CONTINOUS ESTIMATION OF AIRPLANE LOAD-BEARING STRUCTURES FATIGUE

Marek A. DĘBSKI
Institute of Aviation

Daniel K. DĘBSKI
Krzysztof M. GOŁOŚ
Warsaw University of Technology

Presented article is practically a reprint of the [4] paper, published only in polish language. Currently, several domestic and European projects are realized aiming at implementation of this idea. Because previously published paper [4] defines theoretical fundamentals and organizational actions defined in this method of airplane exploitation, we decided to reprint this publication with small editorial changes.

Structural failure of an Aloha Airlines Boeing 737 on April 28th, 1988 [5], by effect of small fatigue cracks extending from adjacent rivet holes in a fuselage lap-splice joint

Airplanes, designed according to the Safe Life method, have (in result of fatigue tests, performed basing on averaged load spectra and characteristic for given airplane class) documented airplane total exploitation time (service life). It is expressed in number of flight hours which, when reached, demands to scrap the airplane. During that time, fatigue failure of airplane load-bearing structure should not appear (with specified probability), failure leading to unsafe exploitation – of course, when manufacturing and using the airplane in specified technological and exploitation conditions.

For an extent of fatigue wear of airplane load-bearing structure one assumes quotient of flight hours spent to structure service life. However, this estimate of fatigue wear does not considers immense, essential substantial dispersion of airplane real exploitation loads. It is particularly essential in case of airplanes, for which the main exploitation loads are maneuver loads and pilot-induced loads. It mainly concerns training and fighting airplanes, fighters, fighter-bombers and agricultural airplanes.

The main sources of dispersion of exploitation loads are:

- differences in skills and pilots personal attributes,
- differences in airplanes exploitation intensity, either between airplane exploitation units and internal in these units.
- airplane individual attributes.

Measurements of the exploitation loads of agricultural airplanes and preliminary load measurements of training-fighting airplane, performed in Institute of Aviation showed significant dispersion of exploitation loads for identical flight tasks and flight conditions, but performed by various pilots.

The most significant differences appeared between test pilots and combat pilots. Combat pilots treated airplane as a work tool necessary to perform routine task without exaggerated esteem for it.

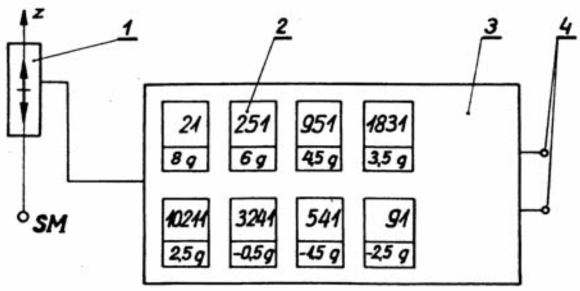

Fig. 1. AVAR recorder main parts: 1 – AVAT transducer, 2 – counters, 3 – AVAS sorter, 4 – power supply, SM – airplane center of gravity

Differences in exploitation intensity between airplane exploitation units result mainly from the fact, that each unit has, in general, defined range of flight tasks which it usually performs, e.g. training in aerodrome circuit flights or navigational flights, or zone flights to basic, advanced or high pilotage training. It is evident, that although for similar flight times, magnitude and intensity of airplane exploitation flight loads will differ and be dependent from airplane exploitation unit. The less essential factors are individual airplane attributes, differentiating airplanes of the same type. They cause that particular airplane is liked or not liked by pilots.

The fact that airplane has flown e.g. for over 30% of its service life does not means that it depleted 30% of its fatigue durability, because on account of exploitation load dispersion caused by a.m. factors, degree of fatigue wear will be dependent on intensity and magnitude of exploitation loads acting on airplane load-bearing structure in its past exploitation.

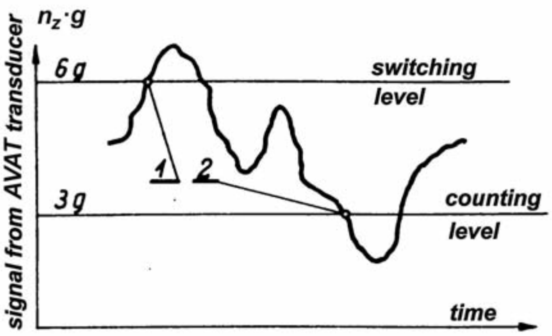

Fig. 2. Signal sorting: 1 – switching on, 2 – counting

If on the board of airplane the measuring device will be mounted for recording physical values representative to exploitation loads, such device will allow estimation of real degree of airplane fatigue wear from exploitation loads, acting on the airplane structure during hitherto exploitation. **A**irplane **V**ertical **A**ccelerations **R**ecorder (**AVAR**) can be given as an example of such device, of fatigue meter type.

