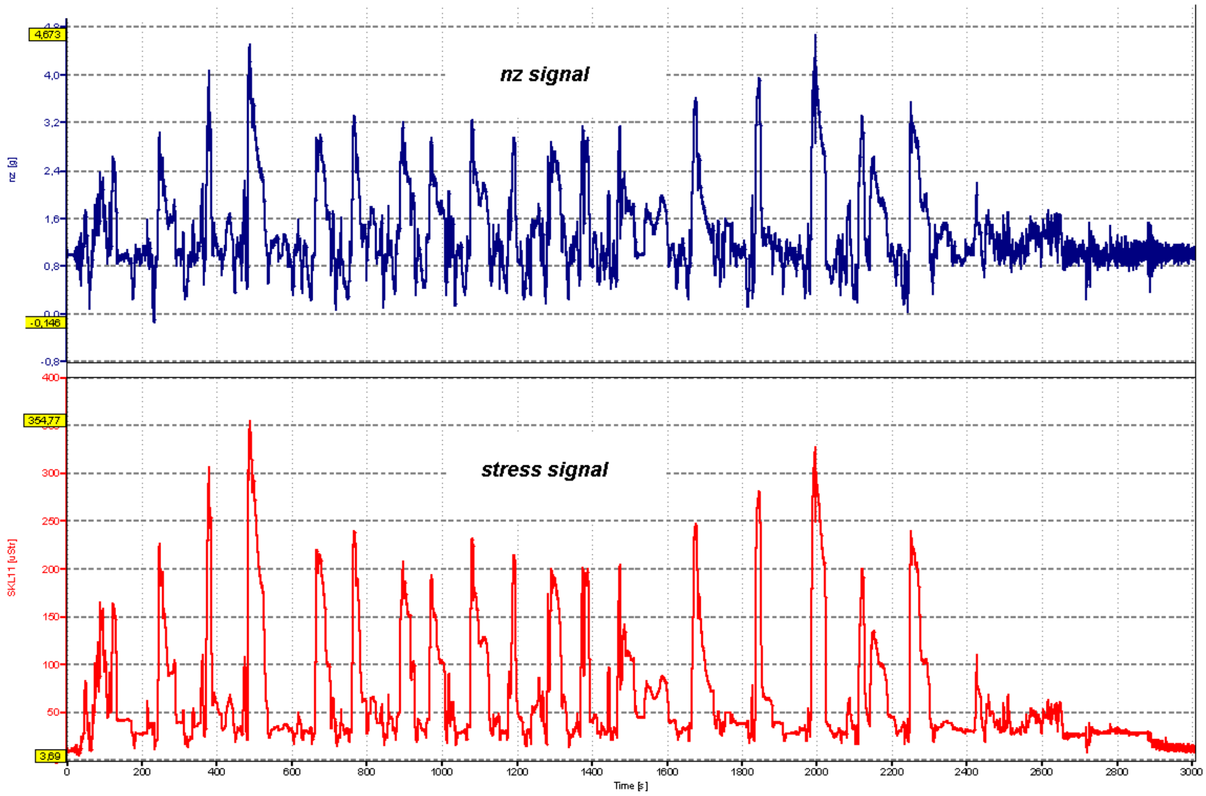

Figure. 1. Correlation between n_z signal, and stress signal

2. An object under examination – the PZL-130 Orlik

The PZL-130 Orlik TCI (further on called ‘Orlik’) is a light, turbo-prop (single-engine) aircraft to give instruction and training in the flying skills. The Orlik is an all-metal aircraft construction; specifications thereof are given in Table 1 below.

