ON TEST PROGRAMS OF AIRCRAFT STRUCTURES

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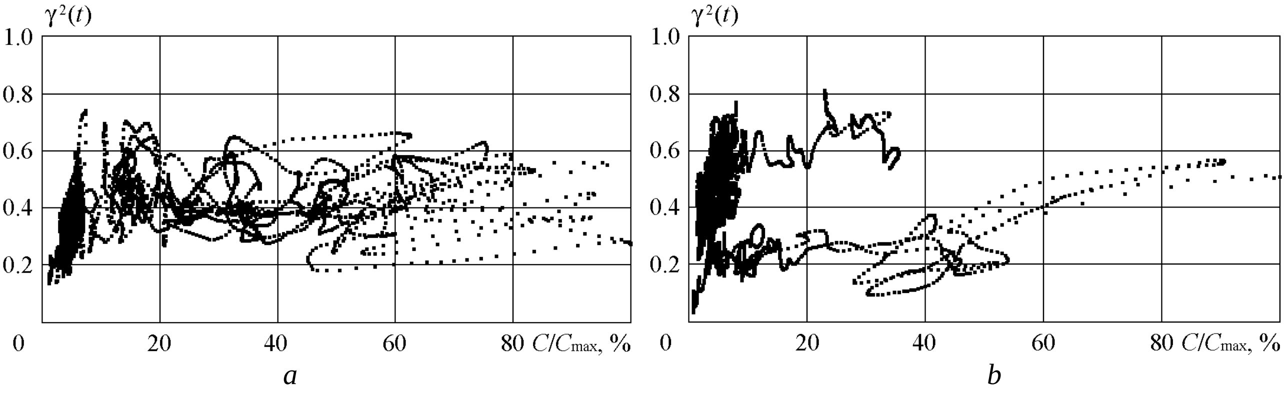
Introduction

Existing methods of fatigue life prediction and test programs development are based on the schematization of load extrema resulting in the information loss. The actual random processes (RP) of loading have the time-averaged characteristics: spectral density, distribution law, and combined characteristics. On theoretical grounds [1], these characteristics are sufficient to synthesize averaged realizations of loading processes as pseudorandom process (PRP) whereby test programs can be obtained and calculation methods verified. It is especially important because failure is a temporal process at any manner of loading.

Existing situation

Aerodynamic loads and forces of inertia initiate in-flight vibrations of the airframe. Reiteration curves of extreme values of load are usually being constructed as characteristics of loading. Moreover, estimation of loading is performed by load factor at the center of mass. This gives a rough measure of actual loadings at structural points of interest.

Figure 1 shows the change of the coherent function [2] of g-loading at the center of aircraft mass and bending moment in a section of a wing according to the power of their cross-spectrum. As it is seen from the diagram, the coherent function varies with time in a wide range. This clearly demonstrates that g-loading is unusable as a single-valued measure of loading. The reason is that such g-loading is the overall result of the combined effect of all operating forces.



a *b*

Fig. 1. Dependence of the coherent function γ^2 of g-loading at the center of aircraft mass and bending moment of a wing from the relative power of cross-spectrum C during 256 seconds of take-off (*a*) and landing (*b*).

The next is an approximate method of evaluation of structures longevity that is based on the “cycle ideology”. Endurance tests of structures and calculations of equivalents in loading are based on this approach as well while the process of failure goes on with time. As consequence the dangerous (weak) points are not necessarily found, because the structure is loaded absolutely differently than in actuality.

The cycle is defined as a characteristic of structure loading and can’t be a unit of longevity, because it hasn’t physical foundation and standard value. A cycle of stresses has five parameters: amplitude, mean stresses, frequency, shape, and may be realized at various temperatures. Their combination will determine the longevity that is the time of failure. The content of the endurance unit (cycles number before failure) depends on the values of these parameters. In Fig. 2 the fatigue curves are presented for different frequencies in traditional coordinates which show the different content of such unit of measurement.

