DESIGN ISSUES OF DYNAMICS OF HELICOPTER MAIN ROTOR BLADES UNDER THE INFLUENCE OF WIND IN THE PARKING LOT

Maksim V. Kargaev*, Yuri M. Ignatkin**

Moscow Aviation Institute (National Research University), 4, Volokolamskoe shosse, Moscow, A-80, GSP-3, 125993, Russian Federation.

e-mail: kargaev_mv@mail.ru*, k102@mai.ru**.

Abstract

The paper addresses the issue of designing helicopter main rotor blades exposed to wind in the parking lot. Necessary wind conditions have been determined to be taken into account when designing the blades. In addition, it shows a method for calculating dynamic stresses in a moored and non-moored helicopter blade blown by a wind flow. The obtained nonlinear partial differential equation by the Galerkin`s method is reduced to a system of differential equations. The Newmark`s method is used for its numerical integration. Formulas are obtained for calculating boundaries of the regions of dynamic instability of moored and non-moored rotor blades of the helicopter. Based on the equations of parametric oscillations of blades, the critical frequencies and excitation coefficients corresponding to the main and two side resonances are determined.

1. INTRODUCTION

Currently, the problem of protecting the main rotor blades of the helicopter from damage associated with wind in the parking lot remains unsolved. Limits of stresses in the blades is achieved at operational wind speeds [1, 2]. While used on most types of helicopters mooring does not ensure their safety. Limit wind speed, the condition of absence of flapping over the lower emphasis of horizontal hinge, moored of the blade only slightly higher than for non-moored [2].

The possibility of a static loss of stability of rotor blades of the helicopter under the action of the wind was obtained earlier [3]. Every time under the action of static loads of a particular kind, possible loss of static stability under the action of oscillation loads, possible loss of dynamic stability.

Wind load is parametric in respect to the transverse deformations of the blade. Parametrically excited oscillations, which is the companion of the forced oscillations, similar appearances, and therefore sometimes qualify as normal resonance. However, if the normal resonance forced oscillations occurs when the coincidence of the own and forced frequency, then parametric resonance occurs when the coincidence of the exciting frequency with twice the natural frequency. The region of instability, lying near so exciting frequency, is the most dangerous and has the greatest practical significance. This area is also known as the main region of dynamic instability. Another significant difference parametric resonance is the possibility of excitation of oscillations at frequencies smaller than the frequency of the main resonance. Finally, qualitatively new in the parametric resonance is the presence of solid areas of excitation (regions of dynamic instability).

This fact necessitates the adoption of measures to prevent the damage stops and non-rotating blades, when they are exposed to wind or slipstream from the main rotor rotary-wing apparatus, which produces taxiing nearby or performs landing.

Designers need to have a clear understanding of the phenomenon of wind loading, as well as a mathematical model that allows with reasonable accuracy to calculate the stress-strain state of the blade.

2. DESIGN ISSUES

The process of creating the main rotor is performed in a certain sequence. At the initial stages of design, the main parameters of the main rotor are selected. The blade design stage consists of iteratively repeated design and verification calculations. In the course of design calculations, the materials of the structural elements of the blade, the shape of the spar are selected taking into account previous experience and existing design, technological and operational restrictions; the formation of sections of the spar along the chord and radius of the blade on the basis of a static calculation of the blade. Verification calculations assume correction of the mass-stiffness characteristics of the blade.

At present, the static strength of the main rotor blades is mainly provided by meeting the following conditions:

- the stresses acting in the cross-sections of the blade from centrifugal forces should not exceed the permissible stresses;

- on the safety of the static overhang of the blade in the parking lot, which does not exceed what is possible for design reasons, under the action of mass forces of the blade;

- the stresses acting in the blade cross-sections at the parking lot from the forces of the blade's own weight should not exceed the permissible stresses.

The presence of wind in the parking lot makes it necessary to take into account additional conditions:

- proving a static deflection of the blade in the parking lot, not exceeding possible for design reasons, under the influence of mass forced of the blade and wind loading (lower bound may be a safe distance from the end of the blade to the elements of the airframe of the helicopter, for example, up to its end of the beam, or the distance to the ground, if the parking location of the blades on the azimuth, while on which is excluded the possibility of their trajectory intersects with any of the elements of the airframe of helicopter);

- the stresses acting in the blade cross-sections at the parking lot from the mass forces of the blade and wind loading should not exceed the permissible stresses for two cases: when the blade is bent up (with or without mooring), when the blade bends down;

- ensuring the static stability of the blade in the helicopter parking lot in the operational range of wind speeds.