Table. 1. Specifications of the Orlik aircraft

Length	9 [m]
Wing span	9 [m]
Lifting surface	13 [m^2]
Weight (max)	2700 [kg]
Speed (max)	500 [km/h]
Altitude (max)	10000 [m]
Engine power	551 (kW)

Figure. 2. The PZL-130 Orlik

The aircraft was designed in the 1980s, in Poland. The Polish Air Force have been using 36 aircraft since 1995. All the aircraft are furnished with the S2-3 digital flight data recorders that record, among other parameters, the n_z signal. The aircraft has been designed and is operated according to the 'safe-life' approach. The aircraft flying time is the parameter that controls operation of each aircraft. It decides upon the time of aircraft operational use, maintenance, repairs and/or overhauls, and determines the time instant the aircraft should be taken out of service. While designing the operational phase of this aircraft, no account was taken of advantages and capabilities offered by furnishing the aircraft with digital data recorders. Data from recorders were used in post-flight briefings as instructive material.

Flight recorders delivered data for the whole population of the Orlik aircraft operated by the Polish Air Force have been filed and are available for fatigue-wear assessment of aircraft structures. Analyses of the recorded history of the Orlik's operational use while with the Polish Air Force have been given in the paper; an algorithm follows of how to use the still-left service lives of some specific aircraft population.

3. Formulation of the optimization task

A flight data recorder records and stores in its memory parameters of aircraft performance in the course of time. In digital recorders analogue signals are sampled with some preset frequency and recorded in the discrete form in the memory of the device. In the case of applying the n_z signal to estimate wear fatigue, one of several algorithms of counting cycles in the course of time, e.g. the rain-flow counting algorithm, is used. Matrices of cycles are the most often used method of presenting the results gained (Fig. 3). The height of each bar in the diagram represents the number of cycles, whereas its position – the amplitude value and the mean value of a cycle. In many cases, the effect of the mean value of the n_z signal is neglected, and the matrix is replaced with a two-dimensional plot (Fig. 4), i.e. the so-called flight profile or operational profile. Such a plot gives information on the number of recorded fatigue cycles of some specific amplitude.

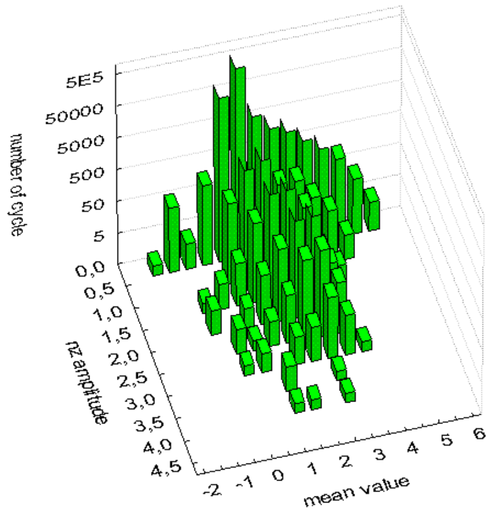

Figure. 3. Matrix of cycles

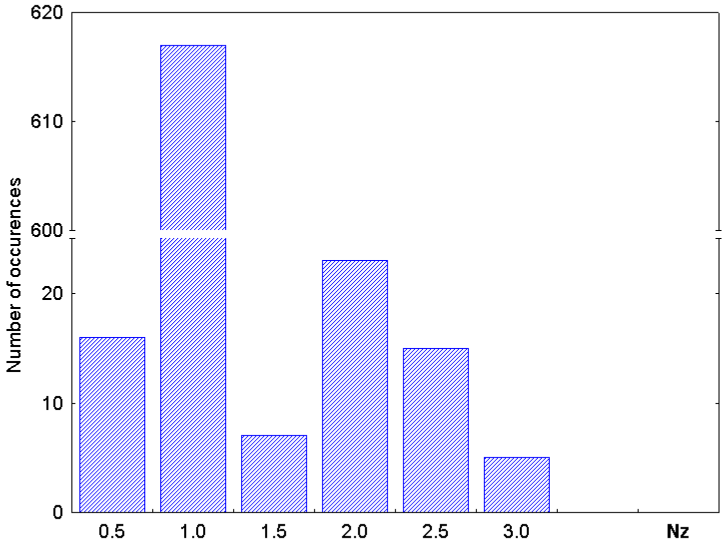

Figure. 4. The number of cycles during a flight (an example)

