Computational Maintenance of Rotorcraft Fatigue Testing by Advanced Program Tools

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The methodology for modeling of rotorcraft fatigue test by using modern engineering software is discussed in the paper. The MSC.NASTRAN static and dynamic modules, the MSC.FATIGUE durability analysis and the in-house developed software tools are used in the methodology. An investigation of dynamic characteristics of test structure, comparison and evaluation of dynamic stresses both for loads in ground fatigue testing and the results of stress flight experiments with finite element analyses are performed. The biharmonic approach is used at forming equivalent set of loads for fatigue testing. In this approach the stress state in structure is generated by periodical excitation with two frequencies. The task is to choose amplitude and frequency characteristics of the excitation.

The considering methodology requires a lot of numerical analyses of structural stresses and dynamic characteristics both for flight conditions and ground fatigue conditions. The computational FEM models of high fidelity developed for advanced program tools are employed for this aim. The full-scale FEM model of helicopter is used for researching dynamic characteristics. Identification of stiffness and mass properties of models is performed by calculation of structural eigen frequencies and shapes. To detect the most essential vibration frequencies the analysis of dynamic response is accomplished. It allows us to model loads on structure for different regimes of flight tests.

The software for determination of structural stresses under dynamic loads and evaluation of structural damage for dynamic loads is developed. Oscillograms from strength flight testing and results of finite element analyses are initial information for the created programs. Analysis of structural damage of the Mi-26 tail beam was performed with the purpose to determine load program for ground fatigue tests. It was shown that high frequencies (greater than 7 Hz) of dynamic action in flight regimes influence insufficiently on structural damage. Recommendations on planning of ground fatigue tests are formulated and quantitative estimates for parameters of dynamic and static loading are obtained.

1. Introduction

The information database used for preparation and performance of the aircraft structure fatigue tests in the laboratory includes the results of measurement of the stressed state strength flight tests performed for helicopter all operating flight modes assumed for estimated assessment of the fatigue and endurance characteristics, as well as the composition and repeatability of the standard flight modes. Based on the analysis of the fatigue flight test results, composition and repeatability of the assumed standard flight modes, an equivalent test load block is developed which is included into the structure fatigue test program.

Up to the present moment this analysis is based on a quasistationary beam approach and on a number of heuristic approaches. The stressed state of the fuselage structure in flight is characterized by a complicated frequency content of the dynamic aspect of the stressed state. Currently, in our country and abroad, in formation of the equivalent test load block, use is made of the so-called biharmonic approach [2] – the dynamic composition of the stressed state of the test object is generated by the dynamic forces containing only two frequencies.

This affects considerably the authenticity of the fatigue bench test results; so, the results of many fatigue tests performed are far ambiguous.

The reason for this inexactness is clear – this is the complexity of the dynamic processes running with the structure in the stressed state and the lack of methodic studies for analysis of the stressed state in the process of development of the equivalent test load block, preparation and set-up of the bench for supporting the tests.

2. Finite-Element Model for Test Support

The methodology under consideration supposes implementation of a large scope of calculating research of the characteristics of the stressed state and dynamics of the test object both on the helicopter and on the test bench. For this purpose, use is made of the modern calculation complexes and respective calculation FEM-models of high level. The Mi-26 helicopter fuselage test object is its tail section. For studying the characteristics of dynamics of such a volumetric object, a full-scale FEM-model of the helicopter is required. Attention should be paid just to the helicopter FEM-model which should contain the necessarily precise FEM-model of the test object load-carrying structure. It turned to be historically, that up to the beginning of Mi-26 helicopter fuselage tail section fatigue and survivability test preparation, the full-scale FEM-models of the helicopter required for this purpose did not exist, that is why for various reasons and on various grounds it was decided to develop a simplified combined model.

It was decided to make a necessarily detailed model of the tail section and of the rear cut zone up to the frame No. 24 based on the results of the work carried out at the MHP in late 80-ths by S.A. Soukhanov with a group of colleagues. And to make a sort of a «moulage» for the other part of the helicopter (from nose to frame No. 24). The obtained model was provided with true mass characteristics for the tail section and with approximate (but integrally correct) rigidnesses and masses for the «moulage». The «moulage» section of the model also included the main gearbox with the main rotor shaft, several frames, landing gear simulators and tie rods holding the structure. As a result, the helicopter finite-element model took on the form shown in Fig. 1.

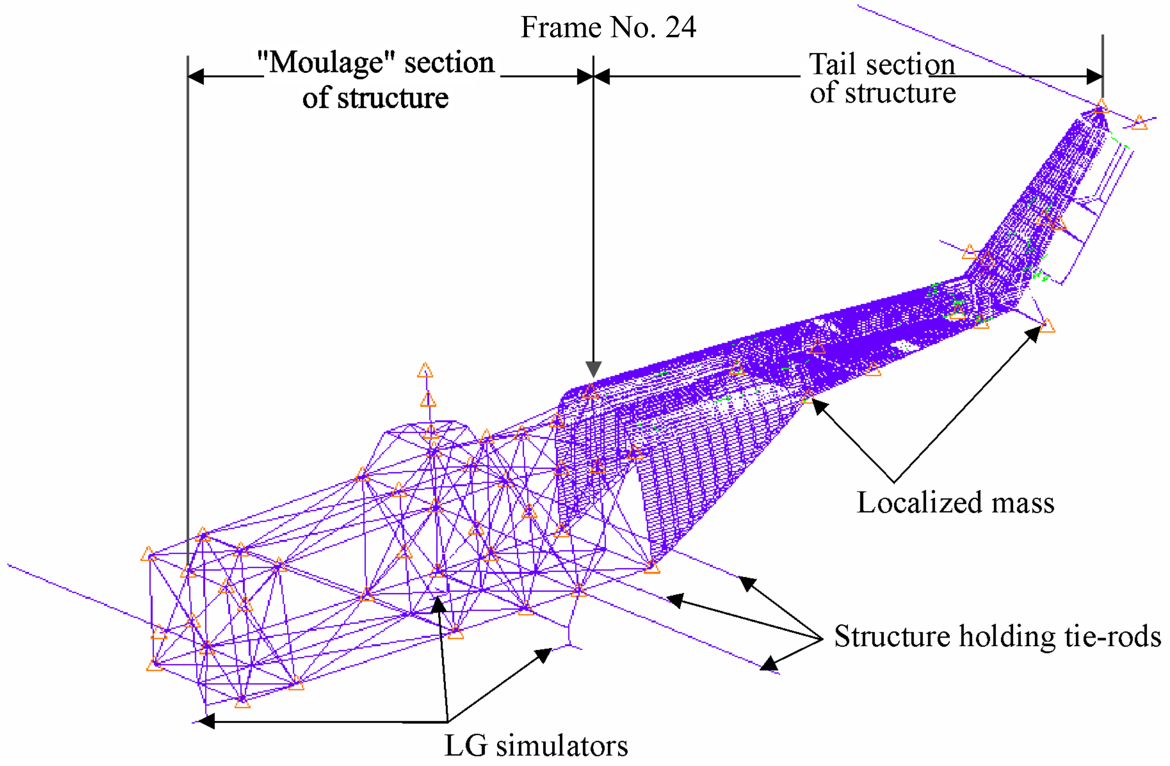

Figure 1 – Mi-26 Helicopter Model for Fatigue and Survivability Tests

This model was used for practicing some issues required in future for performing studies accompanying preparation and performance of tests. Particularly, since during the tests the flight conditions are simulated for the structure positioned on the ground and secured with the aid of tie-rods, determination of their required rigidities becomes very important. Attachment of the structure to the load-bearing floor, rigidity of the tie-rods holding the structure, arrangement of dynamic force drivers, rigidity of the landing gear struts were specified. For the structure standing on the load-bearing floor, the analysis was made of the stressed static state, proper forms and frequencies, as well as the analysis of the dynamic part of the stressed state with expected exciting loads and rigidities of the tie-rods.

It became possible to select the rigidities of the «moulage» section of the structure so thee first four proper frequencies of the free FEM-model were on the verge of the structure frequencies determined experimentally.

Figure 2 shows he forms of oscillations and Table 1 gives comparison of the first four flight frequencies with those calculated for the free model and for the model arranged under the bench conditions. Comparison of these frequencies showed their satisfactory fit which made it possible to rely on the closeness of dynamic characteristics of the structures being in the flight and bench conditions, which is of great importance.

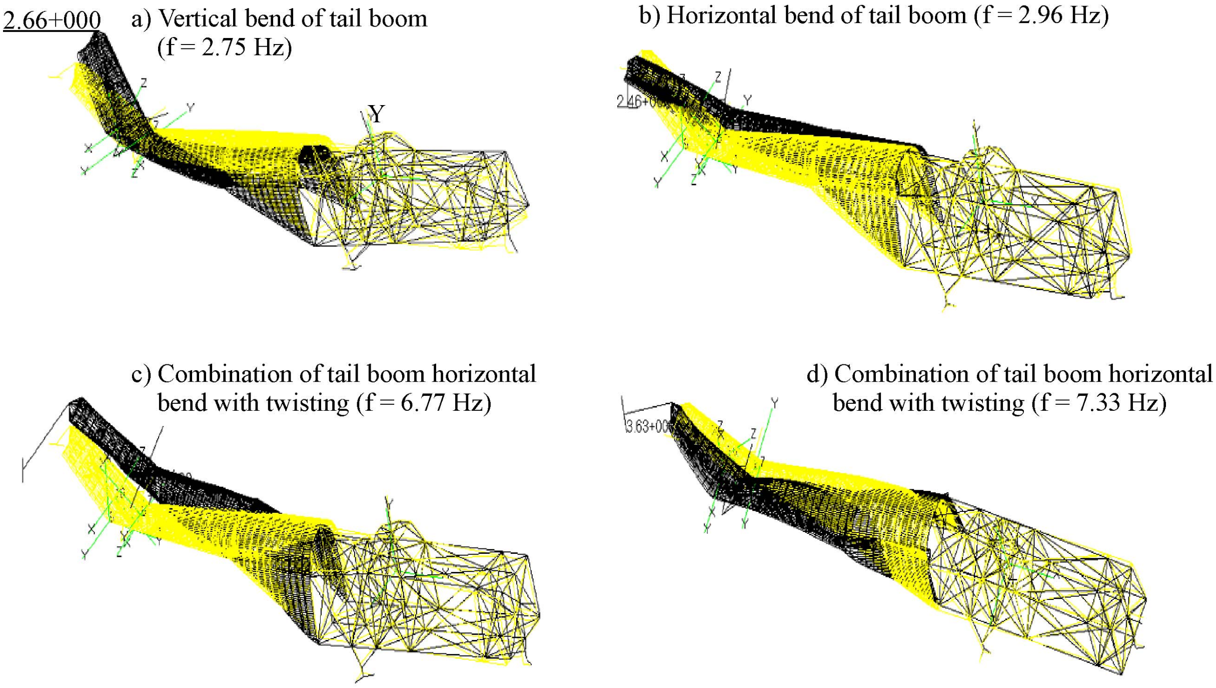

Figure 2 – Forms of Mi-26 Helicopter Natural Oscillations

T a b le 1

Tone No.	Flight frequency (Hz)	Free model frequency	"Ground" model frequency	Error (%)	Tone description
1	2.6	2.75	2.81	8.1 (5.7)	T.b.*) vertical bend
2	3.0	2.96	2.97	1.0 (1.3)	T.b. horizontal bend

*) T.b. – tail boom.