Such recorder consists of the two parts (Fig. 1)

- **A**irplane **V**ertical **A**ccelerations **T**ransducer (**AVAT**) mounted sufficiently close to airplane centre of mass (to avoid recording of linear accelerations component coming from airplane angular accelerations),
- **S**orter of **A**irplane **V**ertical **A**ccelerations (**AVAS**), which classifies signal coming from transducer and records it in memory (in counters, which record crossings for given levels of vertical accelerations signal).

Fig. 2. shows an example of classification for one level of accelerations – 6g.

Condition for counting of 6g level crossing is the positive result of product of events, first term: 6g level crossing by increasing transducer signal and second term: 3 g level crossing by diminishing transducer signal. First term is called switching level, because it sets the counter in watching state, second term, crossing of which conditions counting is called counting level. Inside such recorders, from 6 to several tenths of level pairs (switching and counting) is used. Greater number of counters is used in electronic, not mechanical recorder memories. The problem arises for sustaining stored values in electronic memory for the longer pauses in airplane exploitation. This problem does not exist in case of mechanical memories.

It should be mentioned that such classification method allows recording of loads (proportional to airplane vertical accelerations) with relatively big magnitudes, eliminating loads with relatively low magnitudes, which does not have significant meaning for airplane load-bearing structure fatigue durability. And so, e.g. in AVAR recorder (polish designation for RPSS-2 instrument), developed by M. Sadkowski, PhD. and Z. Dygas, M.Sc in Fatigue Strength Group of Institute of Aviation Strength Department, eight pair of acceleration levels was assumed for classification, values are shown at the Tab. 1. This recorder may be used in airplanes with permissible range of load coefficient +8, -4. Because further technical details [1, 2] have no value to the paper, we limit ourselves to broad description of exemplary airplane vertical accelerations recorder.

Table 1.

Switching level	-2,5g	-1,5g	-0,5g	2,5g	3,5g	4,5g	6,0g	8,0g
Counting level	-0,5g	0,0g	1,0g	1,0g	2,0g	2,5g	3,5g	4,5g

Data from recorders in form of conditioned number of given acceleration level crossings are the actual information about real loads spectra applied to airplane during hitherto exploitation. Such spectra are discrete in character of course, and it has as many points as given recorder have counters. To every counter, a pair of levels is scripted, e.g. switching level – crossing of which is recorded, and counting level, crossing of which conditions counting of crossing switching level. As the counter index, value of the switching level is given. Together with increase of the flight time, number of crossings of these acceleration levels will rise. Because that, it is easy to present this spectra in such coordinate system, in which value of the crossings count divided by actual airplane flight time t is laid on the horizontal axis (Fig. 3).

EXPLOITATION INTENSITY ESTIMATION

For every airplane with recorder installed, after certain period of time we receive actual spectrum of exploitation loads. Interpolating points of actual spectrum loads (curve 2 at the Fig.3) by appropriate selected curves (using least square fit method) and assuming linear cumulative fatigue damages hypothesis, we can write a formula describing mean computed fatigue wear of aircraft load bearing structure for a flight hour:

$$\bar{D}_0 = \int_{E_0}^{E_k} \frac{dE}{N} \quad (1)$$

Integral boundaries E_0, E_k should be selected as such, that they embrace a whole spectrum. N – describes number of cycles, taken from assumed preliminary fatigue airplane load bearing structure curve.

$$n_{z\,\text{eqv}}^{m} \cdot N = C \quad (2)$$

Assuming that loading of airplane structure is simply proportional to the load coefficient, its convenient to present a fatigue curve in such a form, exactly.

In formula (2), value of $n_{z\,\text{eqv}}$ is an equivalent airplane load coefficient. It means, that value of fatigue damage resulting from application of single off-zero pulsing load cycle, equivalent to value of coefficient $n_{z\,\text{eqv}}$ is the same, as value of fatigue damage resulting from application of one load cycle equivalent to airplane load coefficient $n_{z\,\max}$ and $n_{z\,\min}$, respectively.

Example of reduction formula, used in computational fatigue strength analyses of airplane structures is Oding relationship:

$$n_{z\text{eqv}} = \sqrt{n_{z\max}\left(n_{z\max} - n_{z\min}\right)} \quad (3)$$

where: $n_{z\,\text{eqv}}$ – is airplane equivalent load coefficient.

For riveted, dural structures, it may be assumed that exponent of power m value is equal to 4 [3].

Knowledge of constant **C** is not necessary for estimation of fatigue wear intensity.