The number of cycles can be counted for any of flights. It is usually shown in the diagrams per 1000 flight hours. This makes comparisons between profiles much easier but it also can cause an misunderstanding when the applied value is not clearly explained.
To determine service life of an aircraft, the way of operating it (i.e. the mean operational profile) need to be defined. Most often, an already known profile of similar-purpose aircraft. Investigations into aircraft operational profiles have been presented in [13]. The service life of the PZL-13- Orlik has been determined using the profile of operation developed on the grounds of data found in the literature [13]. Now, when we have got records for more than 30000 flight hours, the earlier assumptions can be corrected. Investigations into profiles of operation of particular aircraft have proved there are significant differences between the profiles. Fig. 5 shows actual profiles of operation of two selected aircraft, and an mean profile.

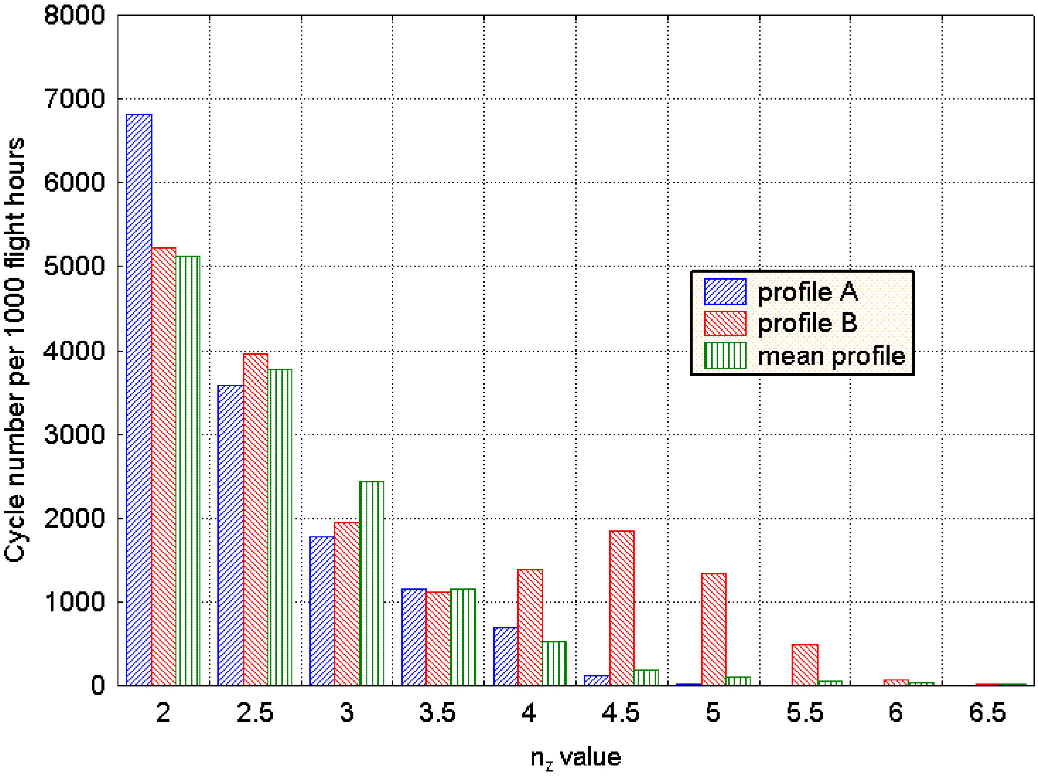

Figure. 5. Exemplary operational profiles, and an mean one

The users of the PZL-130 Orlik are vitally interested in keeping the actual profiles of aircraft operation as close to the mean one as only possible since the risk that untypical damages/failures occur in some unpredictable period of aircraft operation is then minimised. The closer the operational profiles are to each other, the more reliable measure of wear-and-tear the aircraft flying time is. The aircraft flying time is an essential measure of fatigue wear of aircraft operated according to the safe-life concept, including the PZL-130 Orlik. The PZL-Orlik serves in the Polish Air Force for training. It means that most of the time flown they perform manoeuvres/exercises prescribed in the flying training syllabus. The optimisation task in question consists in an effort to reach the objective defined as ‘minimisation of differences among operational profiles of different Orlik aircraft on the inventory’ The objective can be reached by means of suitable selection of particular aircraft for purposes/tasks provided for in the flying training syllabus.
On the grounds of data collected from flight data recorders an operational profile P has been generated for each of Orlik aircraft operated by the Polish Air Force.

$$\mathbf{P}^i = \begin{bmatrix} p_1^i \\ \vdots \\ p_{10}^i \end{bmatrix} \tag{1}$$

The operational profile of each aircraft has been defined as a ten-elements vector. Each element p^i of vector $\mathbf{P}$ defines the number of n_z cycles of some specific value that fall on the 1000th flight hour. The following n_z values that determine the magnitudes of n_z cycles have been accepted for the analysis: 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7.