In addition to static conditions, dynamic wind conditions must also be checked:

- providing tuning from resonant forced oscillations in the parking lot under the influence of wind;

- ensuring dynamic stability on the blade in the operational range of wind frequencies and speeds;

- ensuring the permissible fatigue strength level of constant and equivalent variable stresses in the blade from the action of wind;

- ensuring the required flight life and service life of blade taking into account the impact of wind on the parking lot.

Currently it is possible to meet all the above conditions by using composite materials. It is known that the efficiency of using composite materials in power elements of blades is determined by a number of advantages of these materials in comparison with metals. The use of composite materials allows us to form mass – stiffness characteristics of the blade (bending and torsional) in a directional manner due to the appropriate orientation of the composite fibers, taking into account the complex nature of its loading.

The adjustable anisotropy of the material allows to create the required stiffness within the specified strength parameters, including obtaining the necessary structural and damping parameters. The frequency of natural oscillations of the blade can be changed not only by mass redistribution, but also by the choice of reinforcing fibers having a low or high elastic modulus, including their hybridization (mixing), the degree of reinforcement and the orientation of the reinforcing fibers relative to the axis of the blade.

3. MODELLING

Determine the tension in the blades of the rotor is inhibited when blowing the helicopter parked, a horizontal wind flow. Moored main rotor blades of helicopter in the parking lot are shown in figure 1. Consider the case when the speed of the wind flow is directed at an angle to the longitudinal axis of the helicopter.

The position of the blade is determined by the azimuthal angle measured in the direction of rotation of the rotor, with its zero value corresponds to the position of the blade along the longitudinal axis of the helicopter end back.

The range of variation of the azimuthal angle, limit area from 0˚ to 180˚, counting it is in the direction of rotation of the rotor during the consideration of the modes of the blower blades with a forward edge and against the direction of rotation of the rotor, in consideration of the blowing modes of the blade trailing edge. In this case, the sliding angle will vary from 90˚ to -90˚.

When determining the stresses in the rotor blades of the helicopter, located in the parking lot under the influence of the wind, imagine the blade in the form of a beam of variable cross-section. The parameters of this beam will be considered continuously distributed along the length of the blade.

4. METHODS

4.1. Stress calculation method based on nonlinear loading model

In [4], a nonlinear partial differential equation of a moored blade under non-stationary wind loading is obtained:

$$m\ddot{y}+(EIy'')''+\frac{3}{2}(EIy''y'^2)''-(Ty')'+ \\ +(N^*_{mr}y')'-Y_n(1-\frac{y'^2}{2})+mg+w_{mr}\sin\gamma_{mr}=0. \quad (1)$$

Distributed aerodynamic force acting on the blade is determined by the expression:

$$Y_n=\frac{\rho V^2}{2}C_n b\cos(\chi+\chi_b)^2,$$

where $C_n=f(\alpha_r,M)$ - is determined by the results of the circular purging profiles the Mach number $M\le 0.3$, and α_r, considering the vertical velocity of the cross sections of the blade, defined by the expression:

$$\alpha_r=\theta_0-\theta_1\sin\psi-\theta_2\cos\psi+(y'+\beta_0)tg(\chi+\chi_л)+ \\ +\Delta\varphi_t-k_\beta y'(0)-\gamma\frac{\cos\psi}{\cos(\chi+\chi_л)}-\frac{\dot{y}}{V\cos(\chi+\chi_л)}-\Delta\alpha_v.$$

To find the deformations and internal forces (bending moments and stresses), we apply the method of B. G. Galerkin [5, 6]. In this approach, the partial differential equation (1) reduces to the system of differential equations that are related only through the aerodynamic forces and the force of the tension of the mooring rope. Therefore, if at any time, is possible to calculate the deformation of the blade in any given mode shape are determined independently, because these forms are orthogonal. The solution of equation (1) will represent decomposition into natural modes of oscillation of the blade:

$$y=\sum_{j=0}^{n}\delta_j y_j, \quad (2)$$

where n number of higher mode shapes of the blade considered in the solution; y_j – normalized form j tone of natural oscillations of the blade; δ_j – some time functions (the coefficients of deformation of the blade), which in the present method adopted for the generalized coordinates of the system. The definition of the law δ_j of change in time is calculated.

