Fatigue of Aircraft Structures
Vol. 1 (2009) 131-139
10.2478/v10164-010-0012-z

THE FATIGUE LIFE ASSESSMENT OF PZL-130 ORLIK STRUCTURES BASED ON HISTORICAL USAGE DATA

Andrzej Leski
Sławomir Klimaszewski
Marcin Kurdelski

Air Force Institute of Technology, Warsaw, Poland

Summary

Material fatigue is the basic factor limiting aircraft's durability. It comes from the fact that changing loads affect aircraft structure as well as from the fact that aircraft's mass restrictions do not allow for diminishing stress to the level when material fatigue does not occur. Estimating fatigue durability of a particular structure as well as its actual fatigue damage degree is possible when the history of loads affecting the structure is known.

Accuracy of loads monitoring influences the accuracy of indicated fatigue wear. In case of older structures, which have been maintained according to safe life principle, the number of hours have been commonly used as a fatigue wear indicator. After aircraft structure reaches flying time estimated by the produces, it is considered as fatigue wear and it is no longer in service. In case of a lack of results of loads spectrum measurements, results of tests conducted for other aircraft (of similar structure and assignment) can be used. For this purpose, average loads spectrum has been elaborated for particular aircraft groups, for example, HELIX, FELIX, FALSTAFF, ENSTAFF, TWIST(10). In the case of small aircraft, the data from FAA (2) report have been often used.

This article describes the way of fatigue wear estimation for PZL-130 Orlik aircraft on the basis of historical data from flight recorders.

Keywords: *aircraft structure, fatigue, usage profile*

1. LOAD SPECTRA OF THE PZL-130 ORLIK POPULATION

The PZL-130 Orlik has been designed and is operated according to the 'safe-life' approach. The aircraft's flying time is the parameter that controls operation of each aircraft. All the Orlik airplanes operated by the Polish Air Force are furnished with digital flight recorder S3-1. Flight recorders delivered data for the whole population of the Orlik aircraft operated by the Polish Air Force and are available for fatigue-wear assessment of aircraft structures.

While designing the operational maintenance 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. For many years, no data-protection system has been designed and developed to satisfy the needs of aircraft's structural integrity research. Furthermore, the data-processing software performs the recorded-data compression that consists of data reduction. The n_z signal in the compressed data sets shows the 1 Hz frequency (Fig.1).

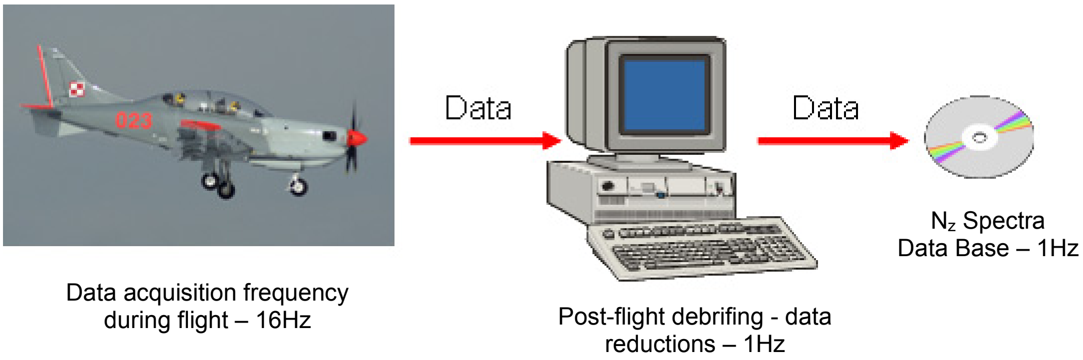

Fig.1. N_z Spectra Data Base

Owing to the efforts made by the Air Force Institute of Technology in Warsaw, the Orlik operational data that cover the total time of operating these airplanes by the Air Force of Poland have been captured. The collected database includes over 36,000 files, each representing a single flight. The actual data capture rate has been estimated at approximately 80%. Unfortunately, all the data are in the compressed form, hence, all the signals are available at the sampling frequency of 1 Hz. It turned out in practice that the sampling frequency of 1 Hz is sufficient to reconstruct loads that affect the aircraft structure except for ground manoeuvres and the moment of landing.