Mean profiles for each of the performed exercises E^j have been generated in a similar way.
Here, an exercise means a single flight flown by a student pilot after some specific plan. In such a flight, particular manoeuvres/sequences are strictly defined; however, practical accomplishments have proved to differ, depending on a different level of skill of each pilot. In the present analysis 170 types of exercises have been taken into account. The number of flights recorded for particular exercises was different, but normalisation against flight time up to the 1000th hour has been taken into consideration, as well. The way of defining the measure of similarity among the profiles proves of fundamental importance. Classical norms do not suit the purpose, not too much, anyway. It follows from the physical sense of information included in the profiles. First elements of

vectors denote the numbers of low-amplitude cycles, which predominate in the course of flight (10e7 cycles / 1000 flight hrs), whereas the number of cycles of the highest amplitude that occur in exactly the same time is significantly lower (approx. 1/1000 hrs). On the other hand, cycles of higher amplitude prove of greater importance to the depletion of the aircraft service life.

The following norm has been defined to examine operational profiles:

$$\|\mathbf{AB}\| = \sum_{k=1}^{10} \frac{A_k - B_k}{B_k} \tag{2}$$

Using equation (2), distances d^i between profiles of particular aircraft to the mean profile were determined:

$$d^i = \|\mathbf{P}^i \mathbf{M}\| \tag{3}$$

where:

$\mathbf{P}^i$ - vector of operational profile of the *i-th* aircraft,

M - the mean operational profile.

The next issue to examine is the way each of the performed exercises modifies values of d^i. What should be taken into account while making calculations is the aircraft flying time flown hitherto – T^i, and the exercise duration – F^j. Aircraft of shorter total flying time are more liable to the modification of their profiles by means of a single exercise. The profile of the *i-th* aircraft after the *j-th* exercise has been flown – $\mathbf{V}^{ij}$ – is derived from the following formula:

$$v_k^{ij} = \frac{1000}{T^i} p_k^i + \frac{1000}{F^j} e_k^j \tag{4}$$

where:

i - superscript that denotes the aircraft,

j - superscript that denotes the exercise

k - superscript that denotes the profile component $k \in \langle 1,2,...,10 \rangle$,

v_k^{ij} - component k of the profile of the *i-th* aircraft after the *j-th* exercise was flown

p_k^i - the *k-th* component of the profile of the *i-th* aircraft

e_k^j - the *k-th* component of the profile of the *j-th* exercise.

