OUTLINE OF AIRCRAFT STRUCTURE HEALTH AND USAGE MONITORING SYSTEMS AND METHODS USED FOR THEIR REALIZATIONS

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Summary

This paper outlines the main approaches that are being developed in Russia to create the airworthiness monitoring system with respect to service life, residual strength and damage tolerance. The correlation of these approaches with Aviation Regulations is shown.
The paper provides a brief overview view of research results basically obtained in TsAGI.

1 Introduction

In this paper we address the development of the aircraft monitoring system in Russia. The major attention will be paid to Aviation Regulations, because complying with them is crucial for practical usefulness of results acquired by monitoring. Aircraft Health and Usage Monitoring Systems (HUMS) are needed to provide safety and cost efficiency of aircraft. Various methods are used and are under development in Russia to implement these systems.

1. The main techniques being also currently used are developed for systems consisting of ground and in-board parts in order to acquire, process and store the data of the so-called “flight experience”. The main source of data is the flight recorders, however in some cases special software to measure the bending moments and the strain histories in some points of Structural Significant Items (SSI) are used. These systems do not provide online information about the monitoring results for the crew. Such systems are usually called as “batch HUMS”.
2. Other techniques, which are being developed intensively, are focused on in-board systems that provide online information about accumulated damage and failures of individual aircraft. Such systems are called as “real-time HUMS”.

In order to provide the proper flight safety, the Aviation Regulations set was developed. These regulations take into account all main strength issues including the fatigue life and the damage tolerance. The long and relatively self-sufficing development of the regulations resulted in formation of three clearly defined approaches: American, European and Russian ones.

The European approach was greatly influenced by two crashes of British commercial aircraft “Comet I”, caused by the fatigue failure of pressurized fuselage. That's why a particular attention was paid to fatigue life issue in order to predict reliably the time of fatigue failure. Fundamental generalizations of results obtained became a basis for British Civil Airworthiness Requirements (BCAR) of that period, the main focus of which was on the fatigue lives requirements supplied with detailed and specific guidelines on the required fatigue life safety factors related to data obtained experimentally. The enforcement of Airworthiness according to these requirements was called as “safe-life” approach.

The Russian approach at its early stage (in the 1950s) was subjected to European influence, therefore, the "safe-life" approach was considered as the only approach of airworthiness enforcement for durable service live in the first versions of Russian Aviation Regulations. The experience of "safe-life" approach application shows that it must be applied first of all for Principle Structure Elements (PSE), in which the emergence of multi-site fatigue cracks is possible. These cracks are small and poorly inspectable; moreover their merge may result in catastrophic failure. Such PSE are normally located at longitudinal bonds and joints of pressurized fuselage, transverse joints of wings and other elements. The application of "safe-life" approach is also reasonable for such structural elements if their failure and complicated repair in service life result in excessive rise in cost of aircraft itself and expenses caused by forced outage.

As far as it concerns the structural elements, the service life which of is estimated by the "safe-life" approach, a monitoring system must track first of all the service conditions (load history and environment parameters), because tracking the damages would not provide safety anyway, due to the fact that damages occurred would rapidly propagate.

The American approach to Regulations was based on experience of highly intensive and durable service of huge different aircraft type's fleets that operated around the world and belonged to large number of companies rather differentiated by type and level. The generalization of this experience resulted in belief that "classic" fatigue does not comprise all issues connected with the durable service airworthiness. The other two factors are of no less importance: different types of corrosion (including the corrosion and fatigue combined) and accidental service (manufacture included also) damages that normally result in fatigue cracks initiation and propagation.

The attempts to find a universal approach to cover all three danger sources simultaneously, generated at first a "fail-safe" approach that provided such a redundancy of multiple load paths in structure, that reliably detected complete failure of one of the load paths does not cause the strength reduction below allowable limit (usually 67% ultimate load). Since the end of 1950s this approach has become a dominant one in American regulations.

However the reliance upon the universality of "fail-safe" approach (like the reliance upon the universality of "safe-life" approach in Russian regulations at the same time) came again into conflict with the service experience. In the 1970s the "damage-tolerance" approach was accepted as a more reliable one, and was adopted in Russian regulations and a bit later in American regulations.

