MULTIDISCIPLINARY COMPUTATIONAL SYSTEM «PARUS-INT» FOR DESIGN AND CERTIFICATION OF AIRPLANES IN STATIC AND DYNAMIC STRENGTH AND SERVICE LIFE

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Abstract: The use of multidisciplinary computational system for structural analysis «PARUS-INT» is discussed here. This system was developed to provide the design process, certification and operation. In «PARUS-INT» are implemented best advanced practices in the field of aerodynamics, aeroelasticity, static strength, determination (normalizing) of static and repeated loading of an aircraft, the performance of computations of durability and survivability, the providing of algorithms of realization of current problems of aviation structure monitoring of aviation structures. Along with our own developments, a wide application of the foreign commercial software packages (NASTRAN, CATIA, ABAQUS and so on) is provided in the system. The inclusion of these packages is done using the modern databases.

1 INTRODUCTION

In «PARUS-INT» system the requirement of carrying out of investigations in the amount providing preparation of recommendations and conclusions at the stages of design, certification and service of airplanes in accordance with the requirements prescribed by the normative documents is the basic requirement. In addition the software complex can be modified to be applied to other objects of aeronautical engineering. Due to the use of general airplane mathematical models, the developed computational methods are applicable to airplanes of different aerodynamic schemes and structural solutions with the both low and high aspect ratio wing. Development of the system version for large computers of the IBM type was totally completed in 1990. It was used on the BVM-2 computer in TsAGI. Later «PARUS-INT» system was prepared for application on personal computers of the IBM family. Based on the results of test and operating computations for a series of airplanes of leading experimental design offices the system was appreciated as the most modern one for carrying out wide investigations in the field of strength and aeroelasticity in the branch. Wide usage ability of the system towards developing aircrafts design and certification is demonstrated.

In addition to the problems of design and certification of airplane projects, the problem of integration of computational and experimental investigations in TsAGI in the field of aerodynamics, strength, aeroelasticity, stability and controllability was stated with the application of «PARUS-INT» system.

2 GENERAL PRINCIPLES OF DEVELOPMENT AND APPLICATION OF «PARUS-INT» SYSTEM

The development of the algorithms and software of «PARUS-INT» system started in TsAGI because of the need to provide design and preparation of resolutions for operation of a supersonic passenger airplane in the period of 1966-1969. In the field of study of dynamic loading under action of discrete gusts and continuous atmospheric turbulence the basic research was carried out by G. I. Turchannikov. The works concerning the development of software for the flutter investigation were completed by V. G. Bunkov, E. N. Nabiullin, A. A. Rybakov. In order to investigate the dynamic loading the domestic method of computation of unsteady aerodynamic forces in the time domain was developed by M. I. Nisht and G. I. Turchannikov under the advisory guidance of S. M. Belotserkovsky.

The effective program of computation of aerodynamic forces, developed by G. I. Turchannikov, remains the basic program in the system for computations of unsteady aerodynamic forces in the time and frequency domain until the present time. In order to compute the dynamic loading due to discrete gusts the "rational methodology" has been developed in accordance with FAR-25, coordinated with computation using the Pratt formula for the subcase $M=0$, $\chi=0$, $\lambda\to\infty$ [1].

In order to solve the problems of dynamic loading in a turbulent atmosphere the procedure of fast transformation of transitional functions of aerodynamic forces to the frequency domain has been developed. As a whole, the mentioned approach provides high accuracy of computations both in the time and in the frequency domains at significant total decrease of time consumption.

In the 1970s mass-elastic airplane characteristics were modeled on the basis of polynomial method [2–5]. In 1985 the problem of development of a multidisciplinary branch system to solve problems of strength and aeroelasticity was formulated by the administration of TsAGI. The plans of cooperative research of TsAGI, of the TsAGI branch office, N. E. Zhukovsky Air Force Academy, experimental design offices of Tupolev, Mikoyan and Myasitchev have been prepared. The first version of the system was developed under the guidance of G. I. Turchannikov in 1987. Maintenance of developments in the part of the package of finite-element method DIANA was done by the collective of the Tupolev experimental design office, in the part of the aerodynamics package by the collective under the guidance of S. M. Belotserkovsky. The system maintenance as a whole was done by A. I. Artemiev and A. P. Krasnov. «PARUS-INT» system was functioning on the large computer in TsAGI. By means of this system the strength computations in separate problems for a series of Tupolev airplanes, S-80, «Aviatics», RRJ-75, RRJ-95, MiG-29 were completed.

The computational capabilities of «PARUS-INT» system are implemented by the package of engineering software and by means of system support. The integration of local data bases for separate disciplines via a global control system of databases is performed in «PARUS-INT» system. In order to solve specific design and certification problems it is considered to be possible to use multilevelness in operability mathematical models. On the highest level they are based on finite-element methods, on steady linear and non-linear theories and also on unsteady linear aerodynamic theories. On the operative level the application of universal beam models of finite-element methods and models of steady aerodynamic theories is allowed. Using the modules solving specific scientific problems, the parameters describing an airplane behavior, distributed and total aerodynamic loads are determined. Also internal force factors and stresses in the structural elements are determined. All these parameters are determined in the form of steady values, time realizations, frequency and spectral characteristics for random processes. The specified loading parameters are recalculated by means of the corresponding modules to the equivalent normalized in static strength values or are used to calculate service life of a structure. Owing to «PARUS-INT» system the basic problems of dynamic aeroelasticity and strength have been solved for the first time in the domestic practice with the use of the most general mathematical models. Such models are formed on the basis of a finite element method to compute natural modes, frequencies and methods of unsteady aerodynamic theory for computation of aerodynamic forces as functions of time and frequency.

The problems of aircraft dynamic loading are solved in «PARUS-INT» system using general mathematical models for the following normalized conditions, namely, flight in a turbulent atmosphere (one-dimensional and multidimensional models), effects of discrete gusts, maneuvers accounting for automatic control system, dynamic landing on a runway, dynamic landing on a deck with the hook engagement, the aircraft taxiing on an aerodrome (spectral approach). It is also seems possible to perform the following investigations on complete models, namely, aeroelastic stability of the system "aircraft - automatic control system" [6], flutter characteristics, static aeroelasticity phenomena. It should be noted that due to the use of general models the complex problem of loading repeatability in flight and on ground operation regimes was solved. This problem is necessary to provide determination of service life characteristics of an airframe structure.

Along with our own developments, a wide application of the foreign software packages (NASTRAN, CATIA, ABAQUS and so on) is provided in the system. The inclusion of these packages is done using the modern databases. The interconnected complex computational system «PARUS-INT» provides completeness of consideration of strength problems, generality of mathematical models of aircraft and adequacy of computational methods and mathematical models at such steps of life cycle as design, certification, operation.