Twice differentiating the expression (2) at the time, you will get:

$$\dot{y}=\sum_{j=0}^{n}\dot{\delta}_j y_j, \qquad \ddot{y}=\sum_{j=0}^{n}\ddot{\delta}_j y_j. \quad (3)$$

Substitute (2) and (3) into equation (1). Further, all terms of equation (1) are alternately multiplied by y_j and integrated along the length of the blade. Because of the orthogonality of natural modes [5, 6], we get the system of differential equations, related only through the aerodynamic load and the tensile force of the mooring rope:

$$m_j\ddot{\delta}_j+C_j\delta_j=A_{3j}\delta_j^3+A_{2j}\delta_j^2+A_{0j}. \quad (4)$$

Here:

$$A_{3j}=-\frac{3}{2}\int_0^l EI(y'_j y''_j)^2 dr,$$

$$A_{2j}=-\frac{1}{2}\int_0^l Y_n y_j y'^2_j dr,$$

$$A_{0j}=\int_0^l Y_n y_j dr-\int_0^l y_j mg dr-\int_0^l y_j w_{mr}\sin\gamma_{mr} dr,$$

$$m_j=\int_0^l m y_j^2 dr.$$

It is known [5, 6] that the frequency j tone of natural oscillations of the blades can be determined according to the formula:

$$p_j=\sqrt{\frac{C_j}{m_j}}=\sqrt{\frac{C_{EI_j}+C_{Y_j}+C_{Nmr_j}}{m_j}}.$$

Therefore, equation (4) it is convenient to transform, attributing all members to the values m_j. Take into account the friction forces in the blade, for which we introduce linear damping [7]. The damping factor ε is determined from the experiment. Then they can be written as:

$$\ddot{\delta}_j+2\varepsilon\dot{\delta}_j+p_j^2\delta_j=\frac{A_{3j}}{m_j}\delta_j^3+\frac{A_{2j}}{m_j}\delta_j^2+\frac{A_{0j}}{m_j}. \quad (5)$$

For the numerical integration of equations (5) we use the implicit method Newmark [8]. It is known [9] that the ideal parameter values, in which achieved unconditional stability of the method and the best accuracy are the following values: α=0.25 and β=0.5. We rewrite equation (5) with respect to the highest derivative, then we get:

$$\ddot{\delta}_j=-2\varepsilon\dot{\delta}_j-p_j^2\delta_j+\frac{A_{3j}}{m_j}\delta_j^3+\frac{A_{2j}}{m_j}\delta_j^2+\frac{A_{0j}}{m_j},$$

or in general: (6) $\ddot{\delta}_j = f(t, \delta_j, \dot{\delta}_j).$

Let us consider a dynamic process on a single step of integration. Let at time t_i all kinematic parameters and all components of equations (6) are known, and you need to determine their values at time t_{i+1}= t_i+ Δt_i. Since the value $\ddot{\delta}_{j,i}$ is not known in advance, the solution must be found through every step by the iterations. Iteration is also necessary to account for the changes in aerodynamic forces and the tension of the mooring rope for the integration step. The following is the recurrence relation for determining *k* iteration on step of *i*:

(7) $$(\dot{\delta}_{j,i})_k = A_{i-1} + (\ddot{\delta}_{j,i})_{k-1}\frac{\Delta t_i}{2}, \quad k > 1;$$

(8) $$(\delta_{j,i})_k = B_{i-1} + (\dot{\delta}_{j,i})_k \frac{\Delta t_i}{2};$$

(9) $$(\ddot{\delta}_{j,i})_k = f(t_i, (\delta_{j,i})_k, (\dot{\delta}_{j,i})_k),$$

$$A_{i-1} = \dot{\delta}_{j,i-1} + \ddot{\delta}_{j,i-1}\frac{\Delta t_i}{2}, \;\; B_{i-1} = \delta_{j,i-1} + \dot{\delta}_{j,i-1}\frac{\Delta t_i}{2}.$$

This iterative process is independent of initial conditions, since it requires the use of a special formula to determine at each time step of the first approximation [8]. The solution starts with defining the initial acceleration (at time *t*=0) from equations (6), which gives:

(10) $$\ddot{\delta}_{j,0} = f(0, \delta_{j,0}, \dot{\delta}_{j,0}).$$

Defining $\ddot{\delta}_{j,0}$ from expression (10), one can begin to compute the iteration for the first step, finding an approximate expression for $\dot{\delta}_{j,1}$ the extrapolation using the Euler formula:

$$(\dot{\delta}_{j,1})_1 = \dot{\delta}_{j,0} + \ddot{\delta}_{j,0}\Delta t_1.$$

Then the first approximation for $\delta_{j,1}$ and $\ddot{\delta}_{j,1}$ are respectively by the formulas (8) and (9). All subsequent iterations in the first time step consists in the repeated use of formulas (7), (8) and (9). Each iteration calculates the aerodynamic forces and the tension force of mooring tether, which depends on its current length.