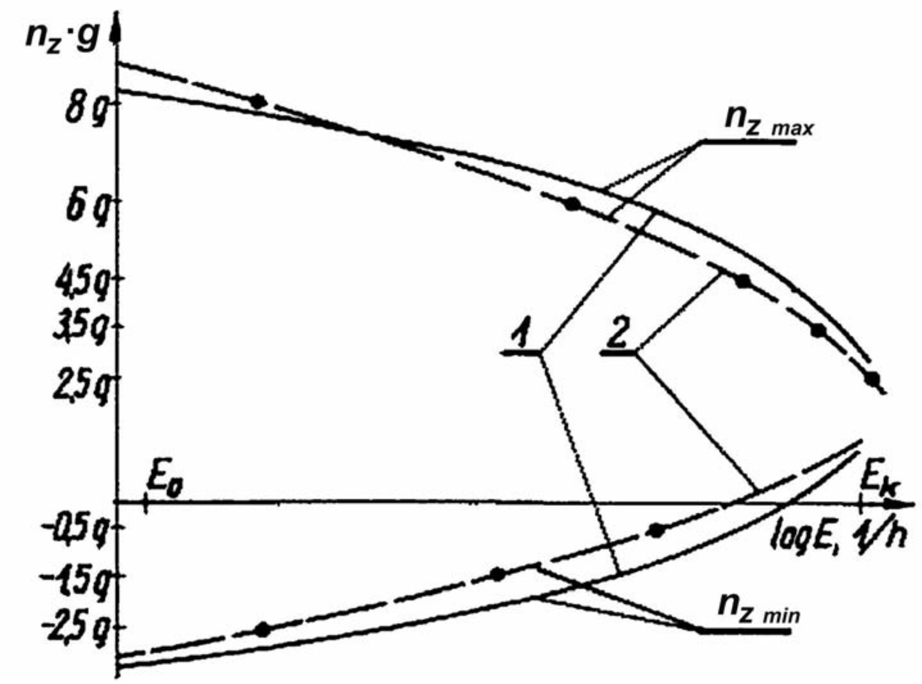

Fig. 3. Spectrum of exploitation loads: 1 – spectrum of loads assumed in airplane fatigue test, 2 – curves, interpreting recorder data, n_z – airplane load coefficient, $g = 9{,}81\ m/s^2$, E – number of vertical airplane acceleration given level crossings ($n_z \cdot g$), mean per 1 flight hour, E_0, E_k – integration borders, • – recorders data (number of flight hours – t)

Having a defined computed mean fatigue wear (1) during hitherto exploitation we can, in a similar way define, computed mean fatigue wear in a airplane load bearing structure fatigue test. Therefore, if fatigue test was realized on assumption of load spectrum, exemplary presented at Fig. 3, that one could present, similarly to a.m. mean computed wear of airplane structure per a flight-hour, represented in fatigue test by dependence:

$$\bar{D} = \int_{E_0}^{E_k} \frac{dE}{N} \tag{4}$$

This time integration is performed on curves, (curve 1 at Fig. 3) which describe load spectrum assumed in fatigue test.

As the measure of intensity of exploitation loads fatigue wear and, simultaneously, measure of exploitation intensity, one can introduce coefficient, called exploitation intensity coefficient and described by relationship:

$$\psi = \frac{\bar{D}_0}{\bar{D}} \tag{5}$$

If, in result of fatigue test, airplane load-bearing structure service life was defined as T_0, maximum permissible structure fatigue wear is equal to:

$$D = T_0 \cdot \bar{D} \tag{6}$$

Coincidentally, if actual airplane flightime is equal to t, than actual load-bearing structure fatigue wear will be equal to:

$$D_0 = t \cdot \bar{D}_0 \tag{7}$$

and extents of fatigue wear defined as measure of permissible fatigue wear can be expressed as coefficient:

$$\xi = \frac{D_0}{D} = \frac{t \cdot \bar{D}_0}{T_0 \cdot \bar{D}} \tag{8}$$

Quotient t/T_0 defines, which fragment of exploitation time was already depleted, but referring only to utilization of defined amount of flight hours. We can call this quotient as utilization coefficient of exploitation time.

$$\varphi = \frac{t}{T_0} \tag{9}$$

Relation between these three coefficients will have the form:

$$\xi = \varphi \cdot \psi \tag{10}$$

Therefore, degree of exploitation loads fatigue wear for airplane load-bearing structure is not only the function of exploitation time depletion - $\boldsymbol{\varphi}$ coefficient, but also function of exploitation intensity - $\boldsymbol{\psi}$ coefficient.