Table 1, continued

Tone No.	Flight frequency (Hz)	Free model frequency	"Ground" model frequency	Error (%)	Tone description
3	6.8	6.77	6.77	3.4 (3.4)	Twisting + t.b. horizontal bend
4	7.2	7.33	7.33	3.4 (3.4)	Twisting + t.b. horizontal bend

3. Analysis of Mi-26 Helicopter Stressed State Dynamic Part

As it was mentioned above, the part of the information data base are the results of the flight strength experiment in the form of materials testifying to variation of stresses and loads in the structure points of interest for all operating flight modes. For preparation and performance of the helicopter fuselage structure tail section test, use is made of the materials presented in [2].

The frequency content of the structure stressed state dynamic part is studied by harmonic analysis of measured stresses and loads. Figure 3 shows content of the coefficients of the normal stress Fourier series. Especially interested are the frequencies at which these coefficients have maximum absolute values. These maxima are designated in the Figure by numbers.

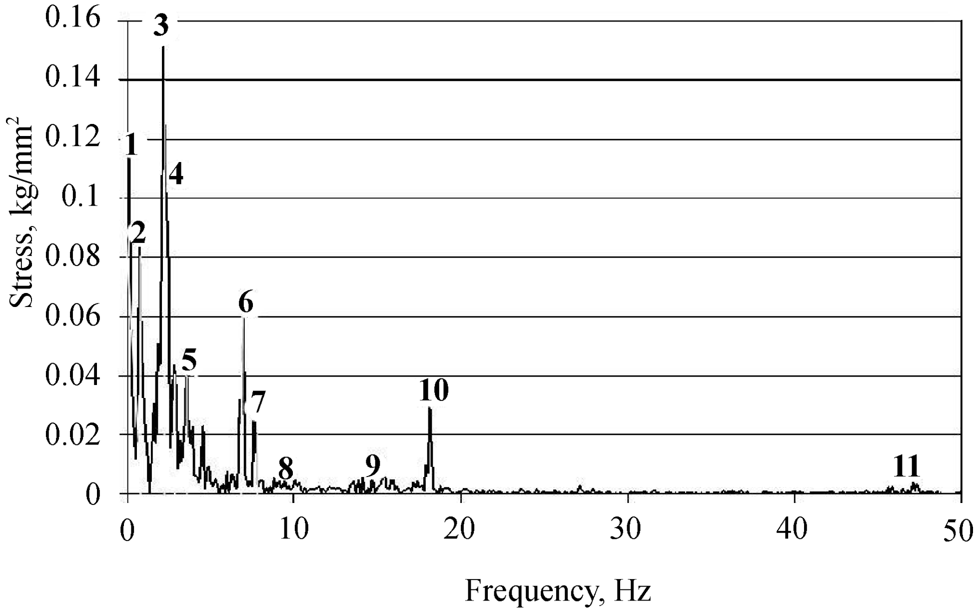

Figure 3 – Diagram of Stress Oscillogram Fourier Serial Expansion Coefficients

1. The first maximum falling on the minimum frequencies appearing during the Fourier serial expansion in this specific case is associated with disharmony of structure loading in real conditions which appears as a difference between the values of the function at the ends of the time period under test.

2. The second maximum falls on the frequency of f ≈ 0.7 Hz, which is always present in the records of stresses during the flight tests. Presence of maximum in the fuselage stressed state at this frequency is probably caused by peculiarities of helicopter dynamics in the air.

3. The third maximum appears at the frequency of f = 2.2 Hz which is the main rotor gyrofrequency. In this connection, the dynamic loads at this frequency acting on the helicopter as a whole and on the fuselage specifically are always considerable.

4 – 7. Maxima 4 – 7 (about 2.7, 3.0, 6.7 and 7.3 Hz) appear at the frequencies which correspond to the proper frequencies whose shape is considerably affected by the fuselage tail section. Appearance of maxima at these frequencies is the result of action of non-sinusoidal loads on the helicopter.

8. The next slight increase of the stress amplitude (most probably it is a flat maximum) within the range of 9.0 to 10.0 Hz is caused by the forces corresponding to the tail rotor gyrofrequency (precise value f = 9.2 Hz). The influence of this excitation is inconsiderable.

9. Then within the frequency spectrum of 14 to 16 Hz some increase of the stressed state amplitudes is caused by the presence of proper frequencies in this range. The role of the helicopter tail section in the shapes of these frequencies is not so considerable.

10. The maximum which follows next corresponds to the helicopter main rotor first blade frequency of f = 17.6 Hz. In most measurements of stresses and loads, this frequency is visible with the naked eye – inconsiderable oscillations of the structure stressed state correspond to it.

11. At the very end of the studied period, the last of the mentioned frequencies – 46.0 Hz appears which is the first blade frequency of the main rotor. This frequency is mentioned in [2], it was specially studied in [2], but in the stressed state analysis performed it did not approve itself in something considerable.

The given harmonic analysis of the stressed state at one of the points of the structure bears the information on specific features of the dynamic load on this point of the structure in flight, shows the dynamic properties and the properties of the structure proper.

4. Study of Excitation Force Point during Ground Test

Figure 4 shows the zone of arrangement of stress sensors and the Mi-26 helicopter tail boom and tail boom pylon moments. Their joint is the most stressed part of the structure subjected to multiple fatigue damage. Naturally, this zone wash checked thoroughly during the test.

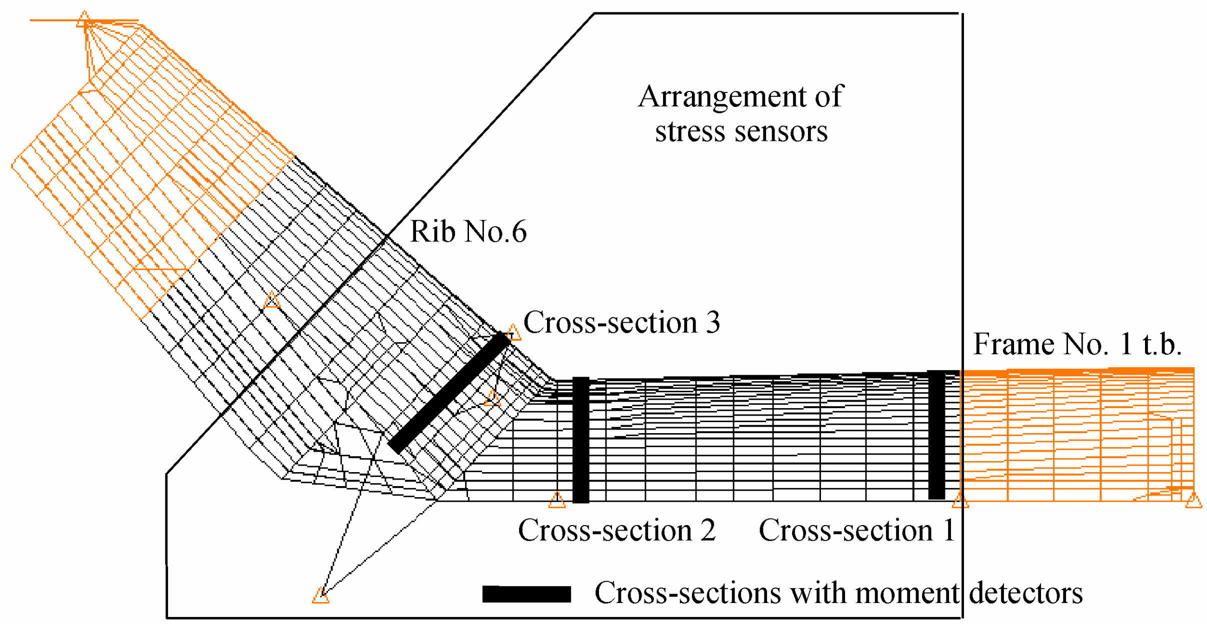

Figure 4 – Arrangement of Stress Sensors and Structure Tail Section Moments

As it was already mentioned, during the bench test of the helicopter fuselages, the dynamic loads were applied to the tail rotor. For the Mi-26 helicopter, it was supposed to apply biharmonic load to the tail rotor with the aid of two frequencies – 2.2 and 17.6 Hz. Calculations were made which were used for studying the respective stress responses depending on the cyclic loads applied to different points of the structure. Considered as the points of load application were tail rotor attachment point (the main point of load application), the assembly on the tail boom pylon frame No. 3 near the stabilizer attachment point, and the main rotor attachment assembly (the point of natural excitation of its gyrofrequency (2.2 Hz) and blade frequency (17.6 Hz) – to be compared). Considered as the point of study of responses was the tail boom-to-tail boom pylon jointing point. It is the most interesting point of the structure surrounded mainly by stress sensors and moment detectors.

Figures 5 and 6 show the amplitude frequency responses within the frequency range of 0 to 20 Hz with the exciting force applied to axes Y and Z. (Loading in X-direction is not meaningful, since the main stresses are caused by the bend created by the forces acting in the Y- and Z-directions.) As it was supposed, it is obvious that excitation of oscillations on the main rotor requires much more forces than that on the tail rotor or near the stabilizer. At the same time, it can be seen that in these two cases of loading, there are those proper frequency ranges in which their use is the most expedient.