Note that the initial length of the mooring rope is determined based on a function of the deflection of the blade by forces of own weight of the blade and force pre-tension of the mooring rope.

As the stopping criterion of the iterative procedure and go to the next time interval will use the following:

$\left|(\delta_{j,i})_k - (\delta_{j,i})_{k-1}\right| < \varepsilon_k,$ where ε_k – small value.

During movement of the blade under wind loads, depending on whether the blade is on the limiter of overhang or walked away from him, in the expressions (2) and (3) should be used in the console articulated mode shapes of the blade. The coefficients of deformation determined from the system of differential equations (5), will also fit swivel or cantilever forms. Therefore, must comply with the condition of conjugation of solutions at the time of the change of the cantilever forms the hinge, and vice versa. It can be obtained by equality of the displacements, velocities and accelerations of the movement of the blade at the moment of changing forms.

The accuracy of determining the shapes of the deformations depends on the number of natural modes considered in the calculation. If you know the coefficients of deformation, it is easy to determine bending moments and bending stresses in the blades. They are defined by the formulas:

(11) $$M = \sum_{j=0}^{n} \delta_j M_j, \quad \sigma = \sum_{j=0}^{n} \delta_j \sigma_j.$$

Here M_j and σ_j are the shape of distributions of bending moments and stresses in the normalized deformation of the blade by the tone of her own hesitation. Included in the formula (11) the values are subject to the relations:

$$\sigma = \frac{M}{W}, \quad \sigma_j = \frac{M_j}{W},$$

where W the moment of bending resistance of cross-sections of the blade.

4.2. The definition of the boundaries of the dynamic instability

For the case of harmonically varying wind flow have equation represent a version of the Mathieu equation with a nonlinear function of the deflections, velocities and accelerations describing the parametric oscillations of the blade under the action of a harmonically varying wind flow. Distributed aerodynamic force acting on the blade is determined by the expression:

$$Y_n = qC_n b\cos(\chi + \chi_л)^2 =$$
$$= (q_0 + q_t\cos\theta t)C_n b\cos(\chi + \chi_л)^2.$$

We get the system of differential equations:

(12) $$\ddot{\delta}_j + \Omega_j^2(1 - 2\mu_j\cos\theta t)\delta_j + \Psi(t, \delta_j, \dot{\delta}_j, \ddot{\delta}_j) = 0.$$

Region indefinitely increasing solutions are separated from the regions of stability of the periodic solutions with period *T* and *2T* [7]. The existence of periodic solutions and their decomposition in Fourier series are known in advance. So we seek the solution of system at the boundaries of the even (periodic solutions with a period multiple of *T*) and odd (periodic solutions with a period multiple of *2T*) regions of the dynamic instability directly in the form of trigonometric series. To find the boundaries of the dynamic instability it is necessary to consider the homogeneous system the corresponding steady-state periodic oscillations.

On the border of even instability regions, the solutions of system (12) are searching for each function δ_j in the form of a number:

$$\delta_j(t) = b_{0,j}(t) + \sum_{k=2,4,6}^{\infty} (a_{k,j}(t)\sin\frac{k\theta t}{2} + b_{k,j}(t)\cos\frac{k\theta t}{2}),$$

where $b_{0,j}(t), a_{k,j}(t), b_{k,j}(t)$ – slowly changing function of time (the increment of these functions over the period is small compared with their average during the period).

On the border of odd instability regions, the solutions of system (12) are searching for each function δ_j in the form of a number:

$$\delta_j(t) = \sum_{k=1,3,5}^{\infty} (a_{k,j}(t)\sin\frac{k\theta t}{2} + b_{k,j}(t)\cos\frac{k\theta t}{2})\cdot$$

To find the boundaries of the dynamic instability it is necessary to consider the homogeneous systems the corresponding steady-state periodic oscillations [7]. Then:

$$\frac{d^2 a_{k,j}}{dt^2} = \frac{d^2 b_{k,j}}{dt^2} = \frac{da_{k,j}}{dt} = \frac{db_{k,j}}{dt} = 0,$$
$$\Psi_{0,j} = \Phi_{k,j} = \Psi_{k,j} = 0.$$