Prior to starting the analyses the database was cleared of files with erroneous (incorrect) data. Furthermore, portions of the recordings that illustrated the aircraft on-ground manoeuvres (not to be used in further work) were eliminated from further analyses.

Since the recorders on the Orlik aircraft do not record the weigh-on-wheels signal, the take off and landing moments are hard to find base on n_z signal only (fig.2). Some other recorded signals were used to find the take-off and landing instants. Algorithms to find the take-off and landing instants were developed. The following inputs are used in these algorithms:

- pressure height,
- airspeed,
- engine torque,
- oil pressure,
- undercarriage (landing gear) lowering.

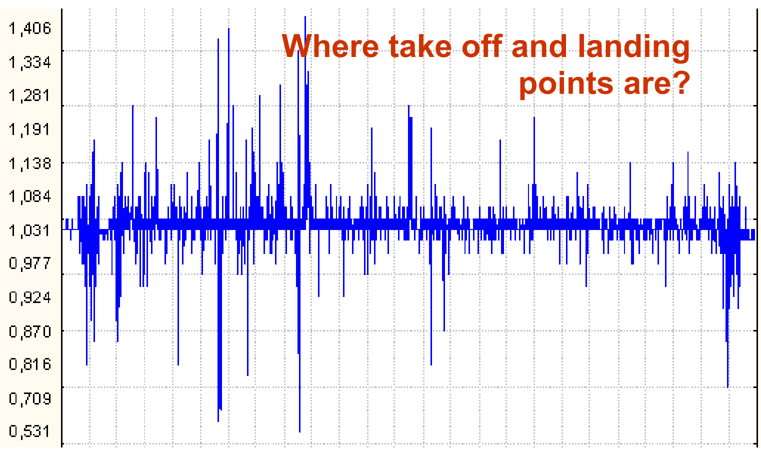

Fig.2. The n_z signal for one flight

The rest of data representing all other flight phases were processed with a cycle-counting algorithm. Different algorithms were used. The one used in this study was the rain-flow counting method.

2. AN ALGORITHM TO FIND FATIGUE WEAR

2.1. The safe S-N curve

Fatigue calculations were made with the S-N curve method. The safe S-N curve is based on the mean S-N curve after some extra safety rates have been introduced in the equation that describes it [4]. The most essential objective of applying the safe S-N curve is to take into account the statistical scatter in fatigue life. The mean S-N curve was the basis to find the safe S-N curve for the material 2024T3, the notch factor $k_t = 2$, and the mean value $\sigma_m = 0$ [16].

The numerical relationship for the mean S-N curve is described with the following dependence:

$$\log \overline{N} = 12 - 3.33 \log\left(S_{eq} - 84.83\right) \tag{1}$$

or

$$S_{eq} = 10^{\frac{12 - \log \overline{N}}{3.33}} + 84.83 \tag{2}$$

where:

$\overline{N}$ – life (number of cycles)

S_{eq} – equivalent amplitude of the cycle determined with the following formula:

$$S_{eq} = \sigma_{\max} \left(1 - \frac{\sigma_{\min}}{\sigma_{\max}}\right)^{0.68} \tag{3}$$

where:

$\sigma_{\min}$ – minimum stress in the cycle (in MPa),

$\sigma_{\max}$ – maximum stress in the cycle (in MPa).

The safe S-N curve was accepted for the calculations, one that was originated by means of displacement downwards by the value of 45 MPa because of the statistical scatter in results of fatigue tests. Furthermore, introduced was an additional factor that increased the equivalent-cycle amplitude by 30%.

The analytical form of the safe S-N curve is expressed with the following formulae:

$$\log \overline{N} = 11.62 - 3.33 \log\left(S_{eq} - 30.6\right) \tag{4}$$

or

$$S_{eq} = 10^{\frac{11.62 - \log \overline{N}}{3.33}} + 30.6 \tag{5}$$

2.2. Estimation of stress in the structure

The level of stress to which the structure is exposed proves of essential significance to the structure's life. The stressed skin forming the lower surface of a wing box has been recognized as critical area in the Orlik's structure (and in those of other aircraft, too) because of its susceptibility to fatigue failures. Correlation between the stress and the g-load affecting the Orlik can be estimated on the grounds of:

- strain gauge measurements, and
- numerical calculations.