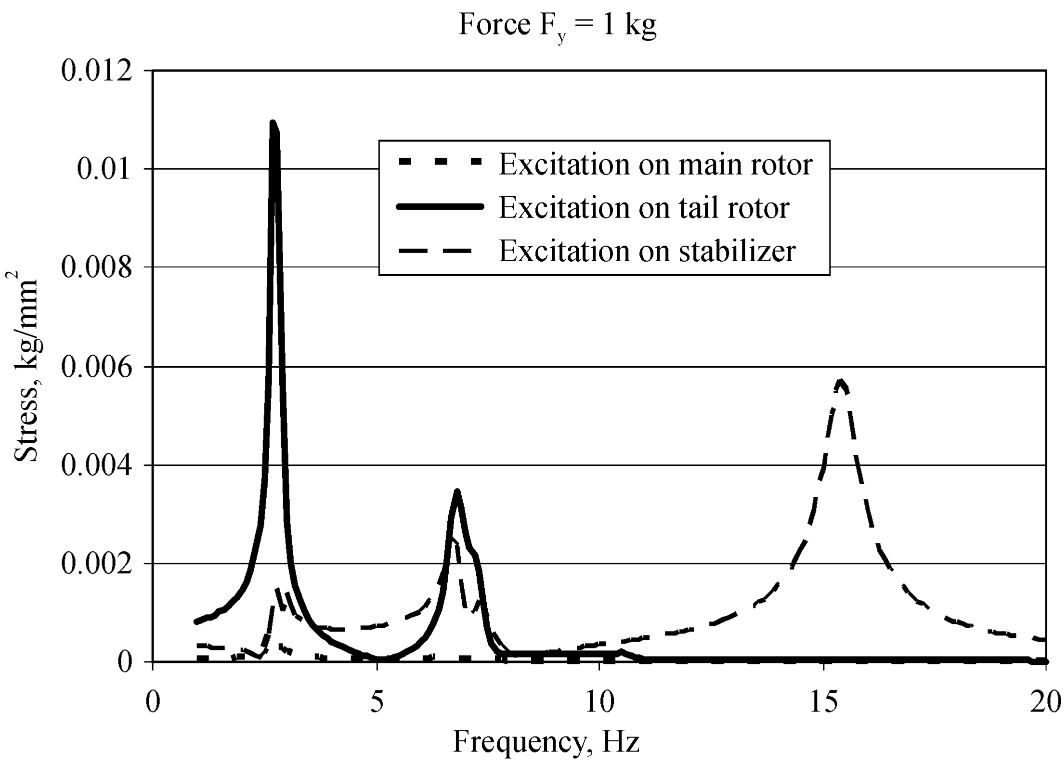

Figure 5 – Frequency Responses with Application of Sinusoidal Exciting Force Fy

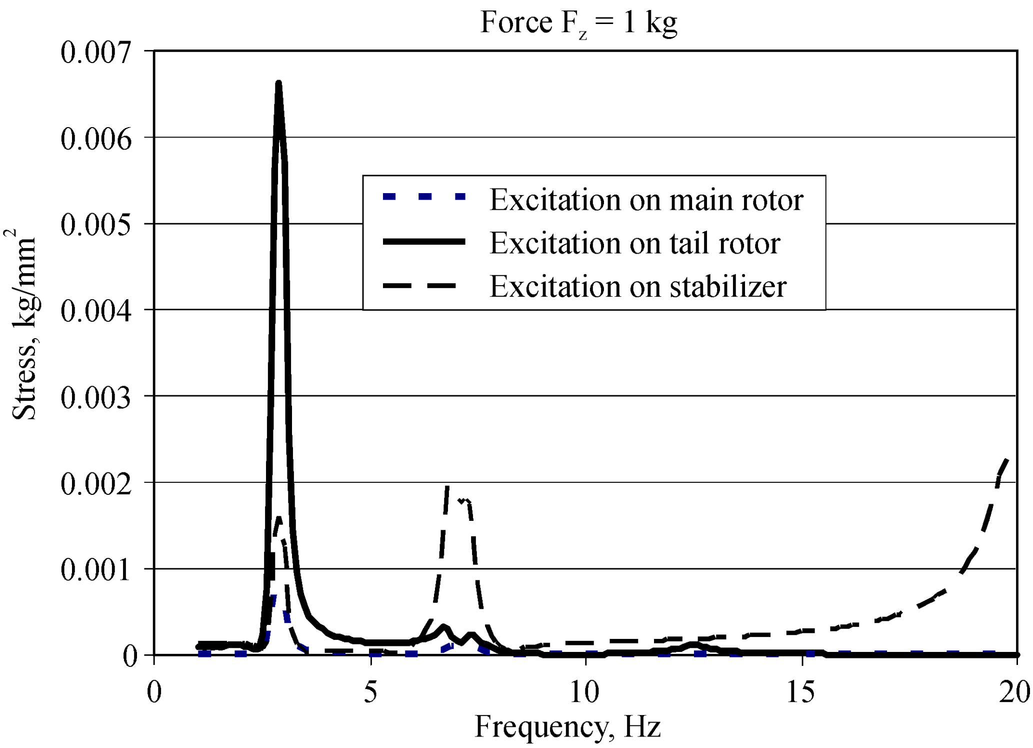

Figure 6 – Frequency Responses with Application of Sinusoidal Exciting Force Fz

The given amplitude-frequency response values show that the most preferable is application of excitation to the tail rotor to the frequency of about 7 to 10 Hz. Further, i.e. also at the frequency of 17.6 Hz, the most liberally preferable is application of excitation to the area near the stabilizer.

Figures 7 and 8 show the results of calculation of responses to the cyclic stresses from the force acting in the vertical direction Fy = 1. The loads are excited on the main rotor (the case of loading in flight conditions), on the tail rotor and near the stabilizer at the frequencies of 2.2 and 17.6 Hz. The results are withdrawn for the right spar passing along the tail boom pylon and the tail boom as a response function depending on the distance between the spar fracture point (the position of this point is assumed to be 0) and the result presentation point. The response values differ in exponents, so, for convenience of their presentation, they are shown in different scales, namely:

- in Figure 7, the scale multipliers for the cases of exciting force application to the main rotor, tail rotor and near the stabilizer are equal to 1.0, 0.05 and 1.0;
- in Figure 8, the respective scale multipliers are equal to 1.0, 0.1 and 0.01.

For the same purpose, the edges of some curves running beyond the chart limits are interrupted. In addition, in the Figures, the numbered vertical lines show the position of some specific cross-sections:

1 – frame No. 10 t.b., sensor and detector arrangement zone boundary, cross-section 1 with moment detectors;

2 – cross-section 2 with moment detectors;

3 – cross-section 3 with moment detectors;

4 – rib No. 3, stabilizer attachment point;

5 – rib No. 6, sensor and detector arrangement zone boundary.

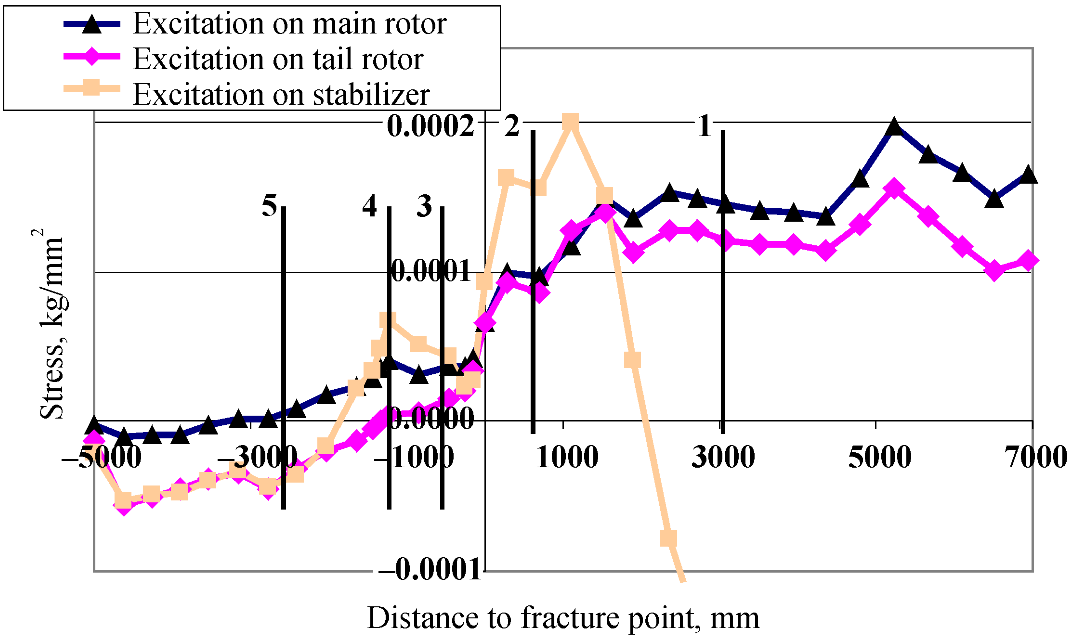

Figure 7 – Functions of Responses for Disturbing Force Fy at Frequency of 2.2 Hz

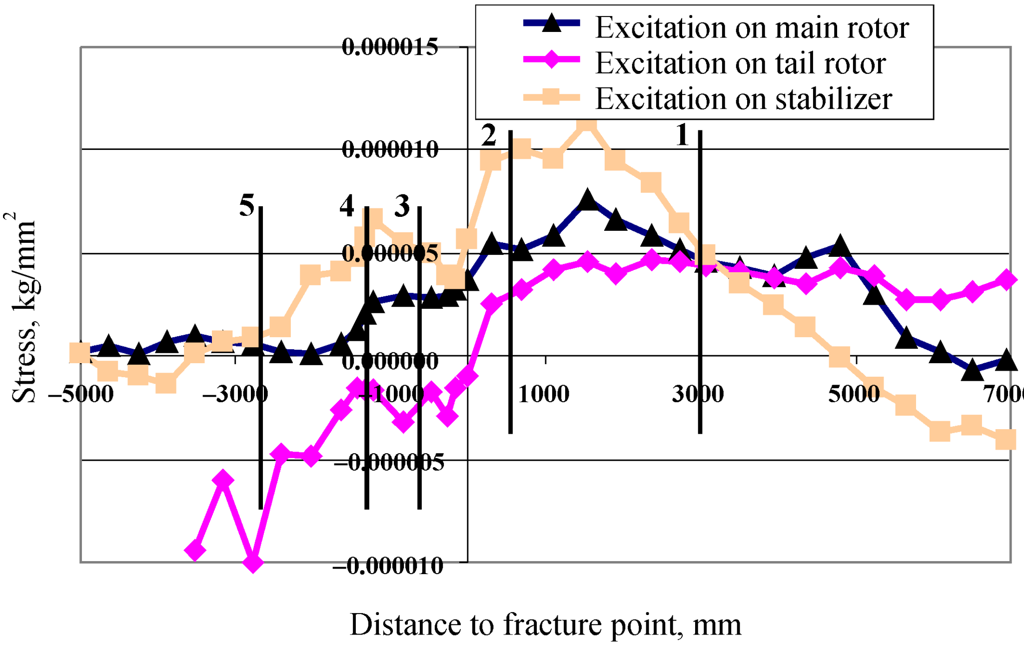

Figure 8 – Functions of Responses for Disturbing Force Fy at Frequency of 17.6 Hz

In consideration of aggregate of charts (Figure 7, f = 2.2 Hz) it can be seen, that the functions of responses corresponding to the respective oscillations excitation points on the main and tail rotors in the stress sensors and moment detectors arrangement area are rather close to each other (accurate to the constant factor). This testifies to the fact that the stress oscillations of structure occurring in flight, at a frequency of 2.2 Hz may be well reproduced during excitation of oscillations on tail rotor. In case of excitation of the oscillations near the stabilizer, the response function is worse in approximation of the function corresponding to the flight case. In addition, as it can be seen from the number of multipliers accompanying construction of the charts, for reproduction of the stresses of the same level the required value of the exciting force near the stabilizer is about 20 times greater than in case of oscillations excitation on the tail rotor. In performance of the ground test, it is rater important. The said factors confirm correct selection of the point of application of the sinusoidal force at a frequency of 2.2 Hz to the tail rotor.