For Principle Structure Elements, the service life which of is estimated according to the "damage-tolerance" approach, a monitoring system must keep track not only of damage initiation but also of damage propagation. For such systems the service usage monitoring would allow to establish the more cost efficient inspection intervals.

2 Batch HUMS

Batch HUMS systems are considered to be the most cost-efficient. Their main features in Russia include:

1) The initial service life is intentionally estimated at its lowest level, and there is a special procedure of step-by-step prolongation of service life using the acquired data.
2) The step-by-step prolongation of service life is based on full-scale and specimen tests using the fatigue life and the crack propagation rate equivalences between the full-scale load tests and the load conditions in exploitation.
3) The service live prolongation procedure is usually applied for total fleet of aircraft which type of is under consideration.

Further, the peculiarities of the used techniques are discussed.

2.1 Russian aviation regulations

In the 1990s the necessity appeared to harmonize the Russian Aviation Regulations with the global ones concerning the airworthiness in reference to fatigue. In line to harmonization principles taken earlier for FAR 25.571 and JAR 25.571, that focused on airworthiness that accented on strength the structure of American regulations was decided to be adopted as a basis for the Russian Aviation Regulations (AR 25.571), because the corresponding Russian requirements (chapter 4.9 of Airworthiness codes, 3rd edition) were essentially similar to the FAR 25.571 requirements. However, the significant changes in the Russian general airworthiness ideology were introduced. Firstly, the necessity to take into account not only the fatigue but the possible corrosion and the accidental damages as well was pointed out. Secondly, the “safe-life” approach is allowed only if an applicant would prove that the “damage-tolerance” approach is not applicable for the structure considered.

At the same time it was reasonable to introduce some principal milestones validated by long-term experience of the Russian aviation in general requirements of AR-25.571. The following two milestones were decided to be the principal ones:

- Russian monitoring methodology based on the step-by-step prolongation of assigned service lives with (if needed) changes of corresponding service instructions connected with these steps;
- Priority of full-scale tests to mathematical simulation.

2.2 How to increase the service life by using batch HUMS

During the long-term aircraft service the reduction of its airworthiness below limitations was prevented not only by the airworthiness condition monitoring but also by the airworthiness support during service, which is a main part of monitoring procedure. This fundamental principle complies entirely with the requirements of the Air Code of the Russian Federation for State control over airworthiness (article 37 clause 7) and the requirements of the Russian Aviation Regulations AR-21 "Certification procedures oh aircrafts", article 6 "Rights and Duties of the holder of a Type Certificate and of Air Operator".

The Russian and foreign experiences showed that the prohibitive reduction of airworthiness may be prevented by the detailed monitoring procedure only. In the Russian practice the monitoring procedure is based on the step-by-step prolongation of the assigned service lives. It is to be noted that it merely structurally differs from the similar foreign procedures aimed at possibility to introduce the needed changes of conditions to get assigned service life (and further). The principal (mandatory!) AR 25.571 requirements do not obligatory insist on following the procedure, referring to MOC (Aviation Circular) 25.571 for details, but regulate a necessity to have a monitoring procedure that provides the equal safety level. Let's quote in connection with above-said the addition (a)(4) to source clause (a) FAR 25.571 included in AR 25.571:

"(4) Documentation developed in accordance with (a)(3) must be periodically corrected on the basis of the accounting and analysis of research results, of tests and of accumulated experience of service for this aircraft type. A procedure that provides reliability and timeliness of such monitoring must be defined. Such procedure may represent the guidelines from chapter 1 of MOC (Aviation Circular) 25.571, or other technique that provides equivalent safety might be used".

Certain changes in airworthiness monitoring procedure may be accepted on grounds of the following considerations:

Airworthiness support by means of continuous service maintenance is realized by step-by-step inspections and if necessary by revision of earlier estimated conditions of service life practice that are represented in chapter “Limitations…”.