In the year 2000, Air Force Institute of Technology took part in directly taken measurements of loads for the Orlik aircraft. One of the strain gauges was placed in the localization critical from the viewpoint of fatigue life, i.e. on the lower part of the wing spar.

Three recorded parameters, and how they change, have been presented in Fig. 4.

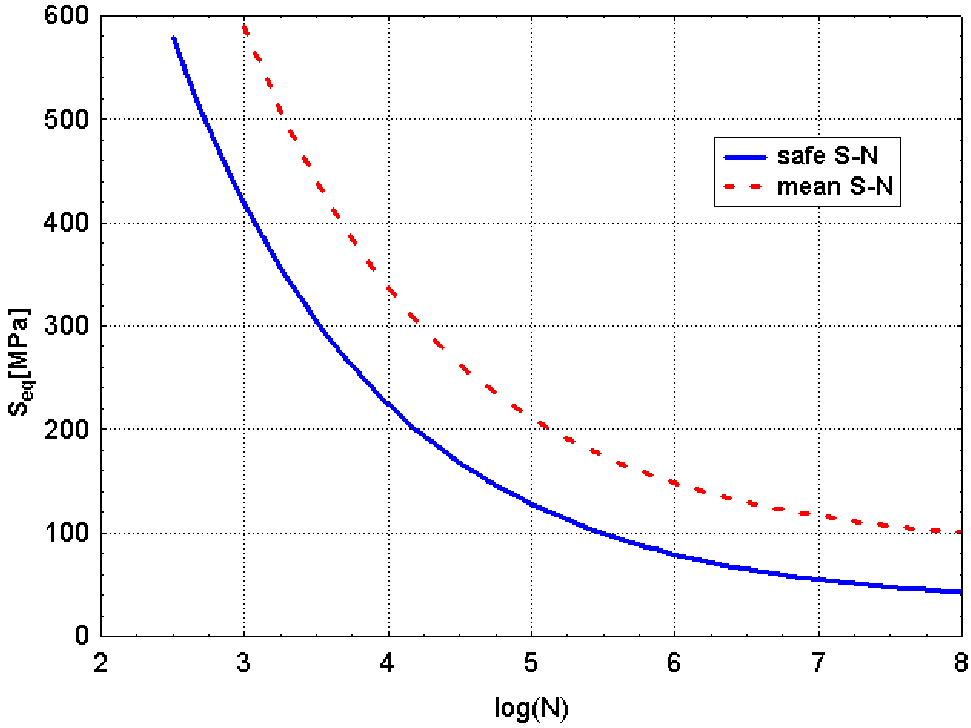

Fig. 3. The mean and safe S-N curves for the material 2024T3

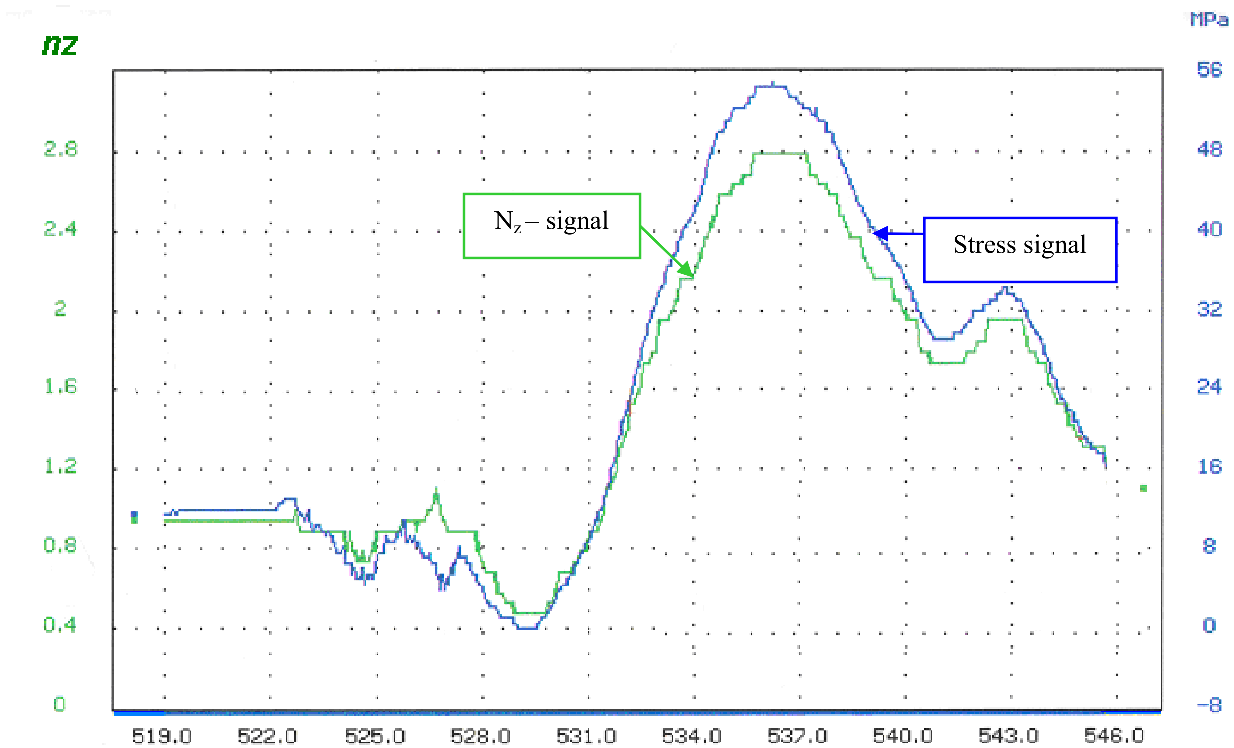

Fig. 4. Changes in the courses of signals – an original drawing

Basing on Fig. 4, the correlation between the g-load and the stress can be written down with the following formula:

$$\Delta\sigma_k = 22.5MPa \cdot (\Delta n_z) \qquad (6)$$

where:
$\Delta\sigma_k$ - change in stress in the critical localization.

The FEM model of the Orlik has been generated in the EADS PZL "Warszawa-Okęcie" S.A. using the MSC Patran and the MSC Nastran software. It is a global model that allows of the estimation of how critical areas are localized throughout the Orlik's airframe structure, and of stress values in the indicated areas. To find local values of loads, these areas should be considered in more detail, which means local models should be introduced.

Fig. 5 presents a FEM model consisting of approximately 3.5 thousand tri and quad surface elements that make up the skin of the wing modelled, and approx. 4.5 thousand two-node bar elements that compose the primary structure. Because of the way of feeding loads into the model, no consideration has been given to mass components such as the undercarriage, assemblies, fuel tanks, etc.