In the second case, (Figure 8, f = 17.6 Hz) the functions of responses pertaining to excitation of oscillations on the main and tail rotors poorly correspond to each other. First of all, it is caused by the fact that in excitation of the cyclic loads on the tail rotor, change of the response function sign at the tail boom-to-tail boom pylon jointing point takes place (i.e. stress converts into 0). For this purpose, the point of application of the loads at a frequency of 17.6 Hz to the tail rotor is unfit, since large loads are required for obtaining at the tail boom-to-tail boom pylon jointing point the stresses corresponding to excitation of oscillations on the main rotor.*) At the same time, the response function pertaining to the case of excitation of the loads near the stabilizer is better in approximation of the flight schedule in location of stress sensors and moment detectors.**) In addition, as it can be seen from the value of the multipliers accompanying the chart construction, for reproduction of the stresses of the same level with those obtained during excitation of oscillations on the main rotor, the value of the exciting force near the stabilizer is required which makes up about 1 % of the force on the main rotor. This shows that application of the cyclic excitation at a frequency of 17.6 Hz near the stabilizer is the most promising if applied during the ground test.

The same occurs also during application of exciting force Fz.

The study performed shows the great importance of determination and analysis of response stresses.

5. Damage Analysis

The spectrum of loads acting on the structure is of an occasional nature. Nevertheless, some typical operating cycles may be discriminated which repeat frequently within a rather long period of time. Such typical operating cycles will be called the aircraft flight modes. In each flight mode, the dynamic load is characterized by increase or decrease of the amplitude of acting stresses respective force factors, such as bending and twisting moments in the certain sections of the structure. In the process of real operation, the accessories of the aircraft structures are rarely subjected to the constant-amplitude loads. So, for many years, various methods have been developed for extraction of "equivalent" cycles with constant amplitude from the random sequence of load. The concept of equivalent cycles with constant amplitude is often rather difficult for understanding. The most obvious cycle during the random loading is the cycle including the maximum and minimum values. On the other side, it is also necessary to determine all other cycles available in the load under consideration. The best fatigue destruction ratio between the schematized and real random processes is produced by the methods of full cycles discrimination [5].

The most efficient algorithm for extraction of all full cycles is the falling rain algorithm which makes it possible to classify the cycles in the meanings of their mean value and load amplitude. In this algorithm, the number of cycles is determined which corresponds to the pair: mean value – load amplitude. Let us describe briefly the procedure for discrimination of full cycles. The algorithm starts searching for the cycles beginning with the absolute maximum value in the load data set. Then follows the search for the load increase and decrease pairs leading to the closed-loop loading over the stress – deformation curve. The software-based "falling rain" procedure was tested in a number of terms. The discriminated

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*) This is testified by failure to receive response to the stresses at a frequency of 17.6 Hz (it was quite insensible) during the proof tests of the Mi-26 helicopter conducted in Riga.

**) The impression is marred to some extent by behavior of the function of responses near the stabilizer (a sort of "sag" in the function value, abrupt change of derivative sign). This is well explainable since it corresponds to the point of exciting force application. Probably, this function could be improved if the excitation point were transferred beyond the sensor and detector arrangement area.

cycle results were compared with those obtained with the use of the MSC.Fatigue software and it showed their full matching in number of cycles and in their parameters.

For analyzing the fatigue characteristics, usually use is made of the curve showing dependence of the stress amplitude on the logarithm of the cycles till destruction. For presentation of the durability line in various graphical views, the Woehler program was developed. As an example, Figure 9 shows the durability line obtained on the basis of the Mi-26 helicopter tail boom fatigue test in the cross-section, where the mean stress was equal to 6 kg/mm^2.

The source structure loading spectrum is presented as a load histogram in which the number of cycles is presented which corresponds to various mean stresses and amplitudes of dynamic stresses. It is practically impossible to obtain the material fatigue characteristics for various mean stresses of additional static load. That is why use is made of the curves showing dependence of the number of cycles till fatigue destruction on the load of material samples during action of the symmetrical load cycles or the so-called zero-to-stress load cycles. In the latest case, the load to the sample is applied to the certain level and then is fully removed.

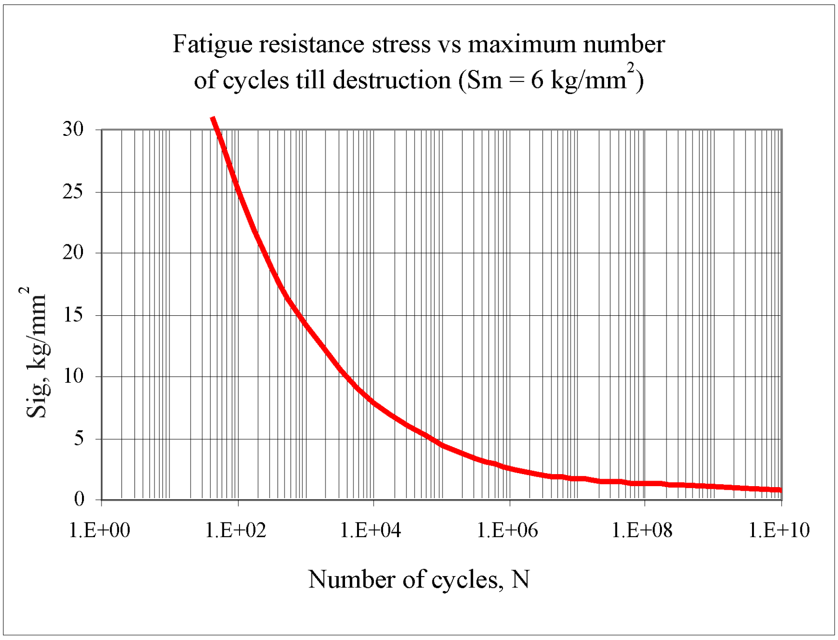

Figure 9 – Durability Line

There exist several different approaches for recalculation of the amplitudes of the real spectrum of stresses to the amplitudes corresponding to the equivalent load cycles. The techniques of foreign companies most frequently employ the Goodman and Herber methods [6]. They are implemented in the system of MSC.Fatigue resource analysis. At the same time, in Russia, the most often used is the Oding method which was field-proven in designing by the life of many structures. The distinctive feature of this method is that the equivalent stress obtained by it is independent of the material rigidity and strength characteristics. They depend only on the mean level of additional static load and on the dynamic load amplitude.

The Oding method [7] is based on the principle of equal fatigue life which is determined by the known dependence:

$$(\sigma_a)^{1-\eta}(\sigma_{max})^{\eta} = const$$

In its turn, the presented dependence is based on observation of the parallelism of the sections of the S-N curve $(lg(\sigma) \to lg\,N)$ for different conditions of asymmetry of load cycles *R*. Parameter η depends on the structure material and type, σ_a – cycle amplitude, σ_{max} – cycle maximum stress.

Taking into account that for the zero-to-stress cycle $\sigma_{max0} = 2\sigma_{a0}$, and for the asymmetrical *i*-th cycle with asymmetry ratio R_i

$$\sigma_{max\,i} = \frac{2\sigma_{a\,i}}{(1-R_i)},$$

we'll obtain the following formula:

$$(\sigma_{a\,0})^{1-\eta}(2\sigma_{a\,0})^{\eta} = (\sigma_{a\,i})^{1-\eta}\left(\frac{2\sigma_{a\,i}}{1-R_i}\right)^{\eta}$$

Here follows the expression for determining the equivalent cycle amplitude

$$\sigma_{a\,0} = \frac{\sigma_{a\,i}}{(1-R_i)^{\eta}}$$

It is noted in book [8] that the η parameter values range from 0.35 to 0.60. For the aircraft structures made from alloy Д16Т, η = 0.45, and from alloy В95Т – η = 0.5. For most of the aircraft alloys, value η is close to 0.5 and this value is usually taken for calculating the life characteristics. In this case, after elementary transformations we'll obtain the expression for determining the equivalent zero-to-stress cycle:

$$\sigma_{a\,0} = \sqrt{\frac{\sigma_{a\,i}}{2}(\sigma_{a\,i}+\sigma_{m\,i})}$$

In the given formula, $\sigma_{m\,i}$ is the mean stress for the *i*-th load cycle.

Foe symmetrical equivalent case, the condition of parallelism of the durability line sections produces the following equivalent stress value:

$$\sigma_{a\,-1} = \sigma_{a\,i}^{1-\eta}(\sigma_{m\,i}+\sigma_{a\,i})^{\eta}$$

If $\eta = 0.5$, the equivalent stress is determined by the following formula:

$$\sigma_{a\,-1} = \sqrt{\sigma_{a\,i}(\sigma_{a\,i}+\sigma_{m\,i})}$$

Comparison of equivalent stresses for the zero-to-stress and symmetrical cycles shows that the equivalent value of the symmetrical cycle stress is $\sqrt{2}$ times more than the respective value of the zero-to-stress cycles. The formulas for calculation of equivalent stresses make sense if $\sigma_{m\,i} \geq -\sigma_{a\,i}$. Nevertheless the experimental studies show that small negative (contraction) stresses are also accompanied by accumulation of structure damage. In this case, we'll consider that the amplitude of equivalent stresses is determined by the linear law, with the zero value of the equivalent stress corresponding to the mean contraction stress which is 5 times greater in module than the amplitude of the reducible cycle. Figure 10 shows the charts of the equivalent cycle stress amplitude σ_{eq} ratio to the amplitude of the reducible cycle versus the mean stress ratio to the amplitude of the reducible cycle for the cases of zero-to-stress ($\sigma_{eq} = \sigma_{a\,0}$) and symmetrical cycles ($\sigma_{eq} = \sigma_{a\,-1}$).