REALIZATION OF THE CONCEPT

The requirement needed for realization of the concept of airplane fleet uniform and controlled exploitation (i.e. continuous estimation of fatigue wear and exploitation intensity) is the outfitting of each airplane with loads recorder, e.g. AVAR recorder. Block schematic, shown at Fig.4 and at Fig. 4a, is the proposed activity graph, targeted on realization of this concept. Unit is the user of the airplane fleet, enclosed in this exploitation system; therefore their airplanes are furnished with recorders. Unit reads periodically each recorder data, creating in the same time a data bank 2.

From fatigue tests 3 of the airplane load-bearing structure we receive data:

- assumed load spectrum, e.g. in the form, shown as example at Fig.3 (curve 1),
- documented exploitation time $\boldsymbol{T_0}$.

Next, in this unit or in the central unit, appreciation of exploitation intensity 5 is performed, assignment of $\boldsymbol{\psi}$ – coefficient and estimation of degree of fatigue wear, therefore designation of $\boldsymbol{\xi}$ – coefficient for each airplane. Data about fatigue failures of airplane load-bearing structures, discovered during hitherto exploitation 4 is gathered and analyzed simultaneously. Data from positions 4 and 5 are fundamental for decision undertaking 6 about future way of airplane exploitation. Recommendation can be issued to the unit of exploitation referring increase or decrease of structure loads intensity in airplane exploitation.

It may mean removal of airplane from planned flights to aerobatic zone and designating it to planned navigational flights. It may also mean necessity of airplane removal from future exploitation, if value of degree of fatigue wear ξ passed level of 1, despite that airplane did not reached its exploitation age limit. Contrary situation can arise, consisting of an admittance of the airplane to further exploitation with service life hour limit passed, but with degree of fatigue wear lower than 1. It allows of an admittance of the airplane to further exploitation, until degree of fatigue wear reaches value of 1. The last variant has great possibility. Sure, realization of this concept may be more simplified with implementation of the recorders, which define on line, in real time values of ψ and ξ coefficients.

THE CONCEPT JUSTIFICATION

Exploitation loads, which influence on every airplane during its service life, belong to rich spectrum of fatigue loads. They are the random loads, dependent of each airplane exploitation conditions and methods. For certain simplification of these considerations, for the measure of these loads we take an equivalent number of cycles n of mutual load. Thus n is a random variable.

Every airplane load bearing structure fatigue strength is also a random value, because of the random character of the manufacturing process. So, let the randomly variable number of cycles N of a. m. mutual load be a measure of fatigue strength. Figure 5 demonstratively shows probability density function ρ (log n) – curve 1 and ρ (log n) – curve 2.

Estimations of the expected values of random variables N and n will be respectively:

- Number of cycles $\bar{N}$ of mutual load, equivalent to fatigue loads assumed in result of fatigue tests of whole structure and its fragments and assumed as fatigue resistance of airplane load bearing structure.
- number of cycles $\bar{n} = \bar{N}/\eta$, where η – reliability coefficient.

Estimation of expected value $\bar{N}$ received in fatigue research of complete structure as a result of single test may appear to be insufficiently reliable. However, in result of this test, fragment of the structure is fatigue destroyed, and fatigue resistance of this fragment is assumed for fatigue resistance of the complete structure. To receive more credible estimate of $\bar{N}$ value and other parameters of distribution function of random variable N, it is possible to supplement fatigue research of the whole structure by much less costly fatigue tests of the structure fragments, representing critical construction areas.

Number $\bar{N}$ corresponds to the structure fatigue resistance T already expressed not as the mutual load cycles count but as number of flight hours. Thus, the number $\bar{n}$ will be counterparted to the airplane service life) $T_0 = T/\eta$.

Importance of reliability coefficient consists on assurance of sufficiently low probability s of airplane load-bearing structure fatigue failure. Association of fatigue strength random variable N and exploitation loads random variable n takes place through exploitation. Considering distribution of random variable log N/n (curve 3 at Fig. 5), then area s (where $N/n \leq 1$) will be equal to probability of airplane load-bearing structure fatigue failure.

Implementation of proposed concept, which assumes controlled exploitation intensity and continuous monitoring of structure fatigue wear related to exploitation loads will result in lowering dispersion of exploitation loads for particular airplanes. This lowering of the load dispersion is shown exemplary at Fig.5 (passage of the curve l (which describes distribution of exploitation loads without implementation of mentioned concept) into curve l' (which describes distribution of exploitation loads with implementation of mentioned concept). Assuring that distribution of structure fatigue strength random variable (curve 2) will not change; we receive distribution of random variable log N/n (curve *3'*), also with a lower dispersion.