After vectors have been found, one can assess, by means of the equation (2), the effect of the exercise upon the profile, i.e. whether any change has occurred. What is calculated is distance d of profiles **V** from the mean profile **M:**

$$d^{ij} = \|\mathbf{V}^{ij} \mathbf{M}\| \tag{5}$$

4. Results

Calculations were made for the whole PZL-130 Orlik population, i.e. 36 aircraft. Prior to the determination of mean profiles, the FDR-delivered data were subject to pre-handling. Information recorded by the flight data recorder is encoded (secret) and prior to any analyses it needs processing. Another step was to check the data correctness. From among 35000 data files, some proved unfit for use, since they included faulty records. Errors could prove attributable to, e.g. some defect in the n_z sensor. The cycle counting to verify the data allowed of counting cycles for each aircraft and each exercise. Basing on what above, 36 operational profiles for aircraft were determined, and 170 ones for the exercises. Fig. 5 shows some selected profiles for aircraft, whereas Fig. 6 – for the exercises.

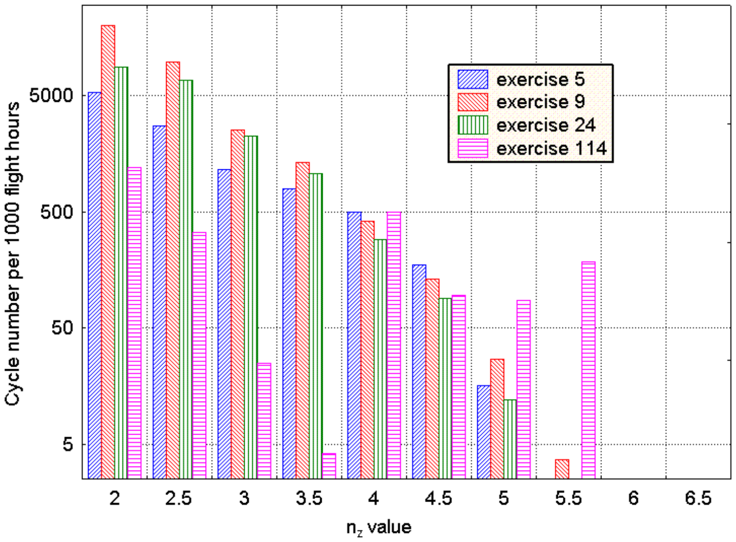

Figure. 6. Some selected profiles for the exercises

Figure 7 shows values of d^i found for the aircraft population under examination.

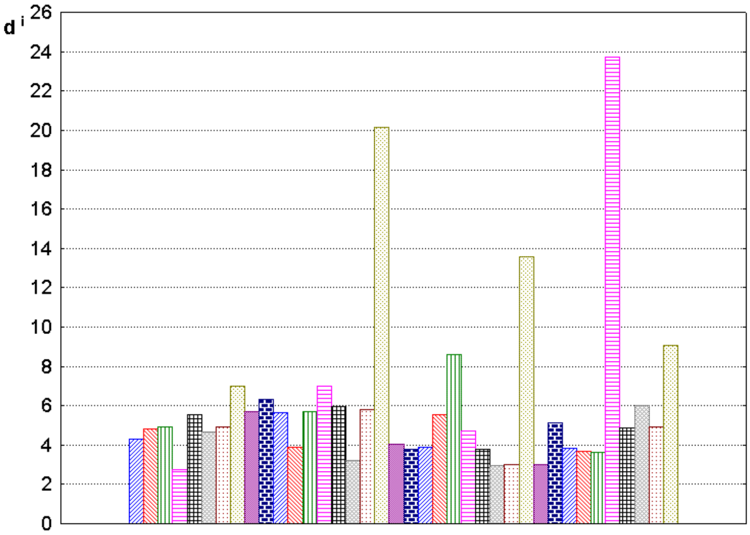

Figure 7. Deviations of the operational profiles from the mean one (base on eq.(3))

As shown in Fig. 7, the operational use of aircraft practised hitherto has lead to discrepancies between the operational profiles of particular aircraft.