3 FORMATION OF MATHEMATICAL MODEL OF AIRPLANE AEROELASTICITY EVENTS

To solve the problems of dynamic aeroelasticity it is necessary to set equations of aircraft motion both in the frequency and in the time domains of analysis. As it was mentioned above, at generation of reliable aircraft models, the schematization accepted in the finite-element method is used in the system to represent elastic-mass properties of the structure and the models of methods of unsteady aerodynamic theory to obtain aerodynamic influence. In the linear formulation the aerodynamic matrices of equations of motion in frequency and time domains are related to each other by the known transformations of the convolution integral type. This fact, in principle, allows us after determination of characteristics in one variation domain to find them in the other domain by numerical integration. Formulation of aeroelasticity equations in the frequency domain can be assumed to be traditional. But in this case the difficulties of determination of unsteady aerodynamic forces at sufficiently high values of reduced frequencies are well known. Due to this fact theoretically understandable transformation of aerodynamic matrices of equations of motion from frequency domain to time domain by the Fourier integral seems to be almost impossible for modern aerodynamic methods and models.

Direct numerical methods of computation of aerodynamic characteristics as functions of time for finite span wings were proposed for the first time in studies of the 1970s by

S. M. Belotserkovskiy and were developed by the authors of the work [7]. The methods allow unsteady aerodynamic forces for an aircraft to be determined with high accuracy as a function of time at first, and after that as a function of frequency. The both approaches to specify the equations of motion are realized in «PARUS-INT» system, namely, the approach in the frequency domain and the proposed approach in the time domain. Unlike other multidisciplinary systems, the primary unsteady aerodynamic forces are determined here at the time domain.

4 COMPUTATION OF MODES AND FREQUENCIES BY THE FINITE ELEMENT SCHEMATIZATION OF AIRFRAME STRUCTURE

The computational models in the aircraft structure can be represented as follows: a) beam scheme; b) beam scheme with the elements under aerodynamic pressure; c) scheme with flexible controls (beams and plates); d) full finite-element scheme.

An elastic airplane is considered as linear or linearized (for ground operating regimes) oscillating system with finite number of degrees of freedom. Usually nodes of an elastic-mass computational scheme do not coincide with the nodes of an aerodynamic scheme; therefore the transition of natural modes on the lifting surfaces from a finite-element mesh to the mesh of aerodynamic computation is performed by interpolation.

5 COMPUTATION OF UNSTEADY AERODYNAMICS

The results of computation of transition functions of unsteady aerodynamic loads caused by the airplane deformations, by the deviations of controls, by the influence of wind gust, are the basis to form a mathematical aircraft model in the field of aerodynamic effect both in the time and in the frequency domain. In this case a spatial aerodynamic airplane layout is considered. The problem is solved in a linear formulation by the method of unsteady discrete vortices [7]. The flow over an airplane is considered in the framework of ideal compressible medium. An airplane is modeled by the system of thin lifting surfaces, located in the space according to the aerodynamic layout. At satisfying the flow-tangency condition, the conditions on the vortex sheet, the initial conditions, the problem is reduced to the solving of an integral-differential equation, connecting the load distribution on the basic elements, schematizing the airplane, to the boundary conditions. This equation takes the form:

$$\frac{1}{8\pi}\cdot\frac{\partial}{\partial n_0}\iint\limits_{S_*}\int\limits_0^{t_*} K\left(\xi_0-\xi,\eta_0-\eta,\varsigma_0-\varsigma,\tau-\tau_1\right)\frac{\partial\Delta p}{\partial\tau_1}\,dS\,d\tau_1 = F\left(\xi_0,\eta_0,\varsigma_0,\tau_1\right) \tag{1}$$

where n_0 is the normal to the surface, K is the equation kernel, S_* is the wing area, Δp is the pressure difference, ξ,η,ς and ξ_0,η_0,ς_0 are the current coordinates of the surface points and the reference points of satisfying the flow-tangency condition, respectively; τ is the time.

The solution of the equation is to be found at satisfying the Chaplygin-Zhukovsky condition at the trailing edges. The equation is integrated along the span and it is differentiated normally to the basic surface. The integrals obtaining as a result along the chord are the singular ones at the Cauchy's representation. While integrating along the chord the values of loads at singular points are emphasized. These values are calculated analytically, the regular values are calculated using the formula of rectangles. The boundary conditions are met sequentially at the discrete time moments at reference points on basic surfaces. The reference points are positioned at the strip middle along the span and between the nodes of the quadrature formula along the chord. The load at the points positioned down stream from the last reference point in each strip is assumed to be zero.

As a result of the described process the transition from the integral-differential equation to the sequence of systems of linear algebraic equations has been made. The sequence in matrix form is:

$$\sum_{s=1}^{r} \mathbf{W}_{r-s+1} \cdot \Delta\mathbf{P}_s = \mathbf{F}_r \,, \quad r = 1,2,\dots R \tag{2}$$

where $\mathbf{W}_{r-s+1}$ is the matrix of m×m dimensionless velocities, induced at the reference points by the unit change of load at the computational points, which happened during the interval of non-dimensional time $[\tau_{S-1}, \tau_S]$; ΔP_s is the matrix with dimensions $m \times k$ of the load changes at the computational points for the same time period; F_r is the matrix with dimensions $m \times k$ of the values of boundary conditions at moment *r*; *m* is the general number of the discrete vortices which is equal to the number of reference points; *k* is the number of the solving problems, equal to the number of columns in the matrices; *r*, *R* are the current and finite numbers of computational time moments respectively.