Area s', bordered by curve *3'*, vertical axis log $N/n = 0$ and diagram horizontal axis is the measure of probability of airplane load-bearing structure fatigue failure, which can be expected in case of airplane exploitation, according to the proposed concept. This probability is lower than **s** (**$s' \leq s$**) probability; therefore one can expect safer exploitation regarding possibility of fatigue failure, which may lead to airplane crash. This advantageous effect is just obtained

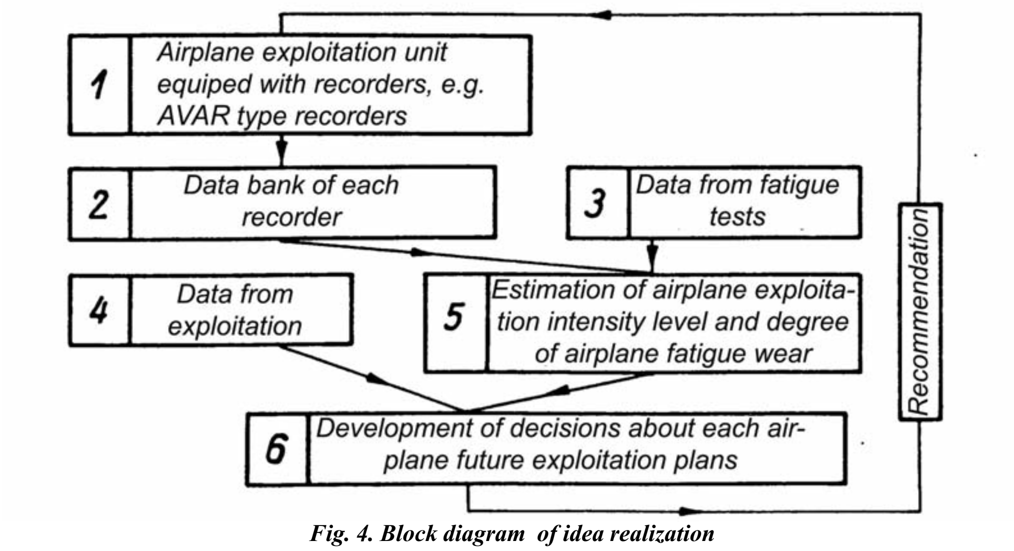

Fig. 4. Block diagram of idea realization

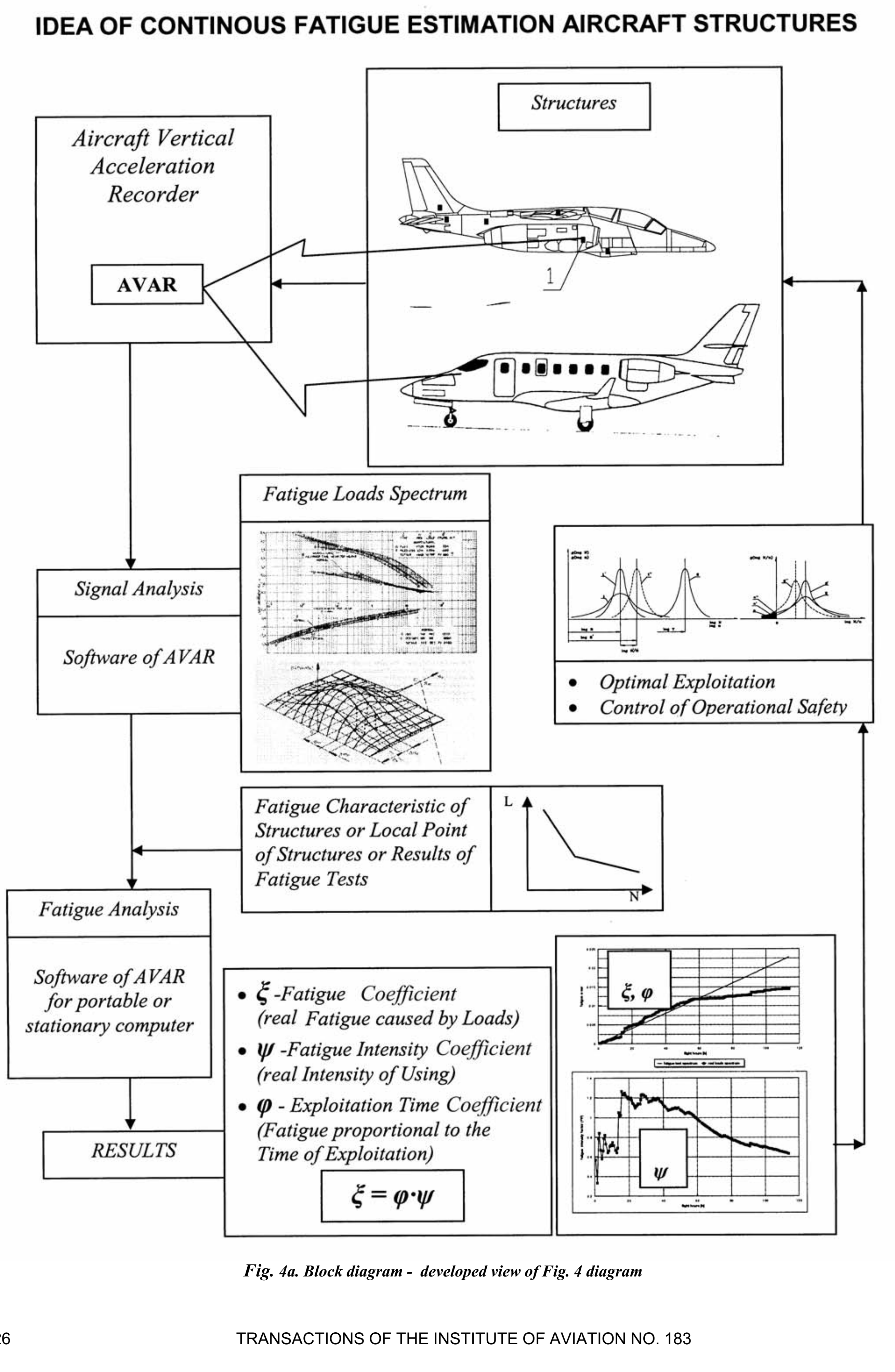

Fig. 4a. Block diagram - developed view of Fig. 4 diagram

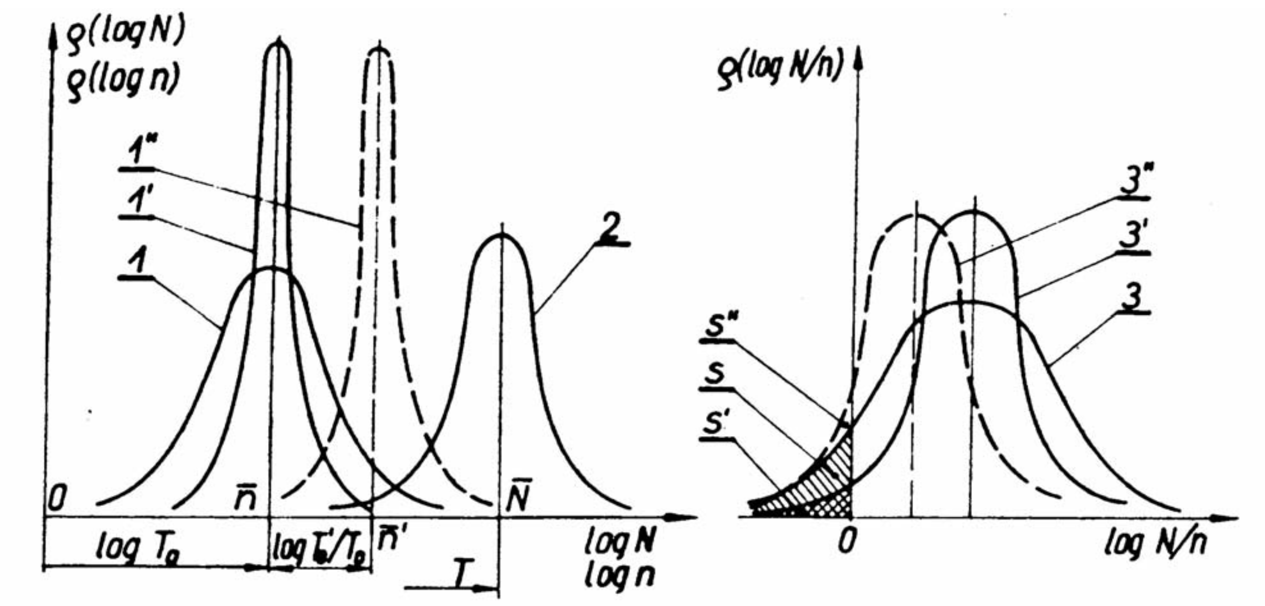

Fig. 5. Probability density function ρ

owing to reduction of exploitation loads dispersion of particular airplanes (curve *1* → curve *1'*).

One can also allow to increase exploitation loads with holding fatigue failure probability *s* at the same level, what means shifting of the *1'* curve to the right in such way that appears curve *1''* owing expected value of $\bar{n}'>\bar{n}$. This increase of admissible exploitation loads should however result such shifting of the random variable log N/n distribution curve **3'**, that obtained curve **3''** will assure retention of required probability of airplane load-bearing structure fatigue failure. It leads to condition of equity of area ***s''***, (bordered by curve **3''**, vertical axis log *N*/*n* = 0 and horizontal axis) with area *s'*

$$s'' = s' \tag{11}$$

This increase of fatigue exploitation loads which are admissible in exploitation from $\bar{n}$ to $\bar{n}'$ will result in increase of exploitation time (service life) from value of T_0 to value of T_0'. According to preliminary estimates, value of this increase will be in the 20÷50% range.