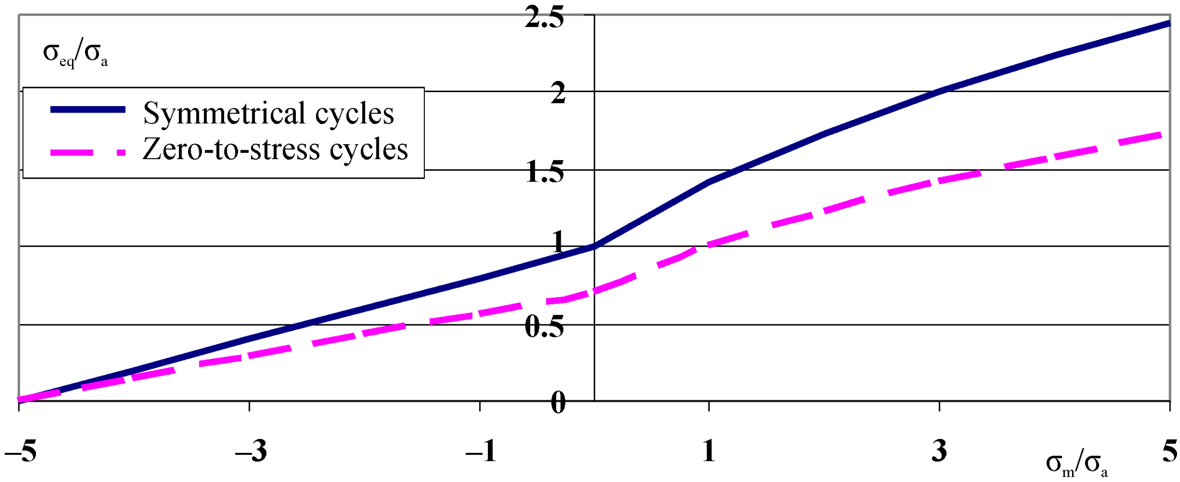

Figure 10 – Reduction to Equivalent Load Cycles

The above mentioned procedures for discrimination of full cycles with the aid of a "falling rain" algorithm, reduction to equivalent cycles and analysis of damage based on the S-N curve were implemented in the form of the Fatigue program in algorithmic language C++ and tested in a number of numerical calculations. The program main window view is shown in Figure 11. The Fatigue program is intended for analyzing the structure random dynamic load signal and calculating its damage during action of dynamic loads. The basic data for the program are the load characteristic versus the time which may be obtained as a result of flight and fatigue tests or calculated for the assigned dynamic action on the structure, as well as the parameters of the S-N curve. The time dependency may be read from the file or entered directly from the Windows system data exchange buffer. As soon as the time signal is entered, it is displayed on the screen and discrimination of full cycles and damage calculation are performed. Distribution of the number of full cycles among the ranges of their mean values and amplitudes may be shown in the form of a Table in numerical (in Figure 11 in the lower left corner of the program window), percentage or color presentation. Any discriminated cycle is displayed on the time dependency chart. The cycles with the amplitudes below the minimum threshold value may be deleted from the signal and not be used during damage calculation.

Calculation of the damage may be effected on the basis of the fatigue curve corresponding to any assigned value of the mean stress. On selection of the damage analysis mode (ref. Damage selector in Figures 11 and 12) the results displayed in the lower left corner of the window indicate the calculated damage.

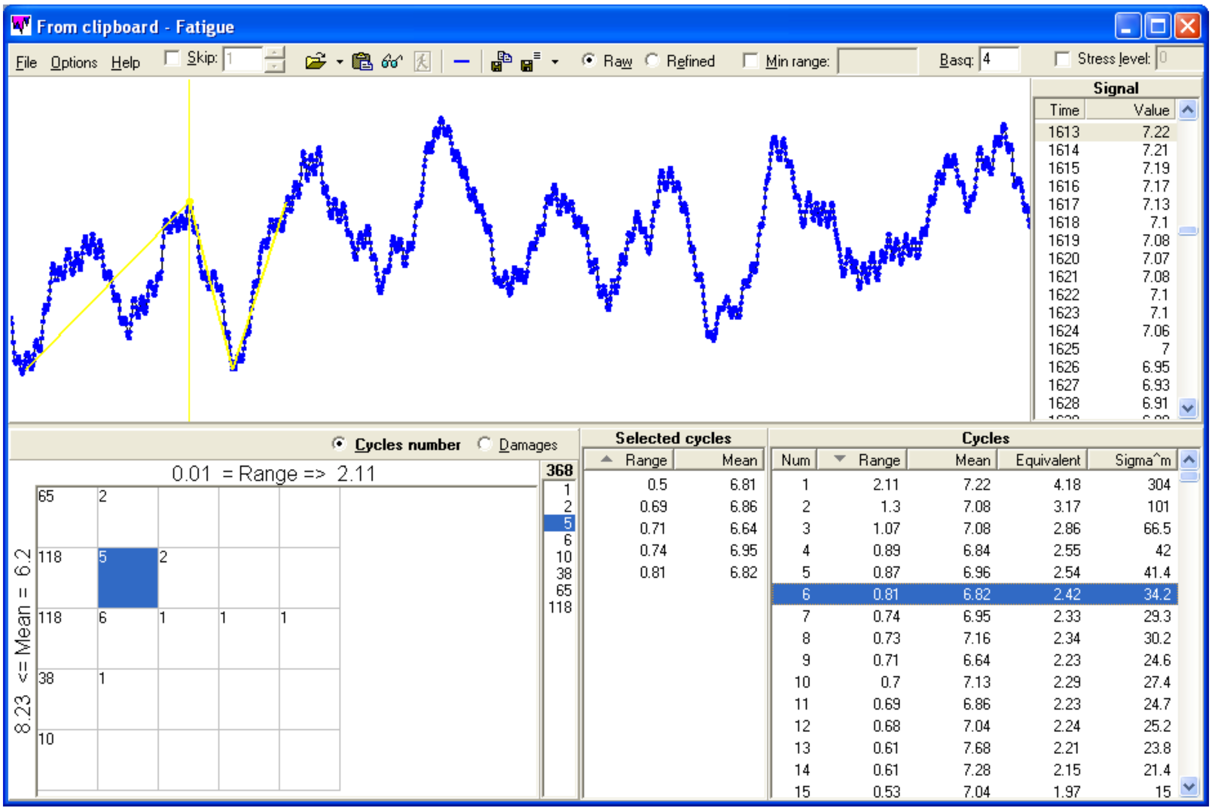

Figure 11 – Main Window of Fatigue Program

Figure 12 shows distribution of damage among the ranges of the mean values and amplitudes of discriminated cycles. As it can be seen from the Figure, the maximum damage corresponds to the range of the maximum cycle amplitudes (the Range axis) and mean stress of about 3.5 kg/mm^2 (the Mean axis). It should be noted that if the material durability line is not available in calculation, the value proportional to the amplitude of the reduced equivalent stress, raised to the assigned exponent of the supposed durability line is considered to be the damage. Such an approach may be used for making a comparative analysis of damage dependent on the effect of dynamic loads of different structure operating modes.

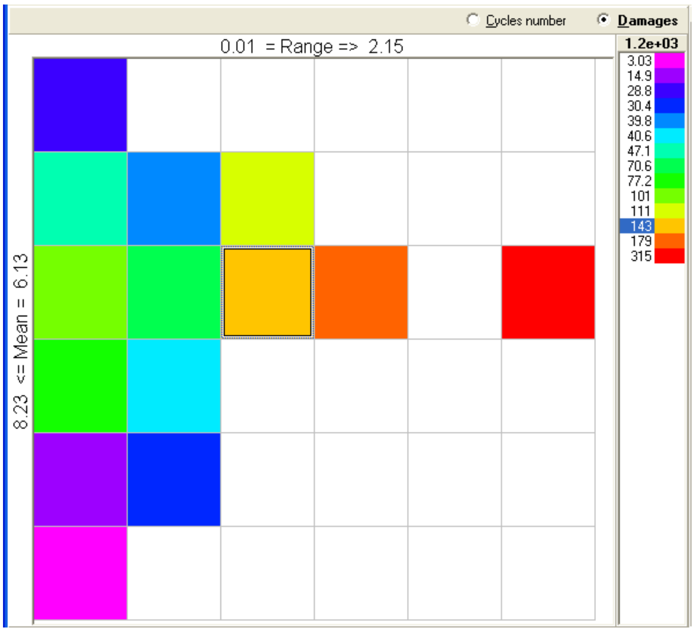

Figure 12 – Damage Distribution

The developed program was used for analyzing damage to the Mi-26 helicopter tail boom structure based on the data obtained during the flight tests performed in the flight test institute for various modes of its operation. Eight modes given in Table 2 were used as the basic ones for determining the load repeatability.

T a b l e 2 – Mi-26 Helicopter Flight Modes for Analyzing Its Damage

No.	Modes	Time, s	Test flight modes
1	Hovering	60	8.1, 8.17, 8.18, 8.19, 5.37
2	Turns in hovering	30	8.23, 8.24, 5.40, 5.41
3	Flight at low speed of 60 to 80 km/h	120	5.12
4	Acceleration – climb	90	7.6, 8.2, 8.3, 13.2,
5	Level flight	1200	5.16, 8.6
6	Slip turns	90	5.24, 5.26, 5.30, 5.32, 8.8, 8.10, 7.11, 7.21, 7.23, 7.29, 7.31
7	Motor gliding	120	8.14, 13.31
8	Braking	90	7.32, 5.15
	Flight	1800	31 flight modes

31 flight modes were considered. In each of the modes, during 8 seconds, in 4096 points, stresses were measured in several tensometers arranged on the helicopter tail boom. Table 2 shows distribution of flight test modes among the base modes and their duration within the helicopter standard flight. In the third column of the Table, the expression, type "8.1", stands for the 1st mode of the 8th test flight.

The stress time variation signal and the obtained load cycle histogram are shown in Figure 11 for tensometer No. 17 for the level flight case. Similar results were obtained also for other tensometers in all considered flight modes. The damage introduced by each flight mode was considered to be proportional to the time of the given mode in the standard 30-minute flight. Based on the frequency curve data, damage for one flight was calculated in location of each tensometer. Figure 13 shows the share of damage for individual flight modes in locations of tensometers Nos 17 and 21. As it can be seen from the diagram, more than 40 % of the accumulated damage is caused by the cyclic loads in level flight.

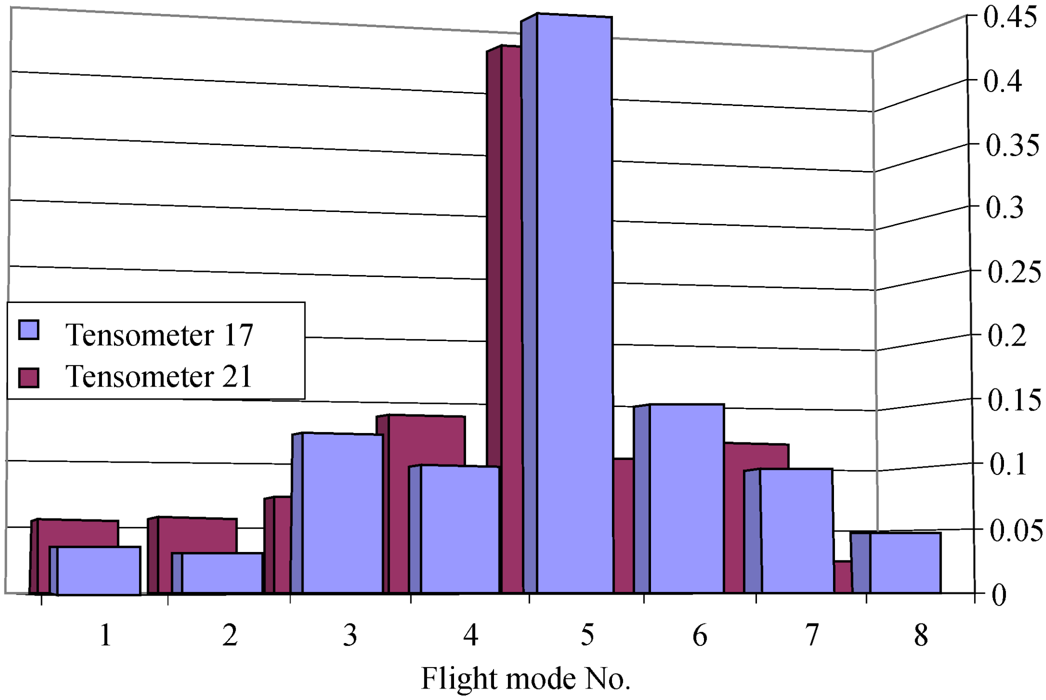

Figure 13 – Share of Damage for Individual Flight Modes

Damage for several locations of tensometers is shown in Figure 14 in calculation of the characteristics for the flight loads and in two locations – for the case of fatigue test with modeled excitation of tail boom oscillations at two frequencies. As it can be seen from the diagram, the level of damage in ground tests is somewhat less but it rather well matches that for the flight test loads. It should be noted that such analysis of damage in individual operating modes and their comparison with those expected in the fatigue test may serve as an important material for development of the test program and correction of the loads in the process of fatigue test.