The types of the solving problems and their number are determined by the system of dimensionless kinematical parameters and boundary conditions. The kinematical parameters related to the deformation of an airframe, to the influence of wind gusts, to the deviations of controls, are written in the form:

$$\varepsilon_j \in \left\{ q_i, \dot{q}_i, \Delta_k, \dot{\Delta}_k, \delta_l, \dot{\delta}_l \right\} \tag{3}$$

The problem linearity allows to consider each of the set of parameters ε_j independently. In this case in order to obtain unsteady aerodynamic characteristics of an airplane at an arbitrary formulated function of kinematical parameters on time and frequency, at first we should solve the problems for stepped change in time of these parameters:

$$\varepsilon_j(t) = \begin{cases} 0, & \tau < 0 \\ 1, & \tau \geq 0 \end{cases} \tag{4}$$

Obtained time dependencies in this case which are the transition functions of aerodynamic airplane characteristics are determined numerically on a finite range of dimensionless time τ. The transition to the arbitrary dependencies of parameters on time is done by the convolution integral (by the Duhamel integral) with a preliminary construction of a respective analytical continuation to infinity. The algorithm for computation of the matrix of load transitional functions ΔP_r (the pressure difference at the upper and the lower airplane surfaces) at computational time moment r is written as:

$$\Delta\mathbf{P}_r = [\mathbf{W}_1]^{-1} \cdot \left[\mathbf{F}_r - \sum_{S=1}^{r-1} \mathbf{W}_{r-S+1} \cdot \Delta\mathbf{P}_S \right], \; \Delta\,\mathbf{P}_{r_\Sigma} = \sum_{S=1}^{r} \Delta\mathbf{P}_S \tag{5}$$

The mentioned above basic assumptions of the numerical method construction at the respective determination of algorithms for computation of wash matrices W elements for subsonic and supersonic speeds of flight allow to obtain matrices of loads for the subsequent computation of unsteady aerodynamic forces, acting on an airplane, at the arbitrary and earlier specified non-periodic or harmonic change of kinematical parameters in time in the equations of airplane motion.

6 EQUATION OF AN ELASTIC AIRPLANE MOTION

To solve basic dynamic aeroelasticity problems it is sufficient to form an equation of a flexible airplane motion in the time domain in the general form in the generalized coordinates in natural modes. In the matrix form the equation is:

$$C\ddot{q}(t)+\int_0^t D(t-\tau)\dot{q}(\tau)d\tau+\int_0^t B(t-\tau)\dot{q}(\tau)d\tau+D_k\dot{q}(t)+C\omega^2 q(t)=\int_0^t Q_w(t-\tau)\dot{w}(\tau)d\tau \qquad (6)$$

where C is the diagonal matrix of the generalized masses; ω^2 is the diagonal matrix of the squares of natural frequencies; D_k is the diagonal matrix of structural damping in elastic natural modes; B and D are the matrices of transition functions, related to aerodynamic stiffness and damping, respectively; Q_w is the vector of transition functions of generalized forces of gusts; $w(t)$ is the law of gust intensity change in time; $q(t)$ is the vector of generalized coordinates in natural modes; τ, t – time.

In order to analyze the gust influence the computation of the specified number of natural frequencies and modes for a finite-element airplane scheme is done. The transition from stepped influences typical for transitional functions to the solutions for arbitrary time dependencies is performed by integral transformations. To compute aerodynamic loads caused by an arbitrary profile gust the integral transformation is:

$$\Delta p_w(x,y,z,M,t)=\frac{w_y(0)}{U_0}\cdot H_{p_w}(x,y,z,M,t)+\int_0^\infty \frac{d}{d\tau}\cdot\left[\frac{w_y(\tau)}{U_0}\right]\cdot H_{p_w}(x,y,z,M,t-\tau)d\tau \ , \qquad (7)$$

where Δp_w is the change of pressures in time for w_y law of the gust velocity change; $w_y(\tau)$ is the law of gust velocity change as a function of dimensionless time; H_{p_w} is the transition function of pressure at a point; U_0 is the flight speed.

7 COMPUTATION OF UNSTEADY AERODYNAMIC FORCES IN THE FREQUENCY DOMAIN USING REDUCED FREQUENCIES

Aerodynamic characteristics in frequency domain are obtained by the strict in linear theory application of integral transformations of the type of convolution integral to the preliminary calculated transition functions of the respective characteristics in time domain. Using the transition load functions (the pressure difference at the upper and the lower surfaces), the summarized and generalized characteristics and matrices of equation of motion, in which we are interested in, are computed. Aerodynamic derivatives of pressure $\Delta p^{\dot{\Delta}}$, Δp^{Δ} for determination of vectors of the right parts of the equation of motion as a function of gust influence in reduced frequencies are computed using the values of transition functions with the following relationships:

$$\Delta p^{\dot{\Delta}}\left(x_i, y_i, z_i, M, p^*\right) = p^* \int_0^\infty \frac{\Delta p\left(x_i, y_i, z_i, M, \tau\right)}{w_y^*} \cdot \sin\left(p^* \tau\right) d\tau \ , \tag{8}$$

$$\Delta p^{\Delta}\left(x_i, y_i, z_i, M, p^*\right) = \int_0^\infty \frac{\Delta p\left(x_i, y_i, z_i, M, \tau\right)}{w_y^*} \cdot \cos\left(p^* \tau\right) d\tau \tag{9}$$

where $\frac{\Delta p\left(x_i, y_i, z_i, M, \tau\right)}{w_y^*}$ is the transition function of pressure at an aerodynamic point;

x_i, y_i, z_i are the coordinates of points; $\tau = \frac{U_0 \cdot t}{b}$ is the dimensionless time; t is the time, M is the Mach number; $p^* = \omega \frac{b}{U_0}$ is reduced frequency, where ω is the circular frequency, b is the characteristic dimension.

The similar transformation is applied to the problems of instantaneous deformation (displacement) of an airplane in forms of elastic (rigid) natural modes of an airplane and in derivatives of these modes (local angles of attack) along the flow. In this case the number of vectors of boundary conditions is twice larger the number of natural modes taking into account in the problem. The transition functions of pressures and of generalized aerodynamic matrices, corresponding in the time domain to the matrices of aerodynamic stiffness B and of damping D, are used to compute aerodynamic derivatives of pressures in the function of reduced frequency, in which the elements of matrices B and D are obtained using the relationships:

$$\mathrm{b}_{jk} = \sum_{i=1}^{m} \iint_{S_m} [\Delta p_1^{q_j}\left(x, y, z, M, p^*\right) - {p^*}^2 \Delta p_2^{\ddot{q}_j}\left(x, y, z, M, p^*\right)]\, f_k(x, y, z) \frac{dx\, dy}{\cos \Psi_m} \tag{10}$$

$$\mathrm{d}_{jk} = \sum_{i=1}^{m} \iint_{S_m} [\Delta p_1^{\dot{q}_j}\left(x, y, z, M, p^*\right) + \Delta p_2^{\dot{q}_j}\left(x, y, z, M, p^*\right)]\, f_k(x, y, z) \frac{dx\, dy}{\cos \Psi_m} \tag{11}$$

where b_{jk}, d_{jk} are the elements of matrices B and D respectively; m is the number of separate strips; Ψ_m is the angle of cross V strip m; q_j is the generalized coordinate of equations of motion, corresponding to j-th elastic natural mode; $\Delta p_1^{q_j}$, $\Delta p_1^{\dot{q}_j}$ are the aerodynamic derivatives of pressure difference for the problem with boundary conditions $\frac{\partial f_j}{\partial x}$; $\Delta p_2^{\dot{q}_j}$, $\Delta p_2^{\ddot{q}_j}$ are the aerodynamic derivatives of the pressure difference for the problem with boundary conditions f_j; $f_k(x, y, z)$ is the natural mode.