Step-by-step monitoring the conditions of service life practice and their revision closely correlates with heavy forms of technical maintenance that imply the partial disassembly of aircraft elements for inspection at factory facilities ("C" and "D" maintenance forms).Such an approach provides a validated and effective way of airworthiness monitoring and control without great management overload and at the same time the stages duration derived from Technical Conclusions about possibility to continue service is precisely estimated. The assigned service life stops being "current" and returns to its basics becoming a service life limitation. The service life issue also expands to economic domain, where the development of "Service life evaluation" (assigning the predicted repair terms and/or the technical inspection periods) becomes important and this evaluation becomes an only technical document on service life and service duration at aircraft sale.

Required airworthiness level at long-term service may be achieved only on condition providing that its control and support account for individual peculiarities of state (corrosion, repairs and fatigue cracks) and service conditions of each unit of the type, thus requiring a necessity to determine conditions of service practice for each aircraft individually.

Combining the procedure of revision of individual service life stage for each aircraft type with the procedure of fixation of aircraft's technical state plus fulfillment of required maintenance schedule may be the most acceptable form of step-by-step process in continuous airworthiness support of aircraft.

3 Real-time HUMS

Real-time HUMS require the additional in-board equipment and much more expenses for their implementation , but one can provide the considerable service life elongation using such systems. For example the mission distribution (brown line) taken at service life evaluation of Be-200 (firefighter aircraft) is presented in Fig.1.

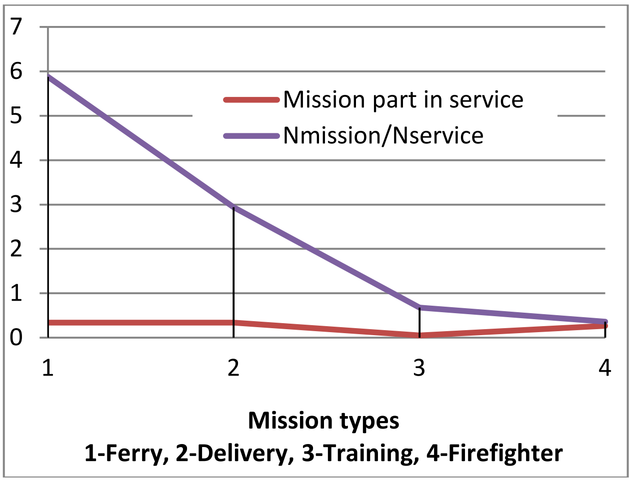

Fig.1 Differences in Be-200 missions

If this aircraft is used for delivery only its service life may be increased 3 times, if it is used for firefighter mission only its service life must be decreased 3 times for safety.

Let's consider the proposed stages of real-time HUMS development in Russia:

1) Individual usage monitoring based on flight recorder sensors
2) Fatigue Load Counter (FALC) based on in-board strain measurement system
3) SHM system based on various types of damage detection sensors. Cracks, impact damages of composites such as holes, matrix cracks and delamination, and so on are considered as damage in this case.

The main developments and research results in this area are:

1. Methods to provide an optimal strain sensor location in order to monitor as many points in PSE as possible. These methods are based on developed mathematical models.

2. Self calibrating strain measurement systems based on resistance strain gages.

3. Algorithms and methods of real-time "rainflow" load history representations and the data reduction for storage and post-processing.

4. Methods for more exact ways of fatigue life estimation based on local elasto-plastic stress-strain approach for geometric

concentrators and joints. These methods do not require the experimental estimation of cyclic stress-strain curves and fatigue life curves of smooth specimens as in the usual local elasto-plastic stress-strain approach. These methods are very important for HUMS because they allow taking into account the acquired load histories.

5. Methods to provide SHM for aircraft composite structures.

3.1 Selection of optimal strain sensor locations

Taking into account that the aircraft has thousands of critical points the important task is to reduce a number of strain gages of HUMS as much as possible and in the same time to provide the reliable data to evaluate airworthiness of aircraft structure as a whole. The optimum is taken using the requirement to get minimal misalignment between the strain gauge data and the exact solution under loads corresponding to the maneuvering conditions A through I on the maneuvering envelope in §25.333(b) AR [1]. The main sources of "exact" solutions are Finite Element Method and tensometry at full-scale tests. Sometimes the optimum estimation by usual mathematical methods [2] does not give the required results because of availability of large quantity of local minimums. In these cases a special method of point enumeration is used.