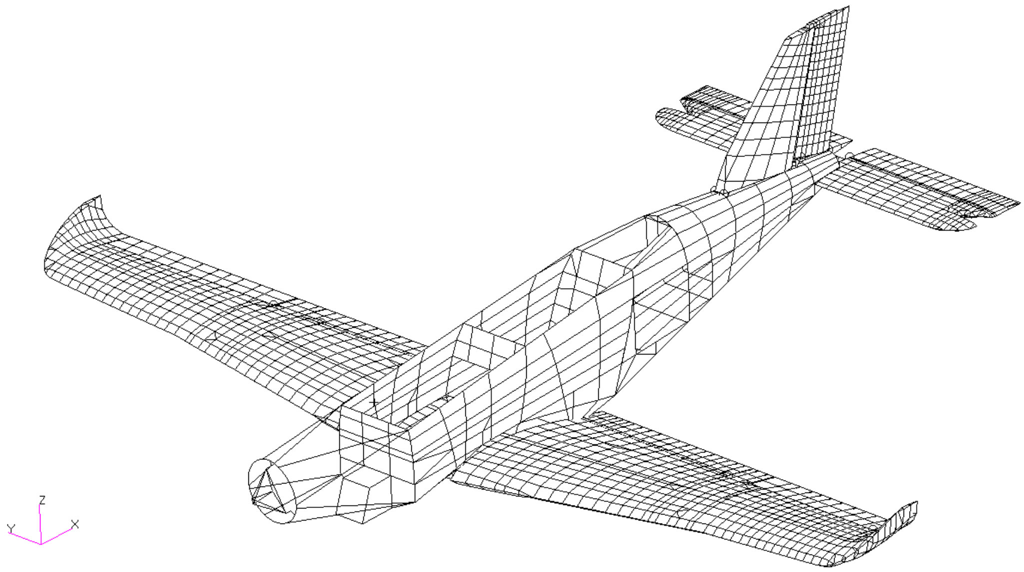

Fig. 5. The FEM model of the PZL-130 Orlik

Presented are results of numerical calculations gained after the FE model had been loaded with the pressure distribution suitable for point A of the manoeuvring envelope n_z= 6 g, V = 400 [km/h], and Q = 2400 kg.

The stress distribution upon the lower wing portion for the Y direction has been presented in Fig. 6.

With the FEM calculations applied, the relationship between the stress and the g-load takes the following form:

$$\Delta\sigma_k = 27MPa \cdot (\Delta n_z) \tag{7}$$

2.3. Estimation of fatigue damage in the course of flight

The fatigue calculations methodology presented in [2] distinguishes the manoeuvres-induced fatigue of the structure from that provoked by gusts. In spite of different nature of each of these effects, their impact upon the structure remains very similar – they both produce fatigue of materials. No flight data recorder distinguishes manoeuvres-induced loads from those effected by gusts. Calculations of fatigue failures were made for each of the aircraft loading spectra (normalized to the amount of 1000 flight hours). The safe S-N curve was applied to do calculations.

A fatigue failure that occurred during the flight was found following the Palmgren-Miner linear cumulative damage hypothesis.

$$D_L = \sum_i \frac{N_i}{\overline{\overline{N}}_i} \quad (8)$$

where:

D_L – in-flight fatigue failure,

N_i – the number of cycles for individual aircraft for total flight time normalised to the amount of 1000 hrs,

$\overline{\overline{N}}_i$ - the number of fatigue cycles to failure at some specific loading level, where

i - the number of amplitude levels and mean values used while counting the cycles.

Fig. 6. Stress distribution for the lower portion of the wing skin

2.4. The GAG (ground-air-ground) cycle induced fatigue failure

It has been presumed that the GAG cycle means some change in stress in the critical airframe localization (the lower portion of the wing skin) somewhere between the maximum stress recorded during a flight (σ_{GMAX}) and the minimum stress that occurs while on the ground or in the course of flight (σ_{GMIN}). The change in the mean stress level for the 'on-ground' and 'in-flight' positions of the aircraft results from the change in the configuration of loads that affect the aircraft structure.

If during the flight negative g-loads occurred, the stresses induced thereby enabled evaluation of σ_{GMIN}. If during the flight there were no suitably low g-loads, value of σ_{GMIN} was based on the change in the load configuration.

In Figure 7 a portion of data recorded during test flights and illustrating the very moment of landing has been presented. The blue line corresponds to the change in stress in the lower part of the wing spar. This localization is very close to the area for which fatigue analysis is carried out. The figure 7 shows changes in stress during the landing allow us to conclude that the change in load configuration during the landing results in the reduction of mean stress by approximately 12.5 MPa.