8 EQUATION OF DYNAMIC LOADING OF AN AIRPLANE STRUCTURE AT FLIGHT IN CONTINUOUS ATMOSPHERIC TURBULENCE

The loading computations are carried out for justification of static strength at design and certification of airplanes in the normalized loading cases and in the service flight conditions to provide computation of service life characteristics. The user can vary the data describing the parameters of the computational turbulence model (the spectrum shape, the scales of turbulence, and probabilistic parameters of atmospheric turbulence).

Preliminary the solution of the matrix equation for the case of a single harmonic gust should be found:

$$\begin{vmatrix} -\omega^2 C + B(\omega) + G & -\omega\left[D(\omega) + D_k\right] \\ \omega\left[D(\omega) + D_k\right] & -\omega^2 C + B(\omega) + G \end{vmatrix} \cdot \begin{vmatrix} \overline{q} \\ \overline{\overline{q}} \end{vmatrix} = \begin{vmatrix} \overline{Q}(\omega) \\ \overline{\overline{Q}}(\omega) \end{vmatrix} \tag{12}$$

where G is the matrix of structural stiffness; $\overline{\mathbf{Q}}(\omega)$, $\overline{\overline{\mathbf{Q}}}(\omega)$ are the vectors of the right sides representing real and imaginary components of generalized gust forces.

The system of linear algebraic equations is solved by the Gauss method for the specified frequency interval. The aerodynamic matrices and vectors are determined with the application of full unsteady theory. After determination of amplitude-frequency characteristics (AFC) for generalized coordinates $\overline{q}$ and $\overline{\overline{q}}$ the AFC are determined for internal force factors of structure and the strain-stress state is determined using the finite elements of the airframe.

Relative spectral density of atmospheric turbulence $\Phi_W(\omega)$ and spectral density $\Phi_X(\omega)$ of the sought force factor X or of a component of strain-stress state are connected by the relationship:

$$\mathbf{\Phi}_x(\omega) = \left|\mathbf{T}_x(i\omega)\right|^2 \cdot \mathbf{\Phi}_w(\omega) \tag{13}$$

where $\mathbf{T}_X(i\omega)$ is the amplitude-frequency characteristic for a force factor X; $\mathbf{\Phi}_w(\omega)$ is the Carman spectrum:

$$\mathbf{\Phi}_w(\omega) = \frac{L}{U} \cdot \left[1 + \frac{8}{3} \cdot \left(1.339 \cdot L \cdot \frac{\omega}{U}\right)^2\right] \cdot \left[1 + \left(1.339 \cdot L \cdot \frac{\omega}{U}\right)^2\right]^{-\frac{11}{6}}, \tag{14}$$

where L is the scale of turbulence; U is the flight speed.

Finally, the AFC for generalized coordinates $q(i\omega)$, amplitude-frequency characteristics of deformations at the nodes of finite elements, and after that the AFC of force factors and their spectral densities, root-mean-square values of loads increments and of strain-stress state components: are determined as,

$$\mathbf{A}_x = \int_0^{\omega_k} \mathbf{\Phi}_x(\omega)\, d\omega \tag{15}$$

In accordance with the regulating requirements the limit loads and the stresses are obtained by multiplication of A_x value to the specified in these requirements gust speed U_{de}, as the function of flight.

9 BASIC STATEMENTS FOR COMPUTATION OF CRITICAL STRUCTURAL LOCATION DAMAGEABILITY FOR THE PROBLEMS OF DETERMINATION OF SERVICE LIFE CHARACTERISTICS

Service life characteristics of a structure are determined by ones of the system of critical locations. At the evaluation of service life aircraft characteristics in the typical conditions of operation the central place takes the determination of spectra in frequency and of realizations of damaging stresses exactly at critical locations. Due to this fact before the computations of loading it is preferable to determine a list of the critical locations and their characteristics (fatigue curves and so on), to mark out in the finite elements scheme the critical elements, supporting a considered critical location.

The durability computation can be performed at the presence of the respective fatigue curves at the levels of the general and local strain-stress state. Damageability of different critical locations of aviation structures is usually determined by the processing of realizations of some equivalent stress.

The computational results in «PARUS-INT» system for the general finite-element scheme are presented in the form of amplitude-frequency characteristics of strain-stress state and loads, auto and mutual spectra of stress and load increments for all regimes of operation.

Spectra of strain-stress state of finite-element elements of critical locations are calculated after that using the real and imaginary components of AFC with the aid of normalized for a typical flight spectra of external influence (disturbed air, aerodrome surface).

The expression of spectra of equivalent stresses takes the form:

$$S_{\sigma_{eq}}(\omega) = \sum_{i=1}^{N} \sum_{j=1}^{N} \alpha_i \alpha_j S_{ij}(\omega) \tag{16}$$

where S_{ij} – auto and mutual spectral densities of the summands in the formula of equivalent stress, α_i, α_j– constant coefficients, determined by the algorithm for equivalent stress; N is the number of the summands in the formula for equivalent stress.

Using the spectral density the repeatability of the stresses is calculated. Application of the spectral summation hypothesis allows an evaluation of fatigue damageability of critical locations to be obtained. Accounting for the fact that the basic data of laws of accumulation of fatigue damage and development of cracks were obtained for time functions, simulation of realizations of stresses by the Monte-Carlo method is provided in the system for application of the most modern and reliable theories of continuous strength prediction. In the general case the combined simulation of realizations of stress components in matrixes of auto and mutual spectral densities of these components is done. Also the modeling of durability was performed with the use of non-linear algorithms for computation of stresses. Additionally by the processing of assembly of several hundreds realizations the tables of total cycles of stresses can be obtained.

10 EXAMPLES OF «PARUS-INT» SYSTEM APPLICATION

10.1 Influence of unsteadiness on the loading of pylons and engines of an airplane with high aspect ratio wing

Let us consider an influence of turbulence on the transport airplane with two engines on the pylons under the wing, namely, the external engine and the internal engine. The dynamic loading computations [8] were done on the flight regime H=6 km, M=0.77 for the variant of normal loading. This flight regime was the determining regime based on the conditions of loading of pylons (engines). In order to describe atmospheric turbulence the Dryden spectral density of gusts was taken.