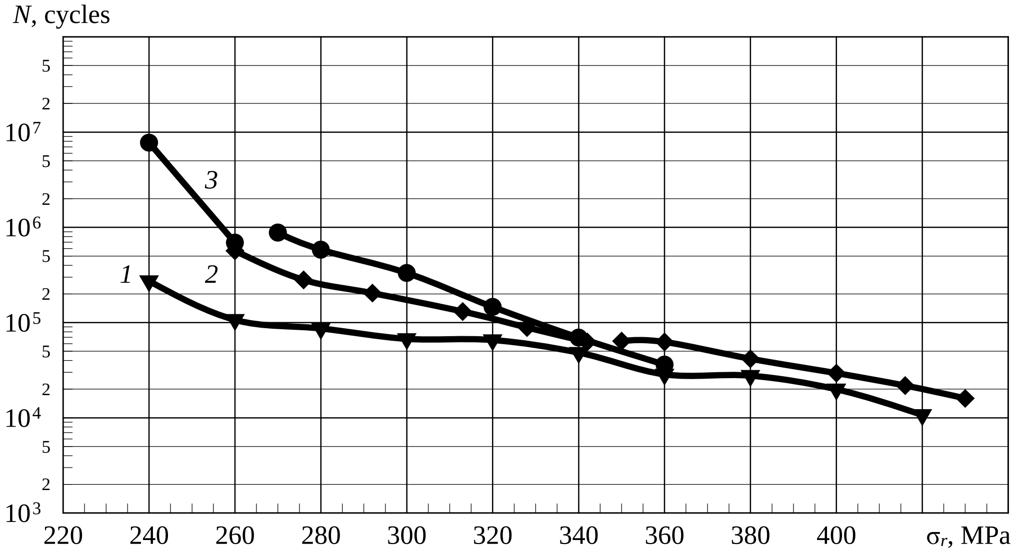


Fig. 2. Fatigue curves of duralumin specimens, tested at various frequencies of loading (mean-logarithmic values of endurance, $\sigma_r = \sigma_{\max} - \sigma_{\min}$): *1* – 0.67 Hz, *2* – 40 Hz, *3* – 380 Hz.

Solution of problems

The alternative is to use a summation of spectral density of actual loading processes. Averaged spectral density shows up as a discrete spectrum of elementary random functions (ERF) for every leg of the flight [1]. Furthermore, the resulting PRP can be defined as the equivalent to RP of loading at fulfillment of certain requirements imposed on the quantity of ERF and their frequency distribution. The test data that are shown in Fig. 3 illustrate a relationship between the longevity τ and discrete degree of the PRP spectrum D_d for specimens with different stress concentration factors (CF). The discrete degree of spectrum is defined by quantities of ERF and their structure. If the process is presented by Z harmonic functions of equal amplitudes, then $D_d = 1/Z$ [1]. The greater is the CF, the less is the required discrete degree of spectrum inasmuch as the contribution of small amplitudes, to which such specimen is sensitive in the total process will be enhanced.

Any more rigorous treatment requires the individual analysis of the time of crack initiation and propagation. It is known that a growth rate of the relatively small cracks is determined by the equation [3]:

$$\ln\frac{dl}{dt} = \ln A + Bl\text{, alternatively } \frac{dl}{dt} = A\exp(Bl)\text{,}$$

wherein A and B are parameters depending on the specimen proportions, material and loading conditions. Whence it follows that

$$l = -\ln[1 - AB(t - t_0)]/B$$

in which t_0 is the conventional time of crack initiation. With several measurements of crack lengths in the course of time in hand it becomes possible to estimate t_0. In Fig. 3 (line *4*) these estimations are shown for spectra with 6 and 24 harmonics of constant amplitudes that are uniformly distributed within the required frequency range. A comparison of the positions of the lines *3* and *4* shows that cracks at 24 harmonics in spectrum (D_d = 0.0417) are progressing slower then at 6 harmonics (D_d = 0.167) despite the fact that the crack has high CF. Figure 4 demonstrates the validity of expression mentioned earlier and Fig. 5 shows realizations of these PRP.