For the first and third regions of instability, from (12), we obtain the system of algebraic equations:

$$(13)\quad \begin{cases} [\Omega_j^2 - \frac{9\theta^2}{4}]a_{3,j} - 3\varepsilon\theta b_{3,j} - \Omega_j^2\mu_j a_{1,j} = 0 \\ [\Omega_j^2(1+\mu_j) - \frac{\theta^2}{4}]a_{1,j} - \varepsilon\theta b_{1,j} - \Omega_j^2\mu_j a_{3,j} = 0 \\ [\Omega_j^2(1-\mu_j) - \frac{\theta^2}{4}]b_{1,j} + \varepsilon\theta a_{1,j} - \Omega_j^2\mu_j b_{3,j} = 0 \\ [\Omega_j^2 - \frac{9\theta^2}{4}]b_{3,j} + 3\varepsilon\theta a_{3,j} - \Omega_j^2\mu_j b_{1,j} = 0. \end{cases}$$

For the second region of instability, from (17) we get the system of algebraic equations:

$$(14)\quad \begin{cases} [\Omega_j^2 - \theta^2]a_{2,j} - 2\varepsilon\theta b_{2,j} = 0 \\ \Omega_j^2 b_{0,j} - \Omega_j^2\mu_j b_{2,j} = 0 \\ 2\varepsilon\theta a_{2,j} - 2\Omega_j^2\mu_j b_{0,j} + [\Omega_j^2 - \theta^2]b_{2,j} = 0. \end{cases}$$

As is known, the system of linear homogeneous equations has a nonzero solution only if equal to zero the determinant composed of coefficients of the system. This provision remains valid in the case when the system contains an infinite number of unknowns. So, the condition for the existence of periodic solutions of equations (13) and (14) is the equality to zero of the determinant of the resulting homogeneous systems. Thus, obtain the equation of the critical frequencies connecting the frequency of wind with the natural frequency of the blade and magnitude of the wind speed. Under the critical frequency refers to the frequency of the wind matching the boundaries of the regions of instability.

To determine the boundaries of the main region of instability should be considered in equation (13). Hold in them the determinant of the first order (central elements) and equating it to zero we get:

$$(15)\quad -\Omega_j^4\mu_j^2 + \Omega_j^4 - \frac{1}{2}\Omega_j^2\theta^2 + \frac{1}{16}\theta^4 + \varepsilon^2\theta^2 = 0.$$

Solving equation (15) with respect to θ will get:

$$(16)\quad \theta_{*1,j} = 2\Omega_j\left(1 - \frac{1}{2}\left(\frac{\Delta_j}{\pi}\right)^2 \pm \pm\sqrt{\mu_j^2 - \left(\frac{\Delta_j}{\pi}\right)^2 + \frac{1}{4}\left(\frac{\Delta_j}{\pi}\right)^4}\right)^{1/2}.$$

Here and further $\Delta_j = \frac{2\pi\varepsilon}{\Omega_j}$. Examine the expression (16). While the domestic expression under the radical is positive, this formula gives for the critical frequency of two real values corresponding to the two boundaries of the main region of instability. Limiting case determines the minimum value of the coefficient of excitation, which may experience sustained oscillations:

$$(17)\quad \mu_{*1,j} = \frac{\Delta_j}{\pi}\sqrt{1 - \left(\frac{\Delta_j}{2\pi}\right)^2}.$$

Formula (17) shows that the larger the attenuation, the greater the amplitude of the external force (wind) is required to cause dynamic instability of the blade. Note that the effect of decay affects to an appreciable extent only at small excitation coefficients.

Define the boundaries of the second region of instability, which would equate to zero the determinant of the second order homogeneous system (14):

(18) $$\frac{-2\pi^2\Omega_j^4\mu_j^2+2\pi^2\theta^2\Omega_j^2\mu_j^2+\Delta^2\theta^2\Omega_j^2}{\pi^2\Omega_j^4}+ +\frac{\pi^2\Omega_j^4-2\pi^2\theta^2\Omega_j^2+\pi^2\theta^4}{\pi^2\Omega_j^4}=0.$$

Solving equation (18) with respect to θ will get:

$$\theta_{*2,j}=\Omega_j\left(1-\mu_j^2-\frac{1}{2}\left(\frac{\Delta_j}{\pi}\right)^2\pm \pm\sqrt{\mu_j^4-\left(1-\mu_j^2\right)\left(\frac{\Delta_j}{\pi}\right)^2+\frac{1}{4}\left(\frac{\Delta_j}{\pi}\right)^4}\right)^{1/2}.$$

The critical value of the coefficient of excitation is:

$$\mu_{*2,j}=\sqrt{\frac{\Delta_j}{\pi}-\frac{1}{2}\left(\frac{\Delta_j}{\pi}\right)^2}.$$

Finally, define the boundaries of the third region of instability, which would equate to zero the determinant of the third order homogeneous system (13):

(19) $$81\pi^4\mu_j^4+64\pi^4\xi_j^2-144\pi^4\mu_j^2\xi_j-27\pi^2\Delta_j^2\mu_j^2+ +9\pi^2\Delta_j^2\xi_j^2-81\pi^4\mu_j^2\xi_j^2+9\Delta_j^4+64\pi^2\Delta_j^2=0.$$

Here: $\xi_j=\left(1-\frac{9\theta^2}{4\Omega_j^2}\right)$.