The analysis of signals with different oscillation frequencies plays a key role in the study of influence of dynamic loads on fatigue characteristics. It helps to understand which of the frequencies should be excited during the ground test and which may be ignored. The approximate assessment of such influence may be obtained during application of the developed program. For this purpose, some calculation should be made of the damage with removal of the cycles having the values below the certain stress levels from the signal. By comparing the calculated damage with the obtained signal frequency (number of cycles per second) it is possible to obtain the dependency of the structure damage on the maximum frequency included in the signal.

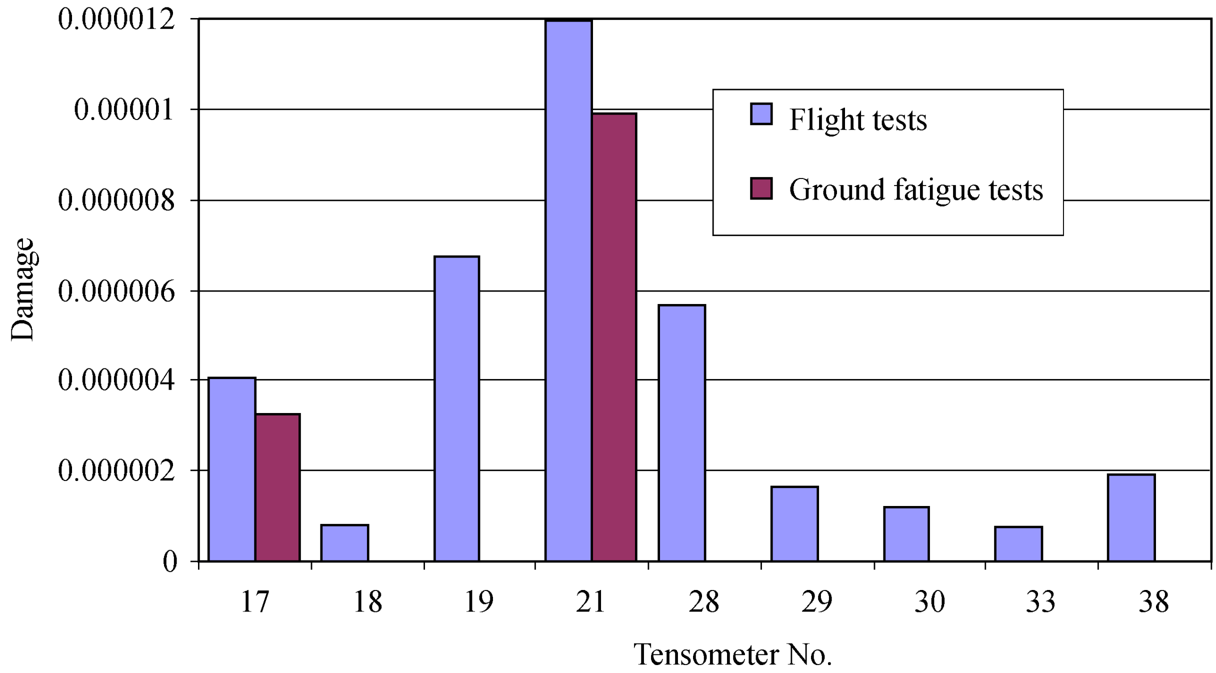

Figure 14 – Structure Damage in Tensometer Location Points

Figure 15 shows the chart indicating change of damage with increase of the load signal frequency for location point of tensometer No. 17. The level flight mode was considered. The 100-% damage is considered to be the damage from the reference signal including all cycles.

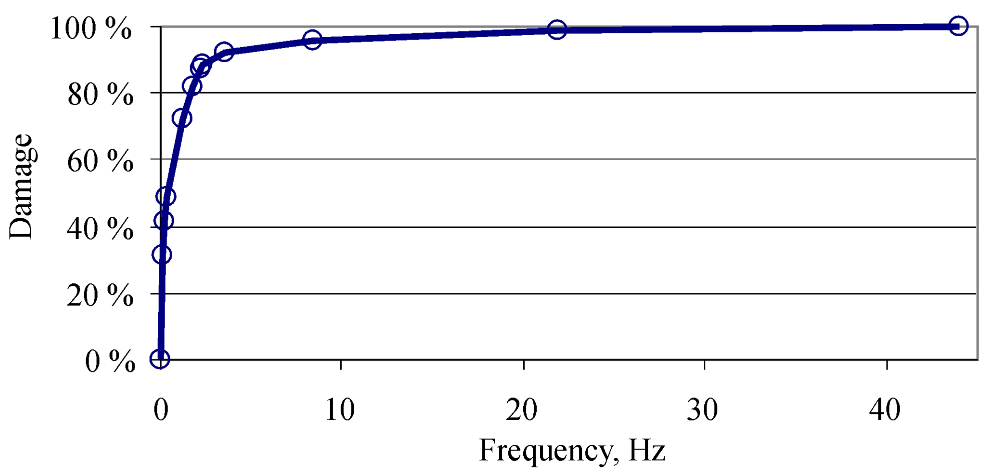

Figure 15 – Change of Damage with Increase of Signal Frequency

In this example, neglect of the cycles with the frequency exceeding 8 Hz results in decrease of the damage by less than 5 % and accounting of the cycles with the frequencies of up to 2.2 Hz reduces damage by 13 % which is rather considerable. It should be noted that nearly the same regularity is observed also for other helicopter flight modes at different considered points of the structure. That is why for more precise modeling it would be reasonable to consider additional excitation of the structure at a frequency of up to 8 Hz in the fatigue test program.

6. Static and Dynamic Load Calculation Program

Currently, the Central Aerohydrodynamics Institute together with the Moscow helicopter plant is developing the computer program to select the static and dynamic loads equivalent to the flight loads during the fatigue test by the results of measurement of the stresses or moments obtained in flight. One of the capabilities of this program is assessment of the helicopter structure damage during the specific flight. Naturally, its first applications were made for the Mi-26 helicopter, for which many previously made studies were also used.

Used as the basic data for functioning of this program are the oscillograms of the stresses in stringers and in skin, or the oscillograms of the moments in the sections which are determined during the helicopter flight strength tests. Particularly, such tests were conducted in the flight test institute for the Ми-26 helicopter. They contain the facts on dynamic processes occurring in the structure in different flight modes. In addition, used as the basic data for this program are the output files (i.e. the files to be printed) of the finite element complex[*]. These files contain the results of static calculations, calculations of the proper forms and frequencies and responses to dynamic excitations and are processed in the program mode. The result of the program operation is finding the best parameters of the excitation force in the form of the amplitudes of the periodical forces at the assigned frequencies, with additional static load and full description of the dynamic processes in all tensometers.

Currently, two operating modes exist in the program: through the stresses, when the records of oscillograms in the stress tensometers are used as the basic information and through the moments when the records of oscillograms in the detectors of the moments acting in the tail boom sections are used as the basic information. The first program operating mode has no principal structural limitations and may be used for calculation of both helicopter fuselage and motor vehicle body. The program second operating mode is principally designed for operation with the boom structures, which is particularly the helicopter tail boom. This mode is introduced in connection with the boom procedure for calculation of the tail boom damage and service life employed at the Moscow helicopter plant, and, in general, is independently valuable.

Not considering the theoretical justification of the approach which is the basis of the program, it should be noted that it is of a variable nature corresponding to the method of the least squares [9]. In this case, minimized is the functional of distance between the functions – initial ones *f(x,t)* corresponding to the oscillograms of the stresses or moments obtained in the flight experiment and $\tilde{f}(x,t)=\sum_{i=1}^{n} a_i \bar{\varphi}_i(x,t)$ approximately representing them. The approximation is essentially the following: in time – an aggregate of sinusoidal functions at several most considerable frequencies, and in space coordinate – responses at points x of the structure to single effects at the force excitation points. The responses to single effects are obtained with the aid of the finite-element method.

The solution is constructed by two methods – through the stresses or moments. In case of solution construction through the stresses, the approximating functions have the form of $\bar{\varphi}_i(x,t)=\bar{\sigma}_i(x)cos(\omega_i t+\alpha)$, where $\bar{\sigma}_i(x)$ is the response to the stresses at point x. In case of solution construction through the moments, the approximating functions have the form of $\bar{\varphi}_i(x,t)=\bar{M}_{xi}(x)cos(\omega_i t+\alpha)$, $\bar{M}_{yi}(x)cos(\omega_i t+\beta)$, $M_{zi}(x)cos(\omega_i t+\gamma)$,

where $\bar{M}_{xi},\bar{M}_{yi},\bar{M}_{zi}$ are the responses to the moments in boom section x.

Figure 16 contains the program functional diagram used for solving this problem. Let us explain briefly its component blocks.

[*] In this case, the NASTRAN system was used in calculations.