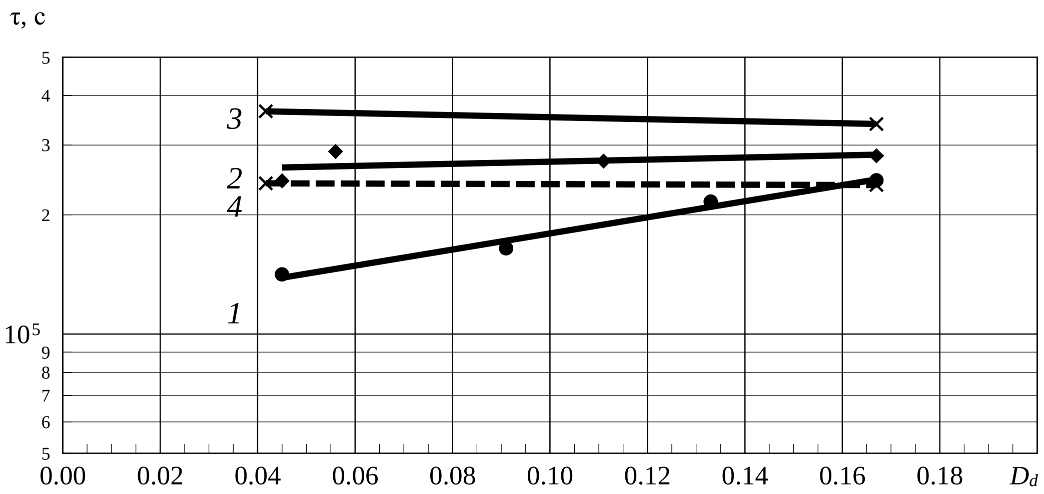


Fig. 3. Relationship between the mean-logarithmic value of longevity and the discrete degree of PRP spectrum for specimens with different CF (constant value of spectral density at various mean stresses σ_m):

1 – specimens with CF of 3.5 in frequency range of 0.5–5.5 Hz at RMSD 35 MPa, σ_m = 0, *2* – specimens with CF of 2.73 in frequency range of 0.1–8 Hz at RMSD 25 MPa, σ_m = 0, *3*, *4* – specimens with CF of 2.73 in frequency range of 0.1–8 Hz at RMSD 20 MPa, σ_m = 40 MPa, (*1*–*3* – total life, *4* – rated time of crack initiation).