Reduced frequencies $p_1^* = 0.385$; $p_2^* = 0.66$; $p_3^* = 0.735$; $p_4^* = 0.986$; $p_5^* = 1.14$; $p_6^* = 1.45$ correspond to the frequencies of the first six natural modes in flow at the characteristic dimension equal to the root chord.

The root-mean-square deviations of increments of loads $\bar{\sigma}_{n_z}$ at the gravity center of engines are shown in Figure 1. They were obtained in the approximate computations (with the use of the steadiness hypothesis at the determination of unsteady aerodynamic forces). The side load factors n_z for the external engine are in 4 times higher than for internal engine. This conclusion follows from the ratio of their root-mean-square deviations. In this case the values n_z, $\sigma_{\Delta n_z}$ for the external engine are determined almost totally by the second elastic natural mode, and for the internal engine – the values are determined by the third natural mode, because almost all values of the load factor n_z dispersion are distributed on the frequencies of these natural modes ($\omega_2 = 14.37\ s^{-1}, \omega_3 = 15.75\ s^{-1}$).

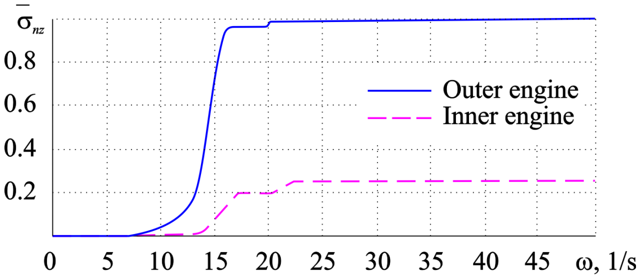

Figure 1: Mean square deviations of load factor increment (stationarity hypotheses)

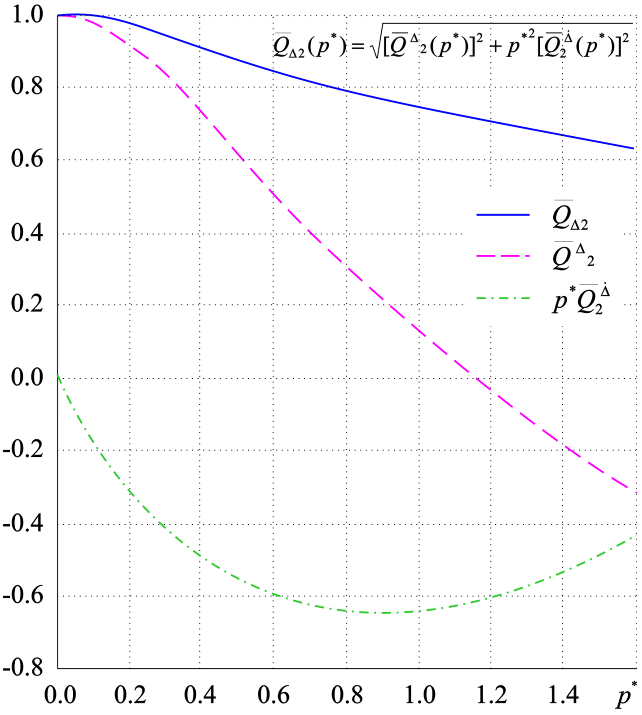

Figure 2: Generalized force transfer function from the gust corresponding to the second natural mode

The elements of vectors $Q^{\Delta}(p^*)$ and $p^* Q^{\dot{\Delta}}(p^*)$, corresponding to the second elastic natural mode and determining the loading of the external engine as a function of reduced frequency,

$\overline{Q}^{\Delta}{}_2(p^*)$ and $p^*\overline{Q}_2^{\dot{\Delta}}(p^*)$ are shown in Figure 2. In addition, the value of the transfer function for the generalized gust force in the second natural mode is shown there.

The values of the transfer function $\overline{Q}_{\Delta 2}(p^*)$ at p^*=0.66, corresponding to the resonance frequency of the second natural mode are 80% of the steady value $\overline{Q}_{\Delta 2}(0)$. At the almost constant left parts of the motion equations and at the domination of one natural mode in the loading of pylons, the change of the load factor is almost totally explained by the change of transfer function of the generalized gust force in the natural modes.

In this case for the most loaded external pylon the load factor n_z reduction is approximately 20% (Figure 3). For the internal engine the amplitude value of the generalized gust force in the third natural mode, determining load factor n_z, grows in a wide range of reduced frequencies and at p^*=0.735 it is 85% of the steady value (Figure 4). It should be mentioned that despite the growth of side load factors of the internal engine in 75%, the reduced in 20% load factors of the external engine remain the dominating in strength conditions (Figure 4). For vertical load factors the decrease in 25–30% was obtained.

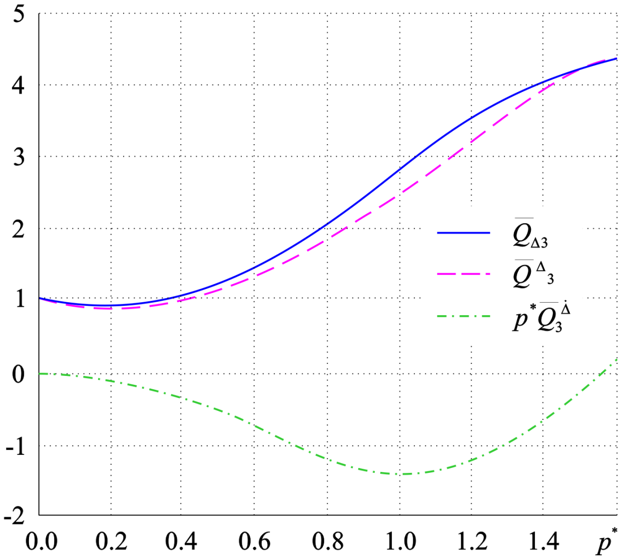

Figure 3: Generalized force transfer function from the gust corresponding to the third natural mode

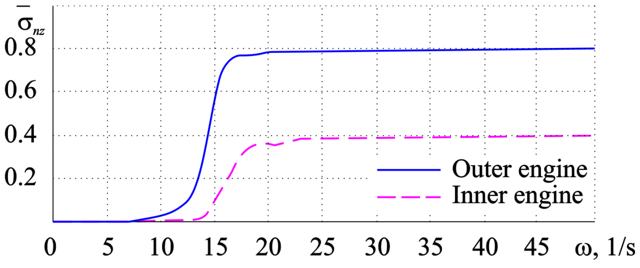

Figure 4: Mean square deviations of load factor increment (accurate calculation)

10.2 Example of dynamic loading computation under influence of multidimensional random velocity field of continuous atmospheric turbulence

The developed methods [9] were applied in this work to investigate the dynamic loading at a flight in a turbulent atmosphere of a heavy airplane with a large aspect ratio wing. For the flight regime at $M = 0.63$ at height $H = 8$ km in the field of skews of a two-dimensional vertical gust, the computations of Nyquist plot and root-mean-square deviations of bending moments at different wing sections and a number of the zero level exceedences N_0 were performed. In the computations at the symmetrical influence two rigid and six elastic natural modes were considered; under antisymmetrical influence two rigid and five antisymmetrical elastic natural modes were taken into account.