Points to be considered in multi-dimensional parameter space are selected in such a way that their even distribution would remain even in the sub-space of each lower dimensionality down to one-dimensional lines of each single parameter values. Then, if for each of ***n*** parameters it is considered ***k*** points evenly distributed along some coordinate axis segment, and then in ***n***-dimensional space of all parameters quantity of even ***n***-dimensional points would remain equal to ***k*** also [3].

3.2 Self calibrating systems

At HUMS creation our POV is that a possibility of system for self-calibrating is its main peculiarity.. In the developed prototypes this feature was put into practice as following [4]:

- The resistance strain gage 8 was manufactured along with the heater 6 and the temperature gauge 7 (Fig. 2). Heating of this resistance strain gage by short-time pulse resulted in temperature deformations. The temperature measurement and the calibration of response allow to make sure about both the gauge operability and the gauge accuracy.

- A system has two channels with high-precision resistors impedance which of practically is not changed during long time. the periodic data acquisition of these resistors gives a base to correct some changes of linear characteristics of the system as a whole during service. It is particularly important for HUMS, that must be able to maintain the operability during long-term service.

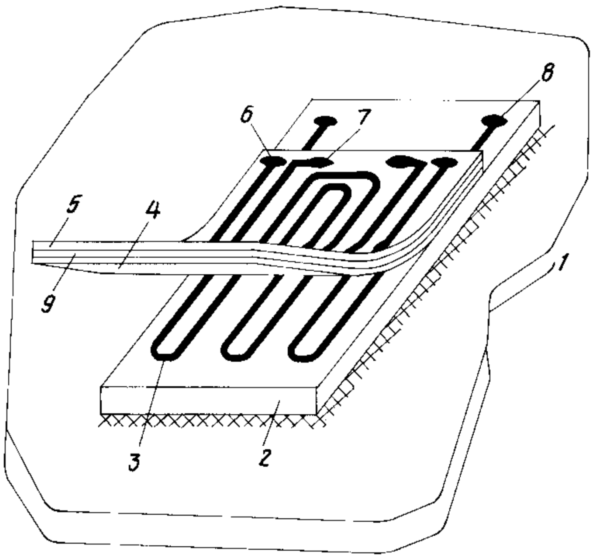

Fig.2 Self-calibrating resistance strain gage

3.3 Methods of accounting the non-linear effects

It is generally known that for many cases the fatigue and the structural residual strength depend non-linearly on affecting factors. It is a base reason to use the non-linear models for their evaluation. The main peculiarities proposed for implementation of these models are shown below.

3.3.1 Parameters estimations

For many cases the parameters used in models depend on test modes. For example, our analysis showed that **κ** parameter in Oding's generalized equation (also named as Walker's equation), that takes into account the load asymmetry:

$$\sigma_{eqv}=\sigma_{max}{}^{\kappa}(2\sigma_a)^{(1-\kappa)} \qquad (1)$$

where σ_{eqv} – equivalent stress of pulsating cycle, σ_{max} – maximal stress, σ_a – stress amplitude

changes from 0.1 to 0.9 at various load conditions (Fig. 3).

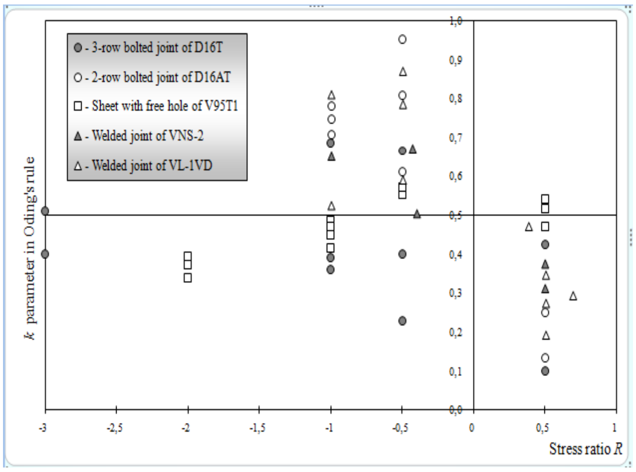

Fig.3 κ - R relation for various specimens

Thus, the effective value of **κ** depends on the distribution of load modes in load sequence and/or in service. The same is true for **m** – slope of fatigue life curve

$$N_f=(C_\sigma/\sigma_{eqv})^m \qquad (2)$$

where N_f – fatigue life, C_σ - constant

Besides the scatter of fatigue lives depends on load mode also (Fig. 4 [5]).