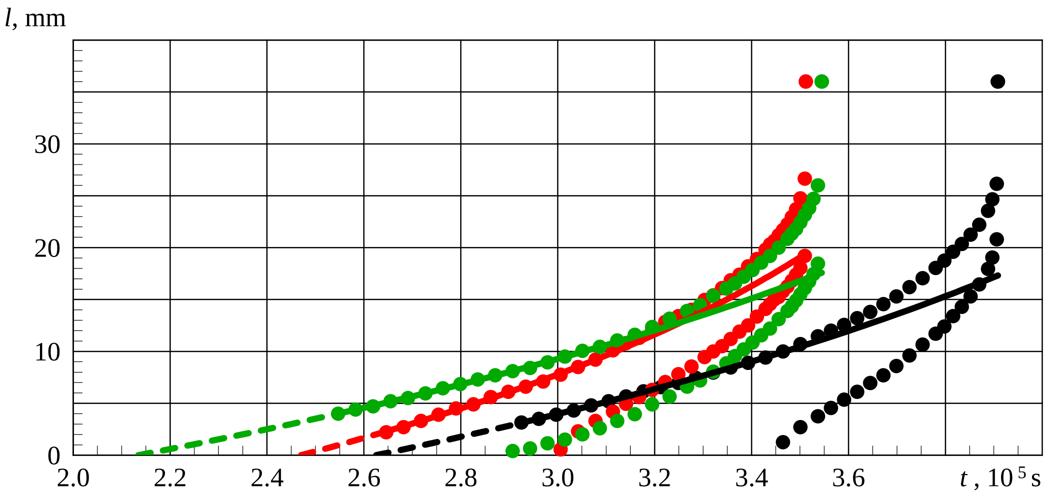
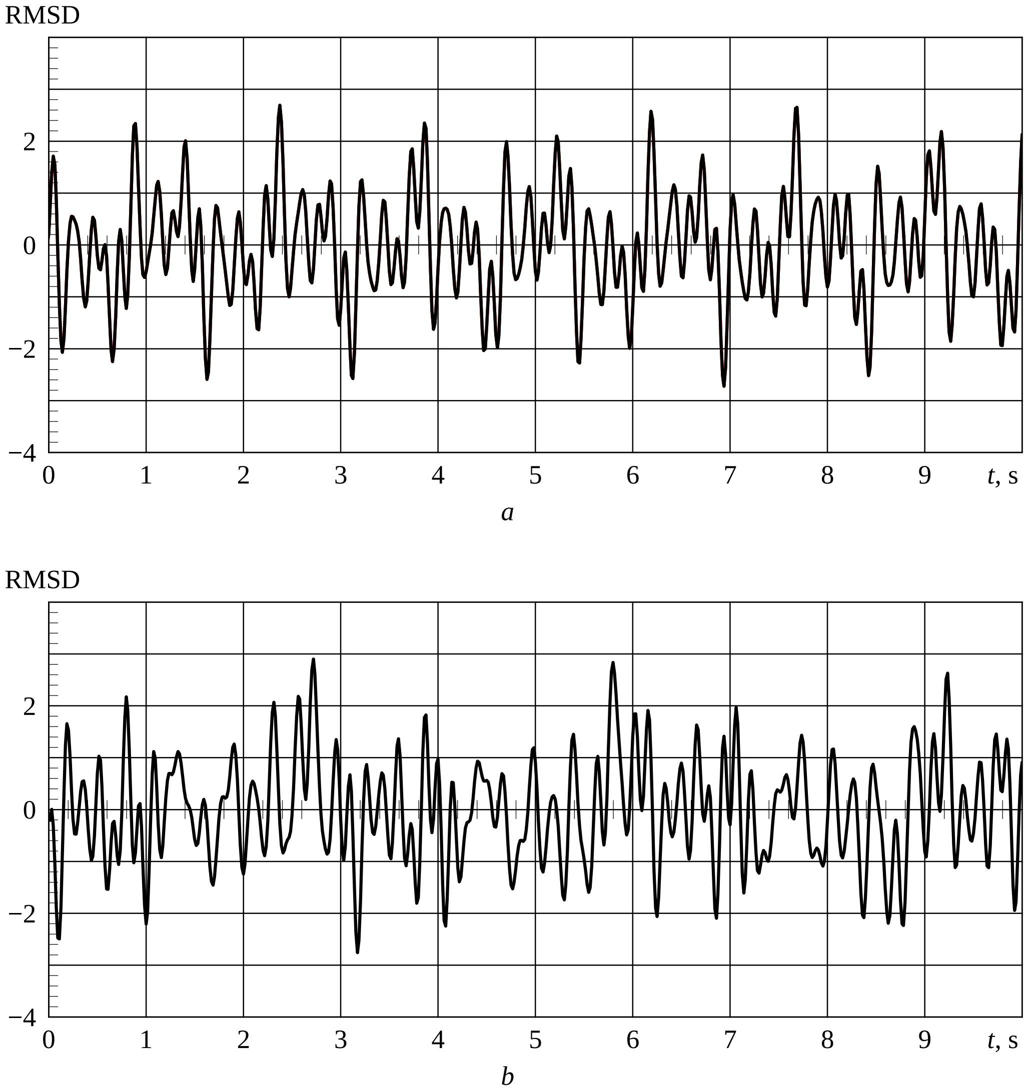


Fig. 4. Fatigue cracks progressing in the plate of 3 mm thickness and 80 mm width with the central hole diameter of 8 mm at 24 harmonics in spectrum of PRP:

lines – rated growth of cracks initiated earlier, points – measured lengths of the first and second cracks in each of three specimens.