In order to compare the computations were performed in unsteady and in the steady formulation when determining aerodynamic forces for a two-dimensional vertical gust. The form of an atmospheric turbulence representation proposed by Dryden with the turbulence scale $L = 300$ m was used in the computations. The symmetrical, antisymmetrical and general loadings were considered. There were two types of improvements in the formulation of the dynamic loading problem. In the first case the atmospheric turbulence model was improved, namely, the transition from a one-dimensional model to the two-dimensional one was done; in the second one the procedure of computation of aerodynamic forces was elaborated, in other words, the transition from the steady theory to the total unsteady one was done.

The transfer functions of increments of the bending moment for $\bar{z} = 0.1$ for a non-symmetric component of the moment are shown in Figure 5. In the loading computations two rigid and five elastic natural modes of antisymmetrical natural modes were considered. The decrease of the peaks of transfer functions in all natural modes except the first elastic natural mode was obtained. The change of antisymmetrical components in dynamic increments of the bending wing moment is 10–15% (Figure 6). The change of the summarized moments values is shown in Figure 7. Further the relative values of damageability along the wing span are presented in Figure 8. These values are normalized by the damageability of the initial steady computation for one-dimensional turbulence model taken as a unit at any section.

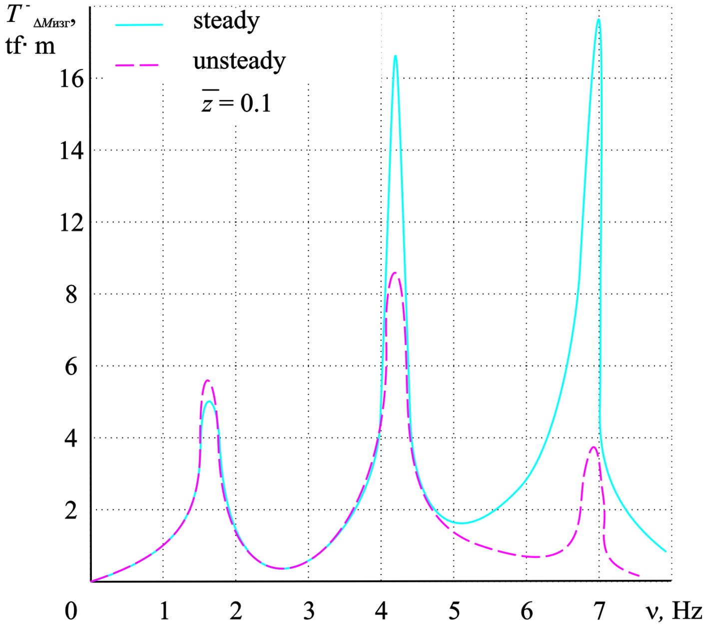

Figure 5: Tranfser function of antisymmetric component wing for bending moment increment