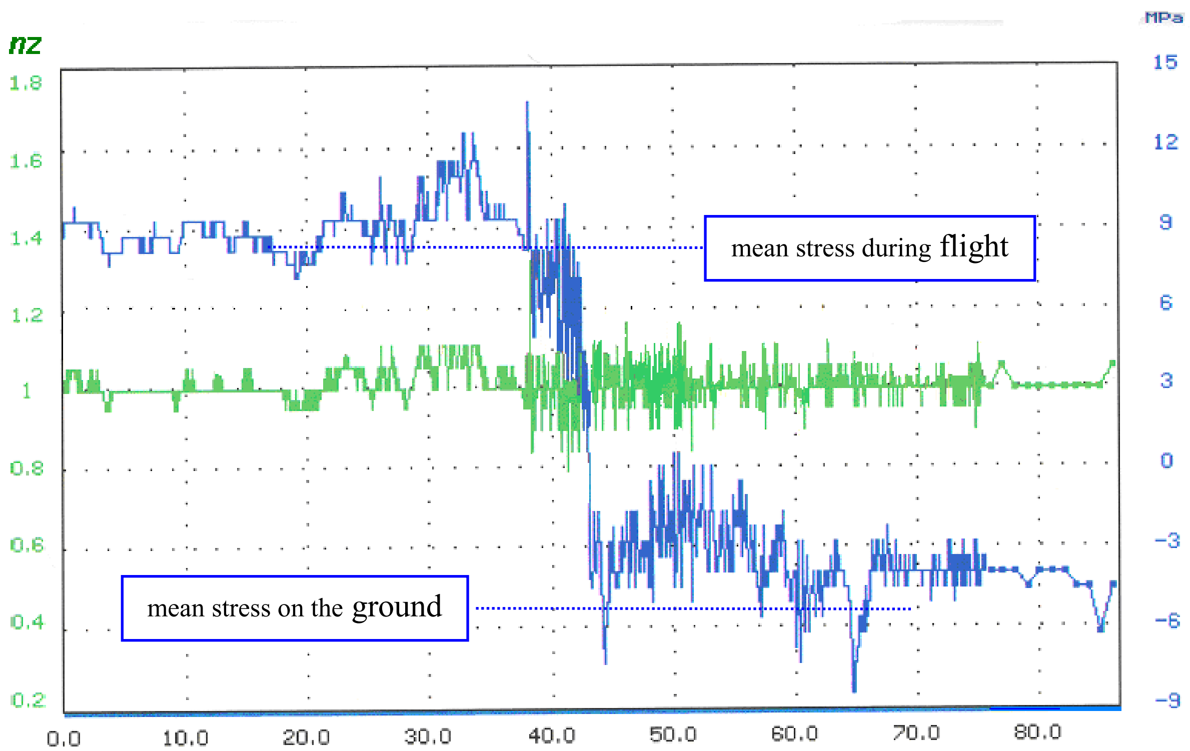

Fig. 7 The courses of signals during the landing

The GAG cycles induced fatigue failure were calculated using the safe S-N curve (Fig 3).

2.5. Total fatigue damage

Total fatigue damage of the airframe is found as a sum of failures during the flight, on-ground manoeuvres, the landing, and those induced by GAG cycles. Summation requires that account is taken of aircraft's flight hours and data capture rate ψ. Furthermore, the landing and GAG cycles induced failures depend on the number of landings performed by the aircraft. The total fatigue failure can be found from the following formula:

$$D = \frac{T}{1000}\frac{1}{\psi}D_L + \frac{1}{\psi}\left(D_{LG} + D_{LD} + D_{GAG}\right) \tag{9}$$

where:

D_L – damage to aircraft structure during the flight,
D_{GAG} – GAG cycles induced damages,
D_{LG} – damages effected by manoeuvres on the ground,
D_{LD} – the landing attributable fatigue failure,
T – aircraft's total flight time [hours], found from the aircraft documentation,
ψ - data capture rate.

Fatigue failures effected by manoeuvres on the ground

With the courses of n_z recorded during actual flights one can find that values of recorded cycles and frequencies thereof suggest that fatigue failures effected by manoeuvres on the ground should be ignored during the Orlik operation/maintenance.

$$D_{LG} = 0 \tag{10}$$

The landing attributable fatigue failure

The landing attributable fatigue failure is difficult to estimate using the recorded parameters. The signal sampling frequency in the flight data recorder is too low to reliably describe the nature of the landing by means of changes in n_z. Also, finding the vertical speed during the landing (by means of differentiating the pressure height signal) does not give reliable results. Basing on [2] the following has been accepted:

$$D_{LD} = N_L \cdot 6.04 \cdot 10^{-6} \tag{11}$$

where:

D_{LD} – the landings induced fatigue failure,
N_L – the number of aircraft landings.