As can be easily seen, increase of admissible exploitation loads will determine increase of admissible value of fatigue wear coefficient from primary value of $\xi = 1$ to value of $\xi = \bar{n}'/\bar{n}$.

A very essential factor is the relation between loads admitted to perform a fatigue test (result of which was used in designation of airplane exploitation time T_0) and real exploitation loads (working on every airplane during exploitation). Without conducting airplane exploitation according to concept of continuous estimate of this loads through periodic designation of ξ, η, φ coefficients values, practically there is no possibility of checking up real exploitation loads, gradually diminishing every airplane load-bearing structure fatigue strength. After all, it may manifest itself that load spectra admitted to fatigue test and based on relatively limited load measurements (often arranged on the basis of not always credible exploitation profile) was to easy. Barely then, likely accidents caused by fatigue failures (despite that airplanes does not spend their service life) will signal that exploitation loads appeared to be greater than assumed. Contrary situation, meaning that load spectra were assumed to steeply in the fatigue test might cause withdrawal of airplanes from flight line with spent flight hours but with fatigue service life load wise not spend. During airplane exploitation leaded according to proposed concept, in both cases the alert signal, which will allow estimating eventual over load or under load of airplane structure will be the time change of ψ coefficient. When this coefficient will be bound to value greater than 1, it means that exploitation loads are greater than expected, and conversely.

In the author's opinion, implementation costs of proposed concept are insignificant in relation to measurable economic benefits, which can be expected from safe and long exploitation of such expensive equipment as contemporary airplane. The data received from likely implementation of this concept will be also the priceless material to the designers, allowing creation of more durable and lighter structures, formed regarding fatigue durability on the basis of probable real loads.

Nevertheless, in contemporary aeronautical designs, the most fundamental and difficult to solve issues are fatigue strength issues. It results from complexity of the materials and structure fatigue phenomena, which we can't model yet with computations credible enough.

On account of this, to determine fatigue durability the costly fatigue test are performed, the results and analysis of which are priceless experience of the design bureau, hidden from potential competition. Preparation and leading of this research demands costly scientific background and test base.

Diagrams presented below show RPPS-2 recorder, developed and produced in Institute of Aviation. Instrument was elaborated and manufactured in frames of PZL-I22 Iryda jet trainer program.

CONCLUSIONS:

Implementation of the proposed concept allows:

- increase of the exploitation safety regarding possible fatigue failure of the airplane load-bearing structure,
- increase of the airplane exploitation time (service life) without increase of probability of airplane load-bearing structure fatigue destruction,
- estimation of load spectra assumed in fatigue tests, on the basis which airplane exploitation service life was defined. If it shows, that assumed for a.m. tests spectra is to steep, than assuming proposed principle of airplane exploitation

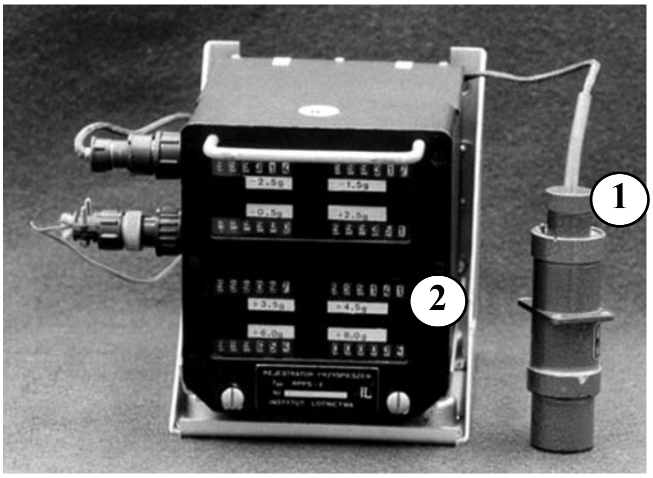

Fig. 6. Polish Aircraft Vertical Acceleration Recorder (RPPS-2)