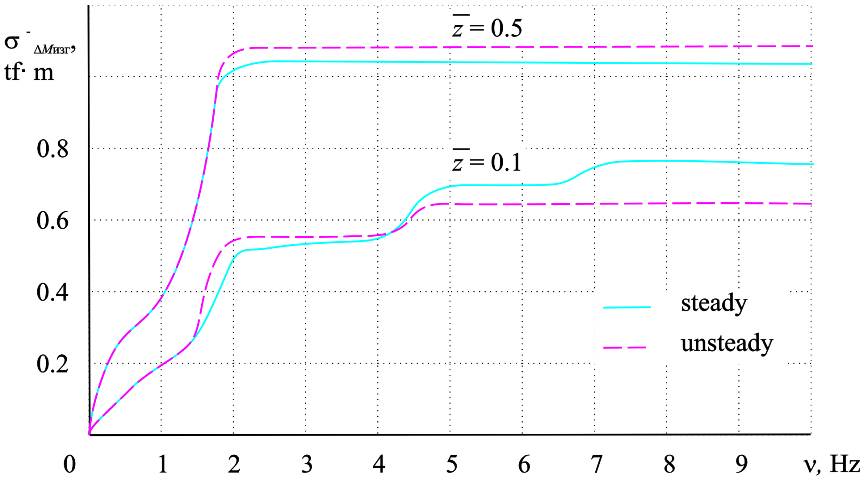

Figure 6: Antisymmetric component of wing bending moment dynamic increment

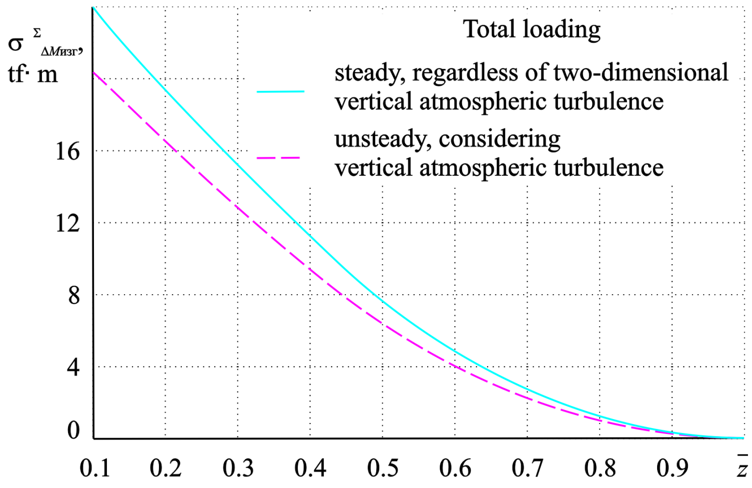

Figure 7: A change of total bending moment values

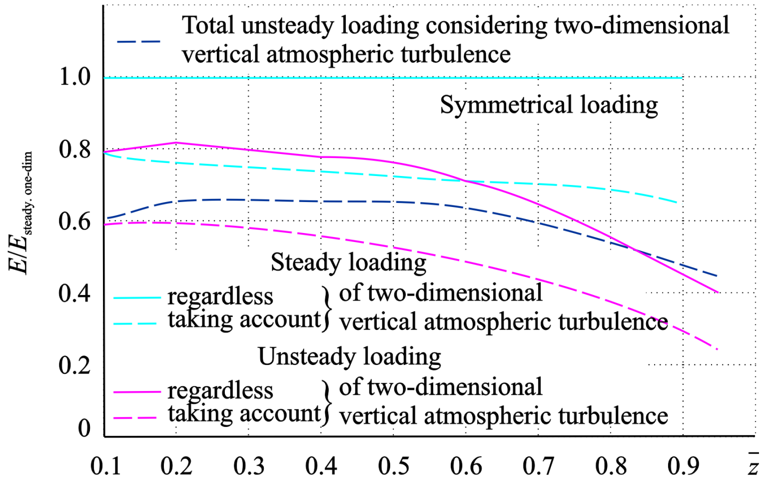

Figure 8: Relative damageability distribution by the wing span

In the methodical computations the damageability reduction in 20–25% was obtained, moreover, the reduction is somewhat higher for end sections of the wing at the isolated account of unsteadiness. In the exact computations performed considering the unsteadiness of change of aerodynamic forces and two-dimensionality of atmospheric turbulence, the damageability reduction in 35–40% was obtained in comparison with the initial computations. As a result of the research it was obtained that at the consideration of influence of a two-dimensional atmospheric turbulence on a heavy airplane with a high aspect ratio wing of a traditional scheme, the two-dimensionality of the atmosphere influence and unsteadiness of change of aerodynamic forces must be considered together. At the chosen flight regime for wing bending moments, the improvements related to the transition to the two-dimensional dependency for atmospheric turbulence and to accounting of unsteadiness of the same sign are close in values, but they significantly differ in N_0 and in damageability. In the exact computations the significant reduction of moments and to a greater extent of values N_0 and damageability was obtained.

10.3 Static and dynamic strength design of a structure of a transport airplane wing with the use of «PARUS-INT» system

The design of transport airplane wing at the stage of sketch elaboration was carried out by the developers of «PARUS-INT» system in the close cooperation with Tupolev JSC and it was used to solve the problem of a possibility of an airplane realization in the specified weight limits. At the presence of only a general airplane view project on this stage and of summarized aerodynamic characteristics data it was possible to perform only an integral evaluation of a load-bearing structural weight of the upper and lower wing box panels in static strength and static cases of loading. The developers of «PARUS-INT» system have performed for the first time the closed cycle of the wing design using the prototype for static and dynamic cases of loading. As a result of the computations, the stresses in the wing and in the centre wing structure were obtained, and also the detailed weight report was prepared. For a transport airplane the dynamic loading cases are the dominative cases both for the structural service life and for static strength. In this computation during the static strength analysis the normalization of the dynamic loads prescribed in Aviation Regulations-25 was done. Computational support system in static strength and in evaluation of service life characteristics on static-dynamic finite-element models was used. The development of a dynamic model was done using the design data of the full finite-element model for static loading cases. The static-dynamic model of transport airplane was prepared on the basis of the similar model of prototype.

The developed finite-element model integrally describes a wing. The slats, flaps, ailerons, a wingtip are additionally included in the model. The zone between the second spar and the internal flap is included in the model too. Due to this fact at the computations of strain-stress state the transmission of loads to the load-bearing wing box from the total wing surface is done. Notice, that the finite-element model of the load-bearing wing-box covers only 30% of the wing area. To compute dynamic loading the beam element of fuselage, tail planes, vertical tail planes, engines are included in the complete finite-element wing models with the centre wing structure. The static-dynamical airplane model of transport airplane is presented in Figure 9.

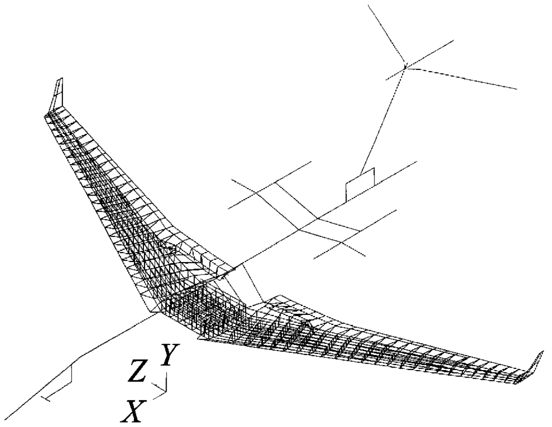

Figure 9: Finite element model

The program of computation of unsteady characteristics allows to obtain more exactly aerodynamic forces at high Mach numbers, than it is possible in the method of steady discrete vortices. This is the reason why steady and unsteady characteristics were determined using the general unsteady method.

The wing loading conditions for the four cases were considered. These are static case (with load factor n_y=2.5 in accordance with 25.337 Aviation Regulations-25) and three cases of dynamic loading at flight in disturbed air. According to the requirements of Appendix G to Aviation Regulations-25, the dynamic loads acting on each part of the structure were determined accounting for unsteady change of aerodynamic forces. In this case two rigid and six elastic symmetric natural modes of wing in the airplane system were taken into account.

Initially the design of the wing and of the centre wing structure was done using the allowable stresses specified by the static strength and service life conditions for the loads of static computational case. Using the obtained load-bearing material thickness, the load-bearing structure weight was determined. The mass data were used to develop a static-dynamic model and to perform the computations of dynamic loading at flight in a turbulent atmosphere. Using the dynamic loading data, the thicknesses of elements and weight of load-bearing material were adjusted.

In addition to the mentioned above problems of static strength design for static and dynamic loading cases, the computations of investigation of repeated loading in the conditions of a typical flight were performed. The spectra of load factors and loads for regimes of climb, descent and cruise flight were obtained. The spectral characteristics of stress in the structural elements for a cruise flight regime were obtained by the direct computation. These results are related to the cycle of static and fatigue strength complex design.

10.4 Computations of service life characteristics of a transport airplane at the early design stage

The purpose of this work is to obtain spectrum of stresses at the structural elements with the locations critical to service life. The work was completed according to the contract with JSC “GSS”.

The service life characteristics of a transport airplane airframe are determined, as a rule, by the wing (first of all, by its lower panel) and to a lesser extent by the fuselage. The basic fuselage loading factor is the excessive pressure, the basic wing loading factor is the bending moment. The wing service life is determined by the longitudinal joint of the skin with the structure, which is unavoidable source of fatigue cracks appearance and structural non-regularities including, mainly, the cross joints and holes in the panels.

The substructures and elemental groups are marked out in the fatigue-critical locations for stress components computations convenience. The eigenvalue analysis for the symmetrical and antisymmetrical cases at take-off and landing regimes was carried out.