3. RESULTS AND CONCLUSIONS

The calculations made on the basis of the algorithm presented above allowed for fatigue damage determining of the whole population of in-service aircrafts. The data from years 1996÷2007 have been used for the calculations. Figure 8 presents fatigue damage for the chosen group of 15 airplanes. Simultaneously, the same figure presents the flying time of these planes. The intensity of particular plane usage can be estimated from the comparison of fatigue wear and flying time.

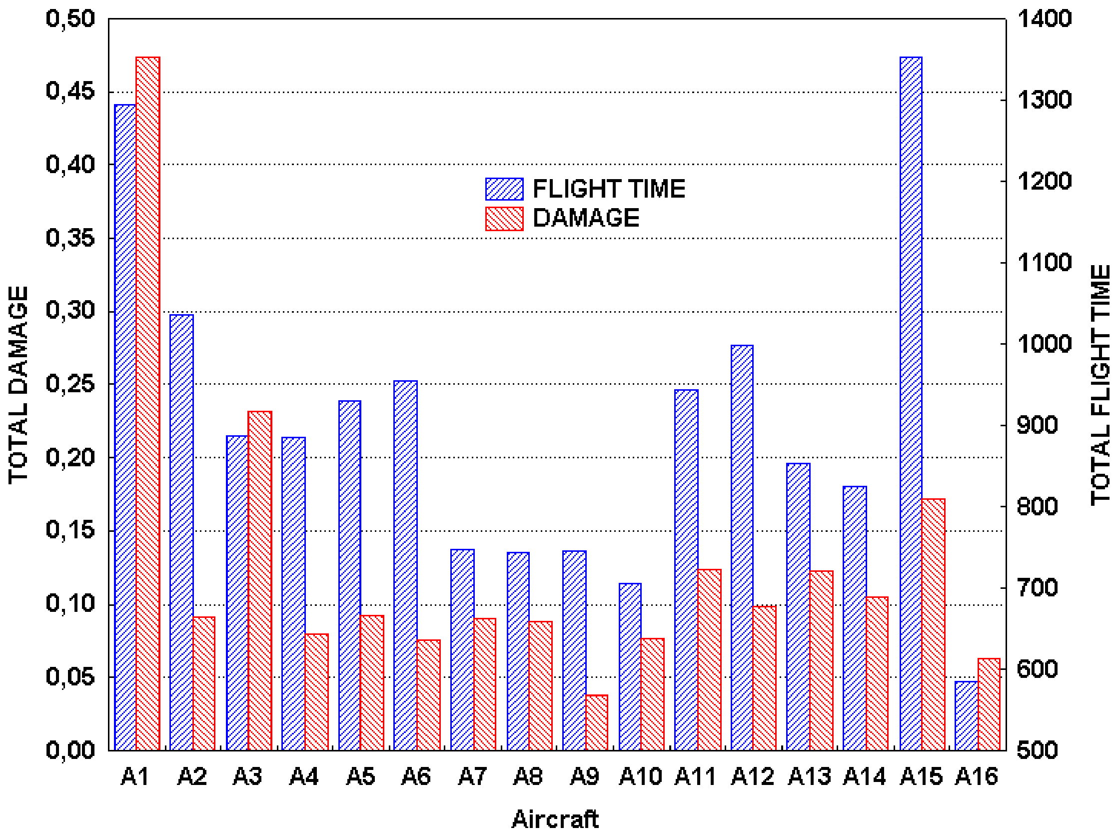

Fig. 7. Results of calculations of fatigue wear

On the basis of the conducted analysis the following conclusions can be formulated:

a) There are significant differences in intensity of usage, flying time and fatigue wear among OZL-130 Orlik aircrafts.
b) On the basis of service life determined by flying time, the use of Orlik aircrafts is not optimal from structural durability point of view.
c) Fatigue damages from maneuvers in the air have the greatest share in structure fatigue of Orlik aircraft.
d) Increasing the frequency of recording and processing nz signal will allow for taking into account the influence of gust on fatigue wear.