Solving equation (19) with respect to with an account of the early designated, will receive:

$$\xi_j=\frac{1}{\left(\frac{\Delta_j}{3\pi}\right)^2+\frac{64}{81}-\mu_j^2}\cdot\left[\frac{8}{9}\mu_j^2\pm\left(\mu_j^6-\left(\frac{\Delta_j}{\pi}\right)^2\left[\frac{4}{9}\mu_j^4-\right.\right.\right. \left.-\frac{4}{27}\mu_j^2\left(\frac{\Delta_j}{\pi}\right)^2-\frac{256}{243}\mu_j^2+\frac{1}{81}\left(\frac{\Delta_j}{\pi}\right)^4+ \left.\left.\left.+\frac{128}{729}\left(\frac{\Delta_j}{\pi}\right)^2+\frac{4096}{6561}\right]\right)^{1/2}\right],\quad \theta_{*3,j}=\frac{2}{3}\Omega_j\sqrt{1-\xi_j}.$$

Limiting case:

(20) $$\mu_j^6-\left(\frac{\Delta_j}{\pi}\right)^2\left[\frac{128}{729}\left(\frac{\Delta_j}{\pi}\right)^2-\frac{4}{27}\mu_j^2\left(\frac{\Delta_j}{\pi}\right)^2- -\frac{256}{243}\mu_j^2+\frac{1}{81}\left(\frac{\Delta_j}{\pi}\right)^4+\frac{4}{9}\mu_j^4+\frac{4096}{6561}\right]=0.$$

Analytical solution of equation (20) is too bulky, so is not given here. However, the critical value of the coefficient of excitation can easily be found numerically.

5. NUMERICAL RESULTS

In accordance with the created method is composed of the program of calculation of parameters of stress-strain state moored and non-moored of the rotor blades of the helicopter and algorithmic programming language Maple under the action of the wind in the parking lot. The object of the study is the rotor blade of helicopters, which by its aeroelastic characteristics belongs to the number of blades more susceptible to the damaging effects of wind.

5.1. The stress-strain state of blade

All the calculated dependences obtained for the blades, located on the azimuth ψ = 90°, angles of attack θ_0= -10° and 5° when the neutral position of the ring of the swashplate. The wind speed changes, given in figure 2 to the laws. Thus for the calculation of the dependencies V_{max}= 25 m/s (curve 1) the selected angle θ_0= -10° and V_{max}= 21 m/s (curve 2) – angle θ_0= 5°. Calculation moored of the blade was carried out on both the dependency of wind speeds for the existing staff when a force of pre-tension of the mooring rope 0 N and 100 N.

The results are shown in figures 3..6, where the designations of the curves correspond to the calculated cases: 1 – θ_0= -10° and N_{mr}= 100 N; 2 – θ_0= -10° and N_{mr}= 0 N; 3 – θ_0= 5° and N_{mr}= 100 N; 4 – θ_0= 5° and N_{mr}= 0 N; 5 – θ_0= -10° the blade is non-moored; 6 – θ_0= 5° the blade is non-moored; 7 – the curvature of the blade under its own weight.

The change in the deflection of the end of the blade is shown in figure 3. The blade is the point in time corresponding to the greatest deviation of an end of the blade. Have the location of the maximum deformation of the blade and spar are of the greatest bending stresses. Stress distribution along the length of the blade, corresponding to the greatest deflection of the end of the blade, for the given loading conditions is shown in figure 4. Based on time-varying of the length of the mooring rope and the force of its tension, for cases moored of the blade shown in figures 5 and 6.

5.2. The regions of dynamic instability

Calculations are performed for a horizontal wind flow. As the initial equilibrium position accepted the position of overhang of the blade under the action of its own weight. The location of the first three regions of the dynamic instability for non-moored blades having different attenuation coefficients ε shown in figure 6.

Region in which initial equation has infinitely growing solutions is shaded. As can be seen from figure 6, the region of instability is a significant part of the parameter plane. So, for the solution of the question of the dynamic stability of the blade need to find in the plane ($\mu,\ \theta_* / 2\Omega$) of the point corresponding to this ratio. If the point falls in the unshaded region, so the initial form of the blade is dynamically stable. If the point will be in the shaded region, any initial deviation, the blades will indefinitely grow with time, i.e. will have the dynamic instability of the blade. It is seen that the presence of damping makes it impossible for the onset of resonance at sufficiently low coefficients of excitation. Note that the effect of damping is not essential for the main region of instability, becoming highly visible for the side areas.