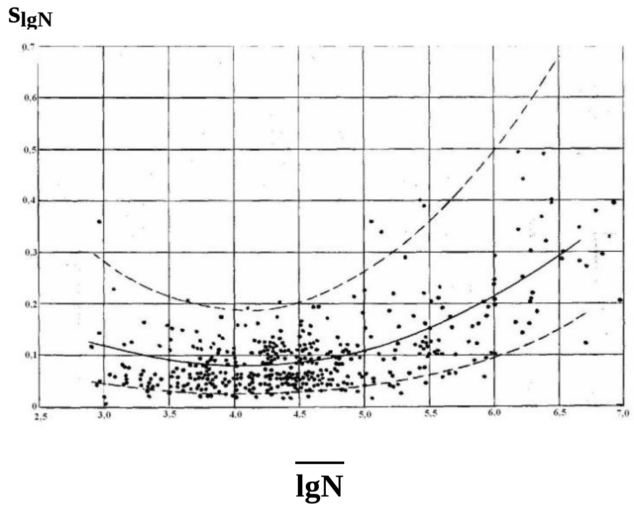

Fig. 4. Scatter of fatigue lives s_{lgN} for D16T alloy (2024-T3 analogue) specimens . (Mean values and 90% confidence limits)

In order to estimate **m** and **κ** values that are valid under service loads to get the so called "design curves" the special procedures were developed. Main requirements to these curves are as following:

- Parameters of these curves must fit the design conditions;
- The tests required for their evaluation must correspond to routine tests.

This approach realization of one of the most important cases will be shown below: the estimation of fatigue life under random service loading.

3.3.2 Load history selection

To evaluate the mean parameters the typical load conditions for this aircraft are selected. For transport aircraft they are represented by 5 segments (take-off, climb, cruise, descent and landing) – the PIRUET program. The TWIST program [6] was taken as a base for the PIRUET program development, so TWIST may be selected as a particular realization of PIRUET. It may be used for the structural elements both of the lower wing surface and of the upper one. To reduce the test duration the filters are used that exclude from the load sequence some loads with amplitudes below selected limit. Such filters allow keeping the sequence of remaining extremes the same as their sequence in original program.

Arbitrary load history with flight-by-flight structure may be done using the PRIMA program. Data for this program are initiated by loading models or taken from flight tests. For cases when the load history must be initiated “manually”, the BLOCK block program is used. This program consists of nested blocks with a lot of nesting levels allowing to include seldom extremes.

The general requirements to generate all load histories are:

1) The cumulative frequency in load history must be equal to the frequency of complete cycles of equivalent stresses.
2) The seldom stresses that may increase the fatigue life are to be excluded from the load history (maximal tension stress limitation) and the seldom stresses are included that can cause the non-linear effects resulting in fatigue life decrease.

High tensile stresses to be excluded from the test program and vice versa high compressive stresses to be remained in the program are determined with regard to the assumed tolerable probability of getting the non-conservative estimates during the tests. Taking into account the very seldom occurrence and the independence of these stresses of each other, it seems natural to assume that the probability of their initiation is well described by Poisson’s distribution. Taking the mean value of stresses expected for the complete lifetime equal to or exceeding L as a(L), the probability of non-occurrence of such stresses for this lifetime is $p(< L) = 1 - e^{-a(L)}$.

Having the maximum tensile test stress equal to L_+ there is a probability $p_+ = e^{-a(L_+)}$ to have a risk of non-conservative situation with the maximum test stress exceeding the maximum service stress for some airplane. Limiting the maximum test compressive stress by the absolute value L_- there is also risk to have a non-conservative situation with the probability $p_- = 1 - e^{-a(L_-)}$ when the maximum compressive stress L_- exceeds for some airplane in service the similar test stress.