Matrix D was arrived at after the numerical calculations described in Section 3 had been made. The size of the matrix (36 x 170) is too large to represent it as a whole. Tab. 2 presents a fragment of the matrix with results for 5 aircraft and 5 exercises included.

Table 2. Fragment of Matrix **D**

Number of Exercise	**Aircraft A**	**Aircraft B**	**Aircraft C**	**Aircraft D**	**Aircraft E**
1	5.520	4.873	4.902	4.925	6.989
2	5.531	4.871	4.913	4.937	6.975
13	5.478	4.889	4.860	4.883	7.034
19	5.484	4.893	4.866	4.890	7.021
29	5.511	4.885	4.892	4.916	6.999

On the grounds of information included in Tab. 2 decisions optimal for the everyday management of the PZL-130 Orlik fleet could be made. If there is a need to perform exercise, for example, no. 1, the lowest value should be found in Tab. 2, in the row that corresponds to exercise no.1. Basing on Tab. 2, this would be the *Aircraft B* (D=4.873). Therefore, from among aircraft A-E, *Aircraft B* should be used to fly the exercise. An optimum exercise number to be flown by a definite aircraft can be found in the same way. In this case, the minimum value is to be found in the column of matrix D. For the *Aircraft A* this would be exercise no. 13, whereas for the *Aircraft E* - exercise no. 2.

Figure 8 shows a plot with values of matrix D for the aircraft no. 1. (the D^{1j} values)

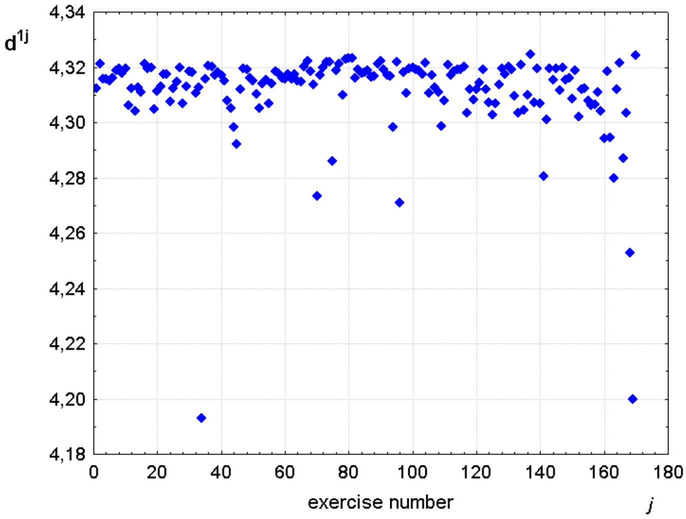

Figure 8. Values of matrix D for the aircraft no. 1.

The exercise being completed will affect, i.e. change the operational profile; therefore, all the calculations should be repeated. However, the time flown in one exercise is approx. 1‰ of the aircraft total flying time, there is only a slight change in the profile, which does not affect the correctness of inferring based on matrix D. Verification (i.e. repetitions of calculations for updated data) can be done periodically, e.g. every three months, or depending on the operational-use rate.

5. Conclusion

The above-presented method of optimization of fatigue life of the structure of the PZL-130 Orlik allows of better, more effective management of the operational use of these aircraft. The task is even easier, since these aircraft have been intended mainly for training.

On the other hand, using the method for practical purposes may prove difficult, because other factors that affect the choice of aircraft to fly a mission, e.g. availability of the aircraft, have not been taken into account. However, if only the choice is possible, results of the conducted analysis will prove helpful.

In the way similar to that presented above, other operational-use strategies could be followed. They may take account of the aircraft fatigue life. A strategy that minimizes/maximizes fatigue wear of particular aircraft also proves feasible, e.g. on account of the planned overhauls or upgrades. To implement other strategies, two things should be defined: objective functions, and the norm that determines distance between the operational profile and the profile minimizing the objective function.

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