6. CONCLUSIONS

Taking into account the results obtained in this study will allow to design the rotor blades of the helicopter, providing the required safety standards of operation, at specified operating speeds of the wind flow. For this purpose:

1 Necessary wind conditions have been determined to be taken into account when designing the blades.

2 The proposed method of calculating the stresses in moored and non-moored helicopter blades blown by wind flow.

3 Significant stress values, caused by the wind, and the presence of the helicopter in the Parking position, for more than 80% of the time of operation, require developers of helicopters to take into account the effects of wind in determining the flight life of the blade.

4 The formulae are presented to determine the boundaries of the main and two side regions of dynamic instability for moored and non-moored of the rotor blades of the helicopter.

5 The dependences for the critical values of the excitation coefficients of the main and two side regions of dynamic instability are determined.

7. REFERENCES

[1] Kargaev M.V., Mironenko L.A. Bending stresses computation in a helicopter unmoored rotor blade blown about by the wind flow. *Aerospace MAI Journal*, 2018, vol. 25, no 3, pp. 34-43 (In Russian).

[2] Kargaev M.V. Stresses computing in the main rotor blade based on the nonlinear loading model under static wind impact. *Aerospace MAI Journal*, 2019, vol. 26, no 2, pp. 34-42 (In Russian).

[3] Kargaev M.V., Mironenko L.A. Static stability of a helicopter main rotor blade at the parking affected by wind. *Aerospace MAI Journal*, 2018, vol. 25, no. 2, pp. 43-51 (In Russian).

[4] Kargaev M.V. Dynamic stresses computing in the main rotor blade based on the non-linear loading model under unsteady wind impact. *Al-Russian scientific-technical journal Polyot, 2020 vol. 4, pp. 52-60* (In Russian).

[5] Mil' M.L., Nekrasov A.V., Braverman A.S., Grodko L.N., Leikand M.A. *Vertolety raschet i proektirovanie* (Helicopters, calculation and design), Moscow, Mashinostroenie, 1966/1967, (457+424) p. (In Russian).

[6] Mikheev R.A. *Prochnost' vertoletov* (Strength of helicopters), Moscow, Mashinostroenie, 1984, 280 p. (In Russian).

[7] Bolotin V.V. *Dinamicheskaya ustoichivost' uprugih system* (Dynamic stability of elastic systems), Moscow, Gostekhizdat, 1956, 600 p. (In Russian).

[8] Timoshenko S. P., Young D. H., Weaver W. *Kolebaniya v injenernom dele* (Oscillations in engineering)/Ed. from English. L. G. Korneichuk; ed. by E. I. Grigoliuk, Moscow, Mashinostroenie, 1985, 472 p. (In Russian).

[9] Yudakov A. A., Boykov V. G. Numerical methods of integration of equations of motion of multicomponent mechanical systems, based on methods of direct integration of equations of dynamics the finite element method. Bulletin of Udmurt University. Mathematics. Mechanics. Computer science, 2013, no. 1. pp. 131-144 (In Russian).

COPYRIGHT STATEMENT

as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ERF proceedings or as individual offprints from the proceedings and for inclusion in a freely accessible web-based repository.

Acknowledgments: The reported study was funded by RFBR, project number 20-38-90028.

Figures

Figure 1: Moored main rotor blades under the influence of wind in the parking lot.