When the both risks are assumed as similar and equal, e.g. (with regard to typical aircraft fleets) $p_+ = p_- = 0{,}01$, it will result that L_+ or exceeding load should occur in service as an mean $a(L_+) = 2 / \lg e = \sim 5$ times per lifetime. The stress L_- should be selected as a very high one that occurs very seldom in service, usually only once per 100 lifetimes. If the error risk increase is assumed tolerable and equal to p = 0,1, then the corresponding values of $a(L_+)$ and $a(L_-)$ would occur 2 times per lifetime and once per 10 lifetimes.

3.3.2 Design curves

If one requires that the linear damage summation rule (Miner’s rule) be valid for test results

$$\sum \boldsymbol{D_i} = 1 \qquad (3)$$

where the sum is counted for all damages $\boldsymbol{D_i}$ ***(D=1/N_f)*** caused by complete (half)cycles represented by “rainflow” algorithm in load history; then using this equation we can estimate some parameters of the so called “design fatigue life curves”, which are effective values of these parameters for selected load histories. For cases, when the service load conditions differ slightly from the selected load histories, this approach is used for usual methods of fatigue life evaluation being based on nominal stresses. To increase the scope of “design curves” fatigue life evaluation the methods must include the models that take into account the non-linear load interaction. The model of fatigue life evaluation based on local stress-strain approach is the most suitable for this purpose [7].

3.3.3 Local stress-strain approach

Let's consider the case when the approach in point is used in a simplified version: regardless the load multi-axiality, the stress gradients and some peculiarities of deformations in joints.

It is assumed that the non-linear deformation of materials follows the ‘stress-strain’ curves which are fitted in $\boldsymbol{e_a}$-$\boldsymbol{s_a}$ coordinates as the power functions:

$$\boldsymbol{e_a = s_a/E + (s_a/K)^n} \qquad (4)$$

where $\boldsymbol{e_a}$, $\boldsymbol{s_a}$ – local strain and stress amplitudes respectively;

$\boldsymbol{E}$ – modulus of elasticity;

K, n – constants of material.

The constants are usually estimated by means of static tension tests or cyclic straining according to special developed programs.

In general case four ‘stress-strain’ curves must be determined: tension and compression static and cyclic curves. When the complete set of curves lacks, the material tension and compression constants are taken as equal and the cyclic curve is obtained from a static one using Masing’s hypothesis [8].

Together with Neuber’s equation

$$(e_a \cdot s_a)=(K_t \cdot \sigma_a)^2/E \qquad (5)$$

where K_t – elastic stress concentration factor;

σ_a – nominal stress amplitude of complete cycle that is represented by “rainflow” method.

‘stress-strain’ curve (4) constitute a system of non-linear equations in unknown e_a and s_a that is solved by usual mathematical methods, for example, by Newton’s iteration method [2].

Using this approach along with material’s “memory” property one receives the local stress-strain history, representation which of results in a “rainflow” matrix $(s_{max}, e_a, r)_i$, where s_{max} – maximal local stress, r – a number of complete half-cycles (reversals) with parameters (s_{max}, e_a). Using Miner’s rule this set of complete half-cycles is reduced to one half-cycle with parameters of half-cycle that occurs the most often. Thus one gets the required data for the evaluation of “smooth” specimen’s “design fatigue life curve” parameters

$$N_f = \left(\frac{C_e}{e_{-1}}\right)^{m_e} \qquad (6)$$

$$e_{-1} = e_a^{1-\kappa_e} \cdot (s_{\max}/E)^{\kappa_e} \qquad (7)$$

where C_e, m_e, κ_e – constants for material and for <u>structure type</u>, e_{-1} – strain amplitude of symmetrical cycle.

This approach has a number of advantages:

- As a design source data for fatigue life evaluation the same specimens are used as for the usual evaluation based on nominal stresses, contrary to special “smooth” specimens required by the usual local stress-strain approach [7].
- Some errors at estimation of local stress and strains originated from errors of approximated equations (4) and (5) are corrected automatically.
- For especially significant cases the manufacturing technology may be taken into account that is practically impossible when the fatigue life curves of “smooth” specimens are used.

The approach described above was proven at structure element tests in TsAGI. It has been realized by development of special algorithms of random history representation [9] and methods allowing to realize dynamically the “rainflow” matrix, designated for the monitoring system and for the drastic reduction of memory requirements for its storage.

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