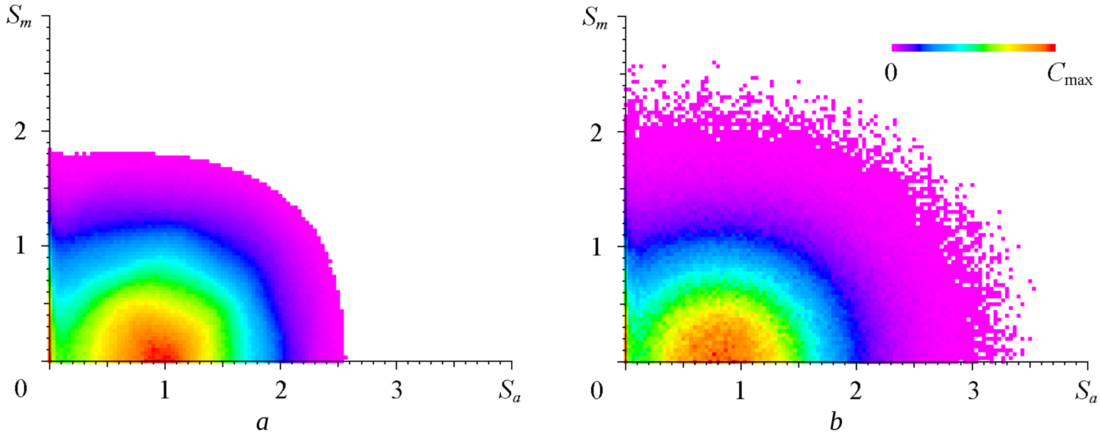
The represented expression of the crack growth can be used approximately to the crack length of 10 mm (to 0.35 of half-width of specimen including hole). If the second crack initiates earlier than this point of time, this expression can be applied to the second crack too. It is axiomatic that distinctions between the crack growth rates are structurally connected with these two PRP of loading. Their realizations point to some differences. The statistical analysis gives more insight into the course of process (Fig. 6), however the answer can be obtained by the experimental approach only.



a

b

Fig. 5. Realizations of PRP as a sum of 6 (*a*) and 24 (*b*) harmonics of incommensurable frequencies with random initial phases (piecewise-linear approximation with the time step of 1/64 s).



a

b

Fig. 6. Statistical characteristics (hit ratio C) of PRP with 6 (*a*) and 24 (*b*) harmonics in the discrete spectrum as the relationship between half-sums S_m and half-differences S_a of two extrema successive values.

In any case a spectrum which is closer to the real one can be obtained by decreasing of D_d at the increasing of ERF number or their complication. For this purpose, amplitude and frequency modulations are used. All these methods are suitable to synthesis of cross-correlated PRP too [1].

Test results under the actual loading

For the purpose of setting forth the requirements to correct methods of test program development, a start has been made on the outlined hereafter investigations. Relying on in-flight experiments, realizations of wing loading were obtained on which the forced test fights of 30 and 20 minutes were constructed. The section of wing was selected where the bending moment changes sign when taking off and landing. In what follows the digital filtration was made to get low-frequency (LF) and high-frequency (HF) components (Fig. 7). The frequency of 0.08 Hz has been adopted as the separating frequency of the filter. Thereafter the high-frequency component was multiplied by heightening coefficient and added with the low-frequency component or used without its addition. Rated stresses for testing specimens were assigned to be numerically equal to the bending moment. The 20-minutes flight was different in that the two legs of flight through the air with RMSD of 6.7 and 4.5 MPa were then eliminated.

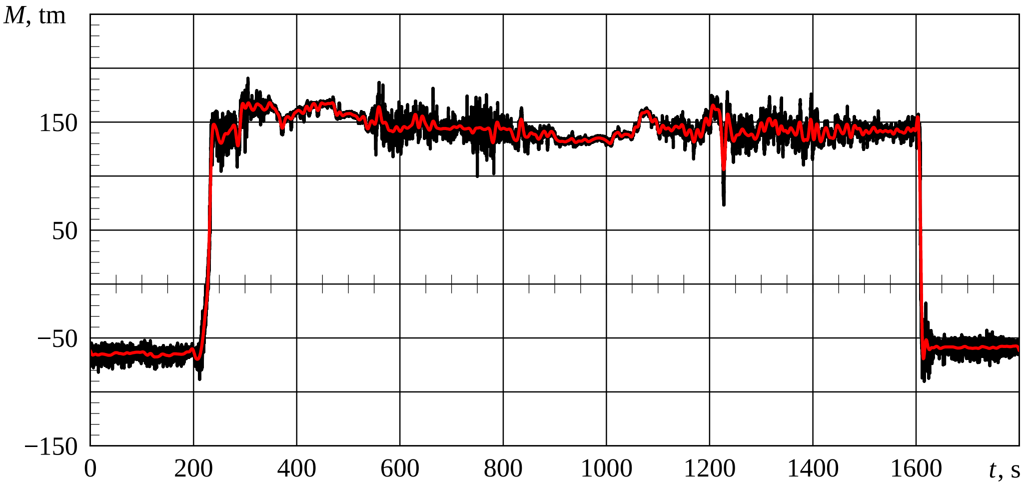


Fig. 7. The forced test fight in 30 minutes and its low-frequency component.