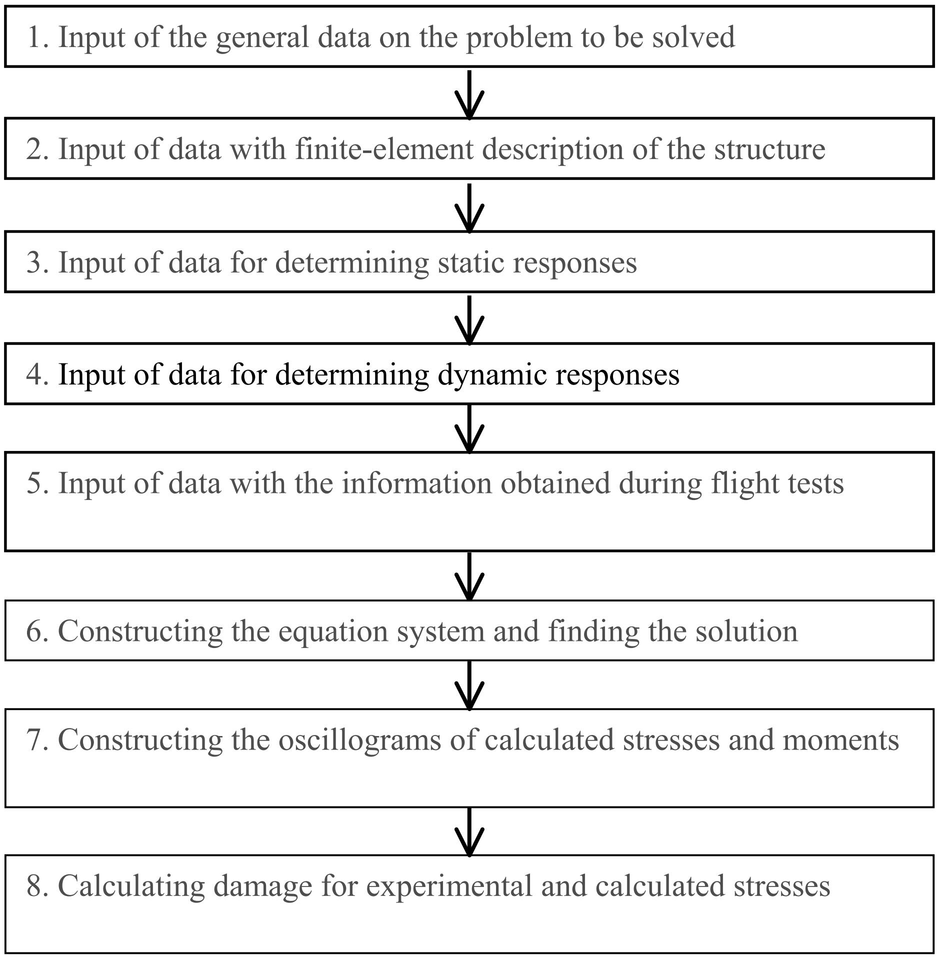

Figure 16 – Program Functional Diagram

1. **Input of the general data on the problem to be solved.** The number of the tensometers and test finite elements is input, as well as correspondence between their numbers. The position of the tail boom sections is input where the moment detectors are located. The name of file with the finite-element description of the structure is indicated. The quantity and numbers of the assemblies are indicated to which static loads are applied, as well as the names of the files containing the information on the responses to single static loads. The quantity and numbers of the assemblies are indicated, in which dynamic loads are excited, as well as the names of the files containing the information on the responses to single sinusoidal loads at different frequencies.

2. **Input of data with finite-element description of the structure.** The required information is obtained from the file containing the finite-element description of the structure. Areas, twisting and bend inertia moments for the required sections are calculated.

3. **Input of data for determining static responses.** The respective information is received including the values of stresses from the single loads. In case of problem solving through the moments, the responses in the form of moment values are calculated.

4. **Input of data for determining dynamic responses.** The respective information is obtained including the values of stresses and phases resulting from single loads. In case of problem solving through the moments, the responses are calculated as the moment values.

5. **Input of data with the information obtained during flight tests.** The data obtained during flight tests are processed and Fourier serial expansion of the entered stress and moment oscillograms takes place. The obtained expansion is used for construction of the approximating functions.

6. **Constructing the equation system and finding the solution.** Use is made of a variation approach based on minimization of the functional of the distance between the

functions – initial, and representing them approximately. The solution is constructed by two methods – through the stresses or through the moments. This approach is used as a basis for construction of the resolving system of equations. Its solution is obtained as a static component, as well as a linear combination of the sinusoidal load with the account of the respective amplitudes and phases.

7. **Constructing the oscillograms of calculated stresses and moments**. The achieved solution is used for obtaining the respective oscillograms of stresses and moments.

8. **Calculation of damage.** Damage is calculated for experimental and calculated stresses. For making this calculation, use is made of the single program module, implemented in the C++ language and presented above in Section 5.

7. Calculations Made

Using the Program in both variants of operation (both through stresses and through moments) rather interesting results were achieved. The first results were associated with the check of program for proper operation and concerned the real flight modes. In the calculations made, convergence of the processes obtained as a result of the calculations to the experimental ones depending on the selected approximating functions was studied.

Initially, no restrictions are laid on the number of the approximating functions, values of the frequencies and combination of the tensometers used for construction of the approximating functions. So, the developed program may be considered as the means for achievement of the calculated stressed dynamic state of the structure (in the permissible zone) according to the results of the strength flight tests. Evidently, in future the certain recommendations, limitations and rules for Program application will be developed upon accumulation of the certain experience of its use.

Calculation 1. In the variant of operation through stresses for the "Low-speed flight" mode, a calculation was made, in which the experimental stresses in the tensometers were compared with the stresses obtained by calculation. The calculation was made with static application of the load to the tail rotor and at 7 frequencies (0.7, 2.2, 2.7, 3.2, 6.7, 7.3 and 17.6 Hz) of dynamic excitation on the main rotor. Selected as the frequencies used for construction of the approximating functions were all considerable helicopter frequencies from those mentioned above in Section 3. The experimental stresses were used as the initial data for calculation and were referred to for forming the equation resolving system. The calculated stresses in the same tensometers were used for comparison. Figure 17 shows the results for tensometers Nos 12, 17 and 18. Their comparison is rather satisfactory.

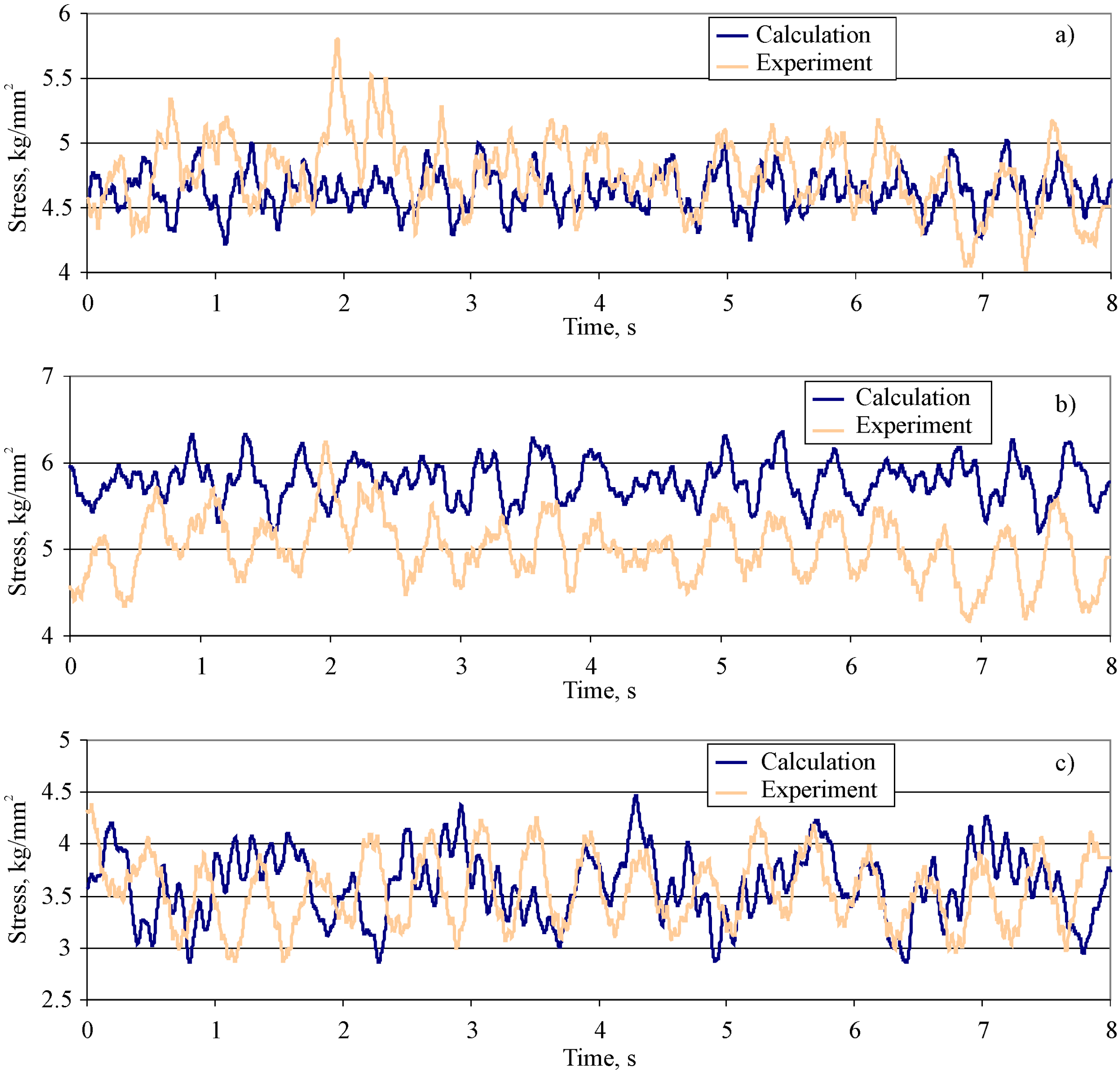

Figure 17 – Stresses in Tensometers 12(a), 17(b) and 18(c)

Calculation 2. In the variant of operation through moments, Figure 18 shows the results of moment calculation in section 1 for the "Level flight" mode. The results are presented for the following cases:

- calculation according to the developed program with automatic determination of the load; the dynamic loads were excited at 5 frequencies (0.5, 2.2, 3.0, 7.2 and 17.6 Hz); the first four frequencies were excited on the tail rotor and the frequency of 17.6 Hz – on the tail boom pylon rib No. 3, near the stabilizer for the reason mentioned above in Section 4;
- calculation according to the developed program with dynamic loads, previously obtained for the test program at two frequencies – 2.2 and 17.6 Hz, which were obtained with the aid of a quasistationary approach; at both frequencies, loads were applied to the tail rotor;
- flight experiment.

Comparison of the experimental moments with the calculated ones during automatic determination of loading shows their satisfactory coincidence. At the same time, it is obvious that application of the quasistationary approach for determination of the loads results in appearance of the fairly elevated dynamic moments corresponding to the frequency of 2.2 Hz and practically insensible excitation with a frequency of 17.6 Hz.