REFERENCES

1. United States Air Force. (1978, January). *Individual Aircraft Tracking Methods for Fighter Aircraft Utilizing Counting Accelerometer Data.* Ohio: Air Force Flight Dynamics Lab. Wright-Patterson Air Force Base. (AFFDL-TM-78-1-FBE)
2. FAA. (1973). *Fatigue Evaluation of Wing and Associated Structure on Small Airplanes.* (AFS-120-73-2)
3. Veldman Ray J. & Peckham C. (1982, October). *Loads and Dynamics Branch Structures Division*. In Handbook of Military Aircraft Design Normal Load Factor Exceedance Data. Ohio: Aeronautical Systems Division Wright-Patterson Air Force Base.
4. U. K. Ministry of Defence, (1999, December). Design and Airworthiness Requirements for Service Aircraft. DEF STAN 00-970, Issue 2. Directorate of Standardization, U. K.
5. FAA. (2000, March). Statistical *Loads Data for B-767-200ER Aircraft in Commercial Operations*. U.S. Department of Transportation. (DOT/FAA/AR-00/10)
6. FAA. (2001, August). *Statistical Loads Data for Cessna 172 Aircraft Using the Aircraft Cumulative Fatigue System (ACFS)*. U.S. Department of Transportation. (DOT/FAA/AR-01/44)
7. FAA. (2003, June). *Statistical Loads Data for the Airbus A-320 Aircraft in Commercial Operations*. U.S. Department of Transportation. (DOT/FAA/AR-02/35)
8. FAA. (2003, June). *Statistical Loads Data for Bombardier CRJ100 Aircraft in Commercial Operations*. U.S. Department of Transportation. (DOT/FAA/AR-03/44)
9. FAA. (1996, December). *Variation in Load Factor Experience - a Re-analysis of Fokker F27 and F28 Operational Acceleration Data*. U.S. Department of Transportation. (DOT/FAA/AR-96/114)
10. Aircher W. & Branger J. (1976, March). A Description of a Fighter Aircraft Loading Standard for Fatigue Evaluation (FALSTAFF). Joint publication by F+W (Schwitzerland), LBF and IABG (Germany) and NLR (The Netherlands).
11. van Dijk, G.M., & de Jonge, J. B. (1975, May). Introduction to a Fighter Aircraft Loading Standard For Fatigue Evaluations (FALSTAFF). National Aerospace Laboratory Netherlands. (NLR MP 75017 U).
12. de Jonge, J. B. (1982). The Analysis of Load-Time Histories by Means of Counting Methods. National Aerospace Laboratory Netherlands. (NLR MP 82039 U).
13. Klimaszewski, S., Leski, A., & Zurek, J. (2003). The Role of AFIT in the Polish Aging Military Aircraft Programs. In: Proceedings of the 7th Joint FAA/DoD/NASA Conference on Aging Aircraft, , 9-11 September 2003, New Orleans.
14. Leski, A., Klimaszewski, S., & Kurdelski, M. (2008). Optimization of Fatigue Life of the PZL-130 Orlik's Structure. In: Proceedings of EngOpt 2008: International Conference on Engineering Optimization. 01-05 June 2008, Rio de Janeiro, Brazil.
15. *Damage Severity of Monitored Fatigue Load Spectra.* (1992, January). National Aerospace Laboratory Netherlands. (NLR TP 92009 U)
16. Rice, R. C., Jackson, J., Bakuckas, J., & Thompson, S. (2003). Metallic Materials Properties Development and Standardization (MMPDS). FAA. (DOT/FAA/AR-MMPDS-01)
17. Swanton, G., & Walker, K. (1997). Development of Transfer Functions to Relate F-111 Aircraft Fatigue Data Analysis System (AFDAS) Strain Outputs to Loads and Control Point Stresses. Melbourne, Australia. (DSTO-TR-0563)

The work was performed within the framework of Research Project N N509 0845 33 sponsored by the Polish Ministry of Science and Higher Education.