One further variation of the simplified test program was that the low-frequency component was replaced by the piecewise-linear (PL) approximation (Fig. 8). By doing so, the low-frequency component was slightly higher through the air than in the actual flight.

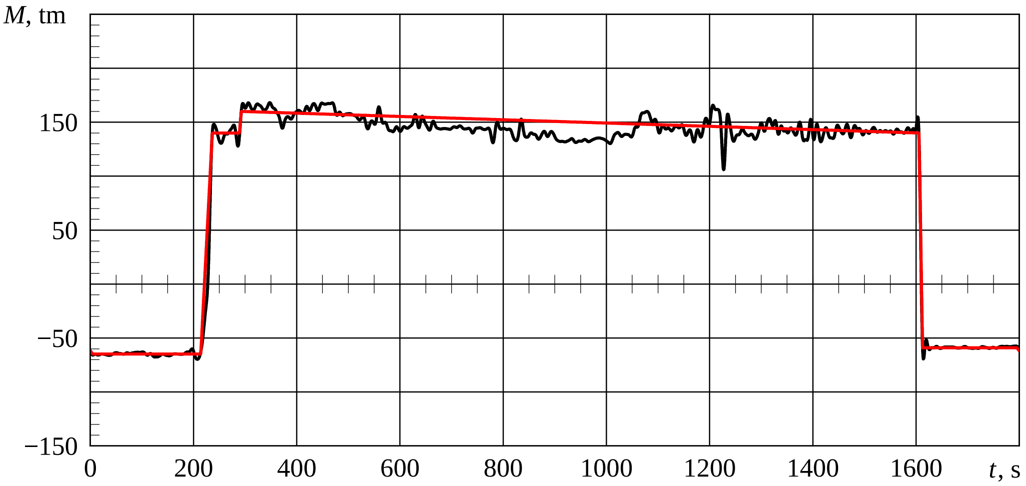


Fig. 8. The low-frequency component of 30 minutes test fight and its piecewise-linear approximation.

The test data of specimens with CF of 2.58 obtained in realizations for the bottom covering of the wing are presented in the table. Here, RMSSR is defined as a root-mean square scatter ratio which is the antilogarithm of the logarithm RMSD of longevity. RMSSR is more descriptive characteristic of scatter. Reasoning from the test results (compared with probability [4]), it is apparent that simplification of the program for this CF and each RMSD has an essential influence on longevity. Even along with a small change of the low-frequency component of loading its value may vary dramatically.

Test results of Al-clod duralumin plate with CF of 2.58 at various loading programs constructed on the in-flight experiment data

Mode of test	Program of loading	Mean-logarithmic value of longevity, flights	RMSSR	Probability of belonging to total sample
1	LF + 3 HF, 30 minutes	292	1.259	0.605
2	LF + 3 HF, 20 minutes	320	1.367	
3	4 HF, 30 minutes	284	1.189	0.132
4	4 HF, 20 minutes	328	1.086	
5	PL LF + 3 HF, 30 minutes	201	1.059	0.008 (with mode 1)

The deduction suggests itself that all kinds of programs should be calculated on the basis of simulation of deformation and failure as physical processes [1, 5, and 6]. This can be arranged by rheological models of material which were used for prediction of longevity [6, 7]. Structural elements of rheological models govern in the specimen both the overall flow (creep, occurrence of residual stresses) and the local flow during fatigue failure [8].

Conclusion

All of the preceding may be summed up as follows:

i. Actual loading process can be statistically represented by a sum of URF for each leg of flight.
ii. Computations of longevity as the result of thermodynamic processes in the material structure are performed in actual conditions of loading and at the assumed program of test for each hazardous site in the aircraft structure.
iii. Forced (accelerated) coefficient is defined as the ratio of longevity in an actual flight to longevity under the test loading by which it may be deduced that the hazardous site of interest would be revealed in the test process.

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