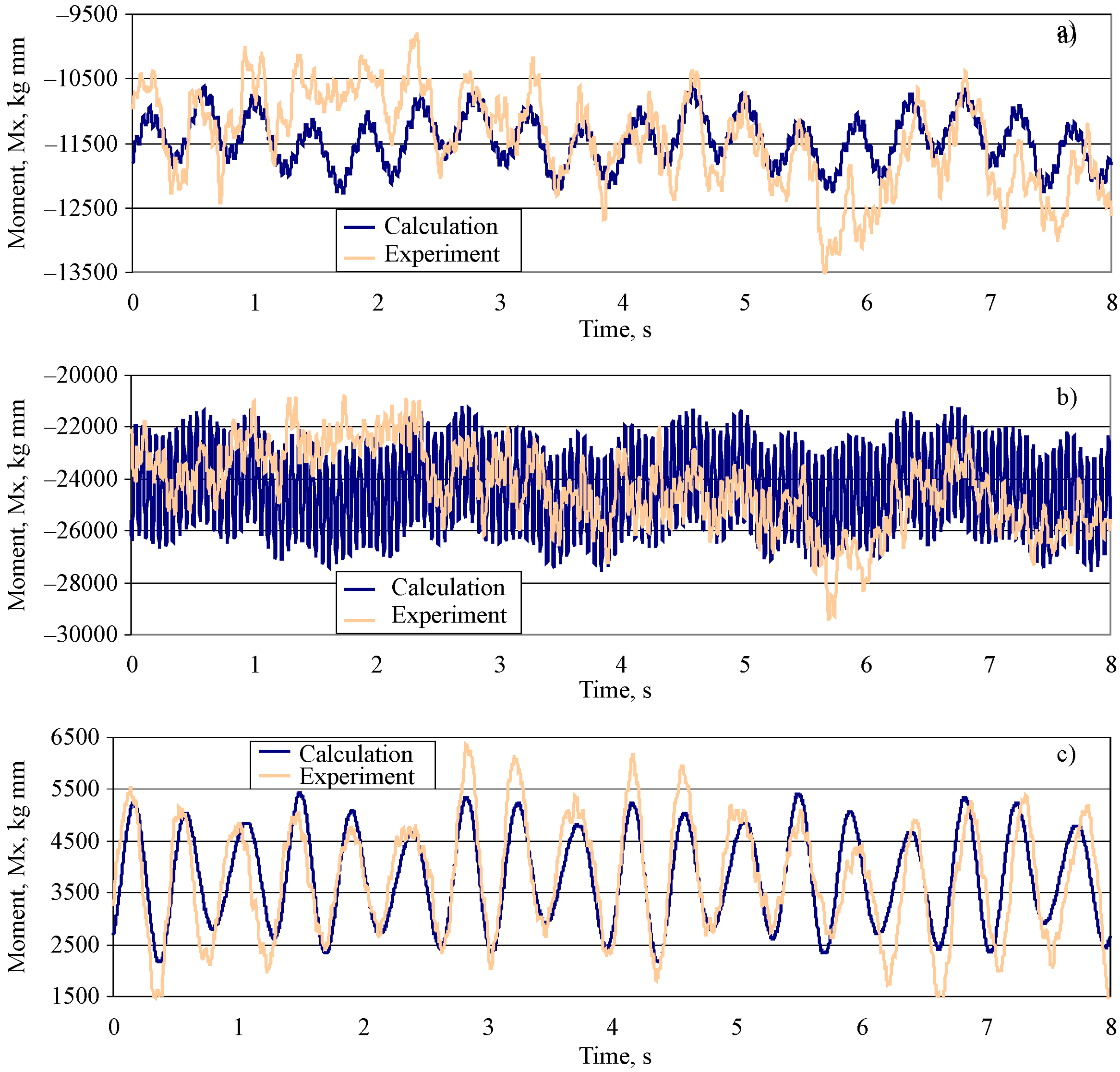

Figure 18 – Moments in Section I

Figure 19 shows the comparison of stresses in tensometers Nos 18, 19 and 21 for the calculation cases with automatic determination of load and experiment. Coincidence of stresses in calculation through the moments looks worse than in case of calculation through stresses. First of all it is related with far not a beam nature of distribution of stresses in the cross-sections of the tail boom and tail boom pylon (due to availability of their jointing area proper and cutout in the lower part of the tail boom between frames Nos 10 and 12). This produces a considerable effect on the accuracy of problem solving through the moments.

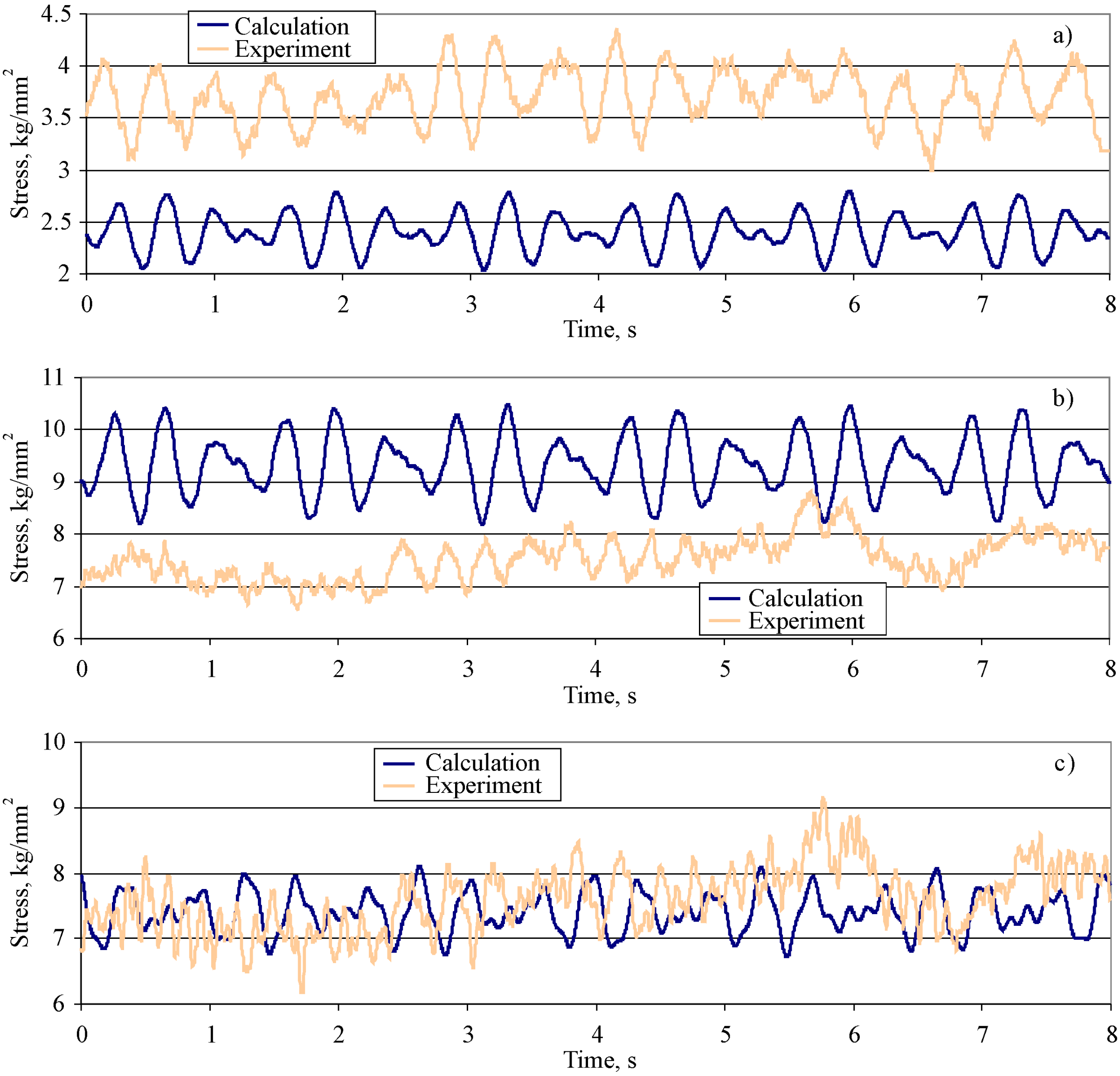

Figure 19 – Stresses in Tensometers 18(a), 19(b) and 21(c)

Calculation 3. In addition to the stresses determined by calculation at the tensometer location points, the cyclic stresses may be determined with the aid of the developed program for any beam or plate finite element of the model. Of course, or these elements, the respective responses should be determined beforehand. The latest calculation made through the moments included determination of the stresses in a number of finite elements where tensometers were not installed. The elements idealizing the internal caps of tail boom frames Nos 8, 9 and 10 and rib No. 1 with the fatigue cracks noted on their port side were of special interest.

Figure 20 a gives the calculation oscillograms of maximum calculation stresses in left internal caps of tail boom frames Nos 8, 9 and 10. For comparison with the level of the maximum experimental stresses in the skin (tensometer No. 19, arranged nearby – between ribs Nos 1 and 2), Figure 20 b shows the experimental and calculated oscillograms in this tensometer.

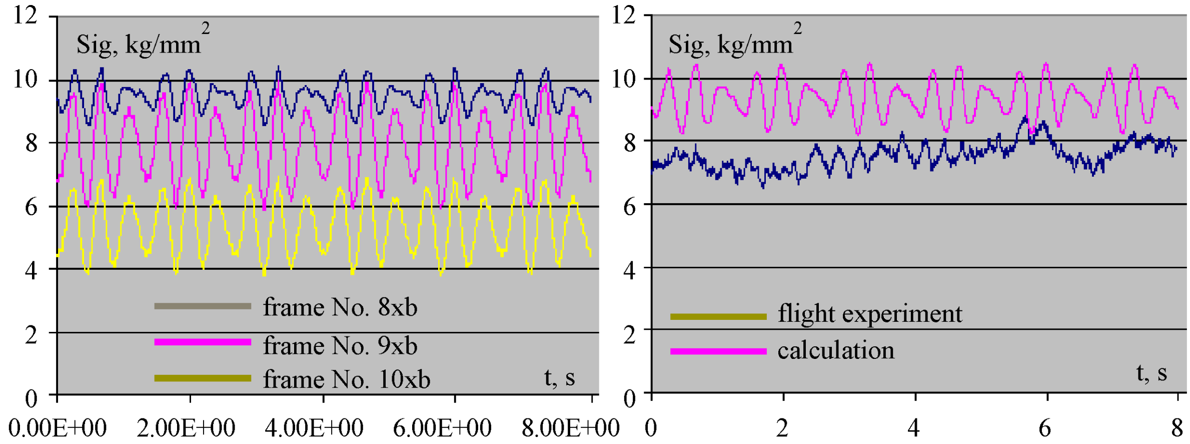

Figure 20 – Oscillograms of Maximum Stresses in Tail Boom Frames Nos 8, 9 and 10

The comparison shows that the static component of the stresses in the elements pertaining to Frame No. 10xb exceeds the level of stresses pertaining to tensometer No. 19. The static components in the elements pertaining to frames Nos 8xb and 9xb are less to some extent than those in the tensometer No. 19 but they considerably exceed the level of variable stresses. This makes it possible to suppose the existence of high-level damage (in the internal caps of these frames) resulting in formation of cracks.

The authors are grateful to the Test Flight Institute employees V.S. Losev and S.I. Efimochkin for performing the work including decoding of the flight test oscillograms and a number of valuable discussions.

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