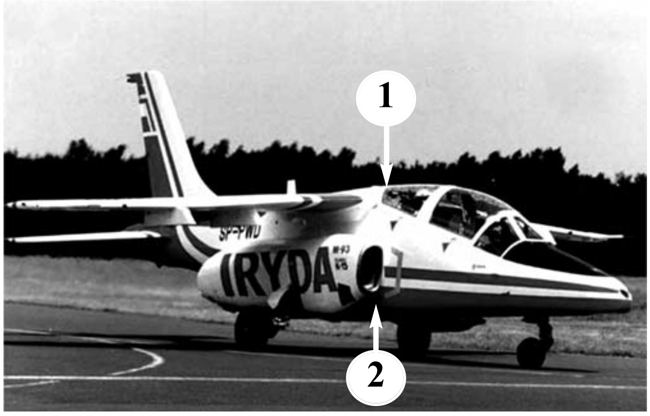

Fig. 7. Installation of RPPS-2 Recorder on the polish jet trainer aircraft PZL I-22 Iryda: 1 - Aircraft Vertical Acceleration Transducer, 2 – Aircraft Vertical Acceleration Sorter

until full depletion of their fatigue resistance (**$\xi = 1$**), one may count on significant prolongation of their exploitation service life. In contrary case, it will be a warning signal of earlier than assumed possibility of fatigue failure.

- receivement of real load spectra, on the basis, which the outstripping fatigue tests may be performed to optimize airplane design.
- receivement at that very moment for every airplane included in system its actual exploitation loads history, together with actual technical state estimate. It may be the basis for decision for future ways of airplane exploitation. Currently, it happens that necessity of prolongation of airplane service life is made only on the basis of its actual technical state, without knowledge of its loads history,
- full, regarding its exploitation loads history, utilization of airplane fleet flight service life.

The next version of the AVAR type instrument was RPPS-2 recorder, developed in Institute of Aviation Avionics Department by late Józef Nikolezig, MSc. Instrument passed full set of tests for conformance with Aircraft Requirements and was accepted later to serial production. Several sets of this instruments was produced and installed on every airframe of PZL I-22 Iryda jet trainer airplane. This recorder was the fundamental element of load bearing structure continuous fatigue monitoring idea, implemented on this airplane. Abandon of the PZL I-22 Iryda program halted continuance into ambitious and innovative plans in area of Smart Structural Health Monitoring System.

Experience gained by us and innovative character of the project gave us participation rights in domestic and European scientific projects – actual projects and projects already realized.

BIBLIOGRAPHY

[1] **Debski M.**: Temporary requirements for the prototype of flight recorder RPPS-2, *Institute ofAviation 57/RW-W 1/83 (internal report of IoA – polish language version only).*

[2] **M. Sadkowski**: Preliminary technical requirements for the prototype of vertical Accelerations recorder RPPS-1/8S. *Institute ofAviation 31/RW-W 1/86 (internal report of IoA – polish language version only).*

[3] **V. Kahanek**: Volba unavovych S-N k¿vek v tamci vyvoje noveho letounu. *Zapravodaj VZLU, No. 1/1986.*

[4] **Debski M.**: Continuous Fatigue Estimation of Aircraft Supporting Structures *Technika Lotnicza i Astronautyczna, No. 2/89 (polish language version only).*

[5] **Chuin-Shan Chen, Paul A. Wawrzynek, Anthony R. Ingraffea** Crack Growth Simulation and Residual Strength Prediction in Airplane Fuselages *NASA/CR-1999 - 209115, March 1999.*

M. A. Dębski, D. K. Dębski, K. Gołoś

CIĄGŁA OCENA ZUŻYCIA ZMĘCZENIOWEGO STRUKTUR NOŚNYCH SAMOLOTÓW

Streszczenie

W pracy przedstawiono podstawy teoretyczne i zasady realizacji koncepcji Ciągłej Oceny Zużycia Zmęczeniowego Struktur Nośnych Samolotów. Warunkiem realizacji tej koncepcji jest ciągła rejestracja obciążeń oraz znajomość charakterystyk zmęczeniowych krytycznych rejonów tej struktury nośnej.

Przykładem rejestratorów które mogą stanowić zasadniczy element realizacji tej koncepcji jest opracowana w Instytucie Lotnictwa rodzina Autonomicznych Rejestratorów Obciążeń i Zmęczenia Struktur Nośnych [4].

М. А. Дембски, Д. К. Дембски, К. Голось

НЕПРЕРЫВНАЯ ОЦЕНКА УСТАЛОСТНОГО ИЗНОСА НЕСУЩИХ СТРУКТУР САМОЛЕТОВ

Резюме

В работе представлены теоретические основы и принципы осуществления концепции Непрерывной Оценки Усталостного Износа Несущих Структур Самолетов. Условием осуществления этой концепций является непрерывная регистрация нагрузок и знание усталостных характеристик критических зон этой несущей структуры.

Примером регистраторов, которые могут быть основным элементом реализации этой концепции, являстся разработанное в Институте Авиации Семейство Автономных Регистраторов Нагрузок и Усталости Несущих Структур (4).