The loading computations for an airplane accounting for the structure elasticity were performed using the continuous atmospheric turbulence scheme. The atmospheric turbulence parameters were taken according to the Aviation Regulations. When solving this complex problem, the following research has to be done:

1. Perform computations of unsteady aerodynamic forces in the time and frequency domains.
2. Compute the values of strain-stress components at the aircraft parking.
3. Compute spectral characteristics of increments of stresses for regimes of a typical flight.
4. Obtain repeatability and damageability of the corresponding stresses components under the flight conditions in a continuous atmospheric turbulence in the structural elements accounting for a static preload.
5. Compute repeatability and damageability of the respective stresses components for ground operation.
6. Compute durability for critical locations with the specified algorithms of computation of the damaging stress and with the parameters of fatigue curve.
7. Simulate realizations of stress components in the structural elements in flight regimes.
8. Simulate realizations of stress components in the structural elements in ground regimes.
9. Obtain realizations of stresses for a typical flight and evaluate damageability by the method of complete cycles
10. Use the realizations to compute damage tolerance.

The computations of amplitude-frequency stress characteristics were done for basic groups of elements. The complete computations were done for a series of zones including the generation of stresses realizations. The stresses realizations for elements on the wing lower surface were taken into account to compute damage tolerance. The damageability computations with the use of fatigue curves of intermediate products, accepted for the basic zones of the lower panel, led to the values of equivalent in damageability stresses from 12 kg/mm^2 to 14 kg/mm^2. In general, the values of the obtained equivalent stresses are in good agreement with the data, presented in Figure 10 at design static stresses 30–31 kg/mm^2, which are assumed for the service life design of the lower surface.

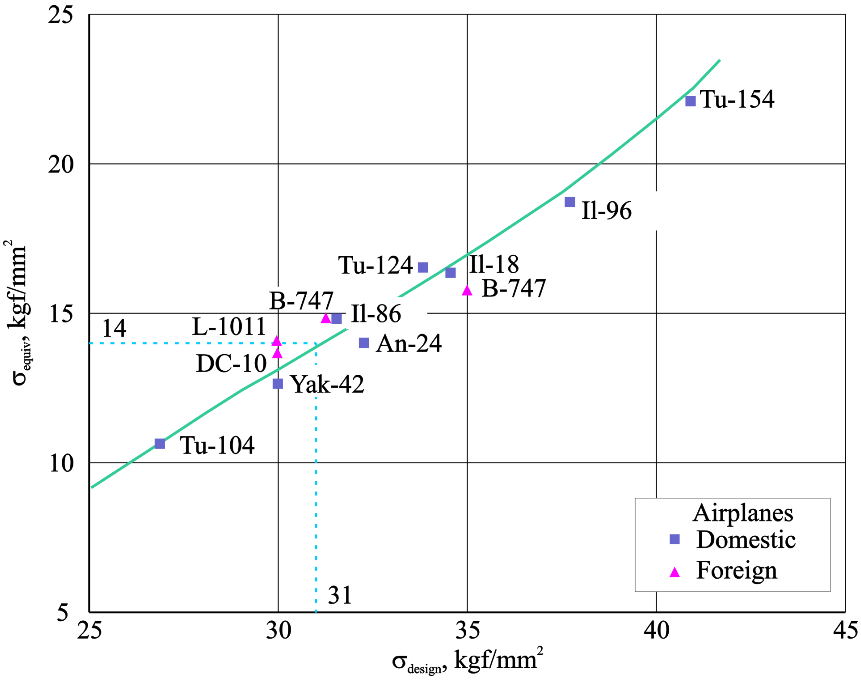

Figure 10: Statistical dependence $\sigma_{equiv}=f(\sigma_{design})$ for the wing lower panels

The further investigation of the cracks growth rate at the specific critical locations demonstrates a possibility to provide a value of service life in 70000 flights at the good accordance of total lower panels loading.

11 RESULTS OF APPLICATION OF «PARUS-INT» SYSTEM

Let us emphasize the distinguished features of a series of computational investigations performed by means of «PARUS-INT» system. The high rate of new results obtaining was demonstrated for analysis of in-service loading by the computations performance at the final static strength certification stage of a medium-range jet airliner with the foreign engines and by the design computations at the early stage of end-to-end certification for two regional passenger airliners.

For the regional passenger airplane the computations of the wing and landing gear beam service life under the ground and flight operation conditions were done in «PARUS-INT» system and were accepted by the Interstate Aviation Committee Aviation Register at the certification.

In the process of collaboration with Tupolev experimental design office for the projects of two regional passenger airliners it was shown that the use of «PARUS-INT» system significantly increases the work efficiency at the performance of computations of a typical loading in stresses.

The computations of loads on the medium-range jet airliner were performed with the use of the beam finite-element models and unsteady aerodynamics at dynamic landing, at a flight in a turbulent atmosphere, and at the loading at ground operational regimes for certification purposes.

The multidimensional turbulence influence investigations were carried out for the heavy airplane project. The damageability reduction in 20–25% was obtained in the methodical computations. In the exact computations performed considering the unsteadiness of change of aerodynamic forces and two-dimensionality of atmospheric turbulence, the damageability reduction in 35–40% was obtained in comparison with the initial computations. It was shown that the two-dimensionality of the atmospheric turbulence and the unsteadiness of aerodynamic forces change must be considered together.

The spectral characteristics of the strain-stress state at the operation of different aerodromes were obtained and were used to evaluate durability of airframe structure and landing gear at the certification of the single-engine airplane AVIATIKA-890. To evaluate the structural survivability the simulation of stresses realizations was done.

Influence of unsteadiness on the loading of pylons and engines of an airplane with high aspect ratio wing is considered. For the most loaded external pylon the load factor n_z reduction is approximately 20%. For the internal engine the amplitude value of the generalized gust force in natural mode determining load factor n_z grows in a wide range of the reduced frequencies and at appropriate frequency it is 185% of the steady value. It should be mentioned that despite the growth of side load factors on the internal engine in 75%, the reduced in 20% load factors on the external engine remain the dominating in strength conditions. For vertical load factors the decrease in 25–30% has been obtained.

The medium-range jet airliner early development stage the wing design was done using the data obtained earlier with aid of «PARUS-INT» system for structure of the regional passenger airliner prototype. The evaluation of the wing structure strain-stress state and weight at complex design for static and dynamic cases was obtained in a short time period. A possibility of a complex static strength and service life design was shown. The service life design required the development of specialized «PARUS-INT» subsystem of computation of repeated loading, damageability and durability.

At the early design stage the evaluation of RRJ life service was performed in accordance with the requirements of Aviation Regulations. A set of calculation was fulfilled using the aircraft dynamic model. The results showed that at given crack growth the sufficient resource is ensured.

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