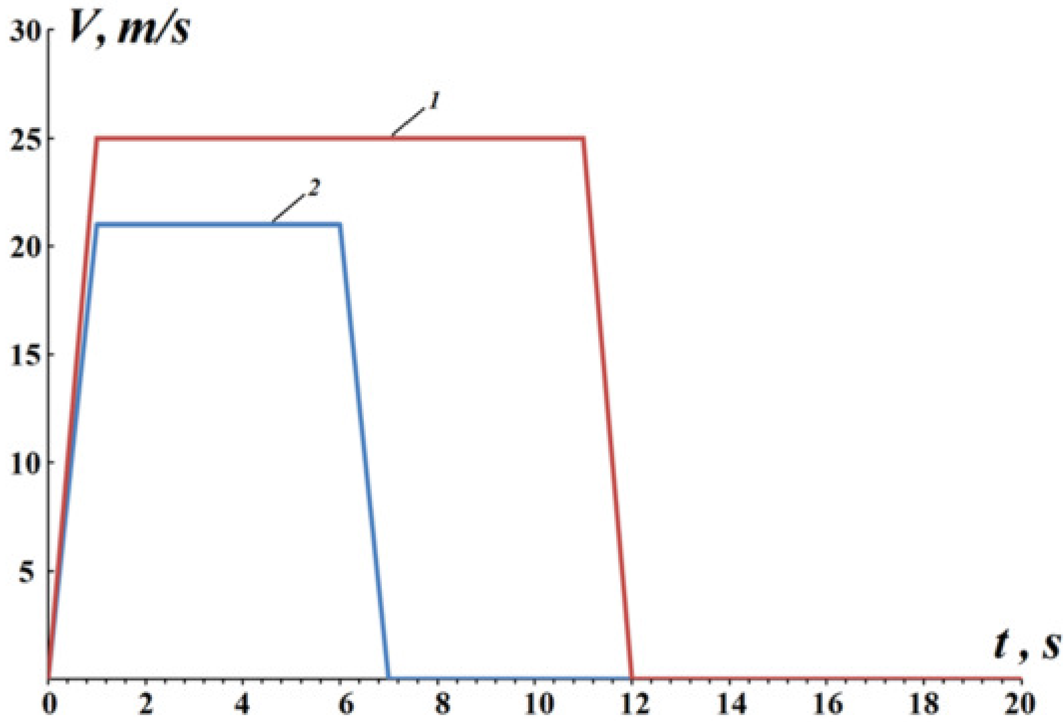


Figure 2: Dependences of changes in wind speed on time.

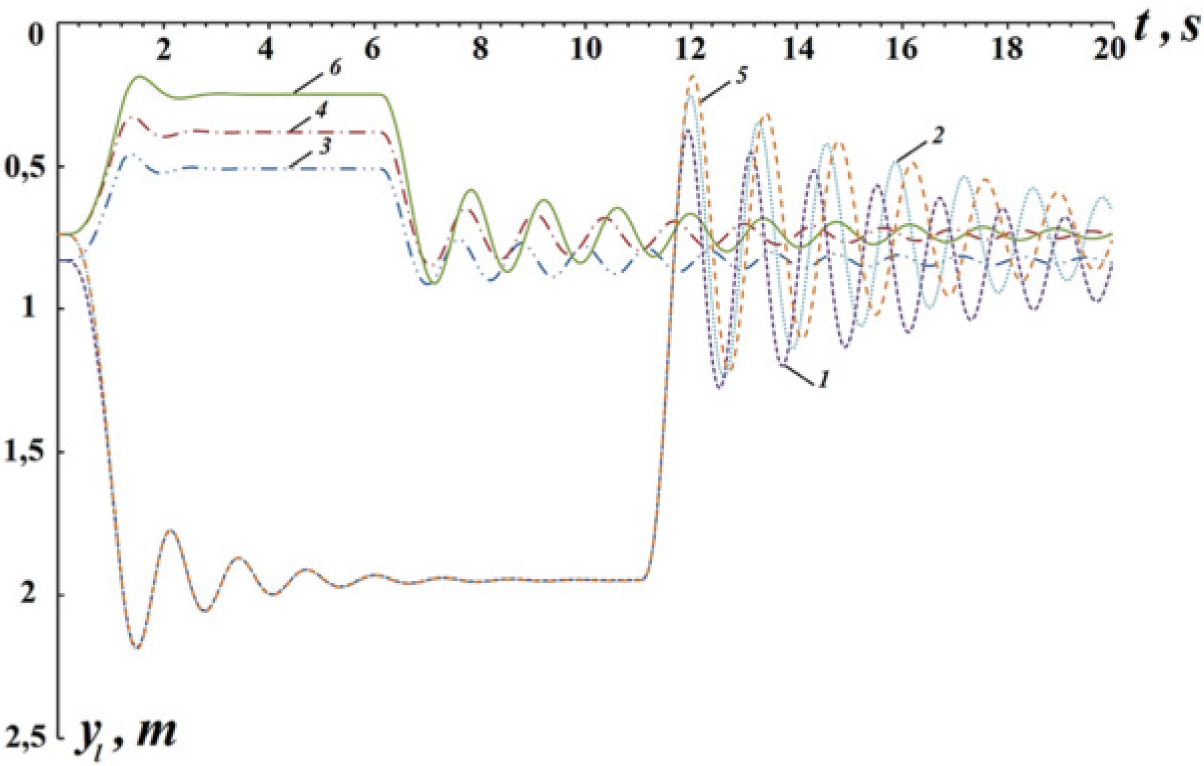


Figure 3: Dependences of changes in the deflections of the blade end on time for the specified calculation cases.

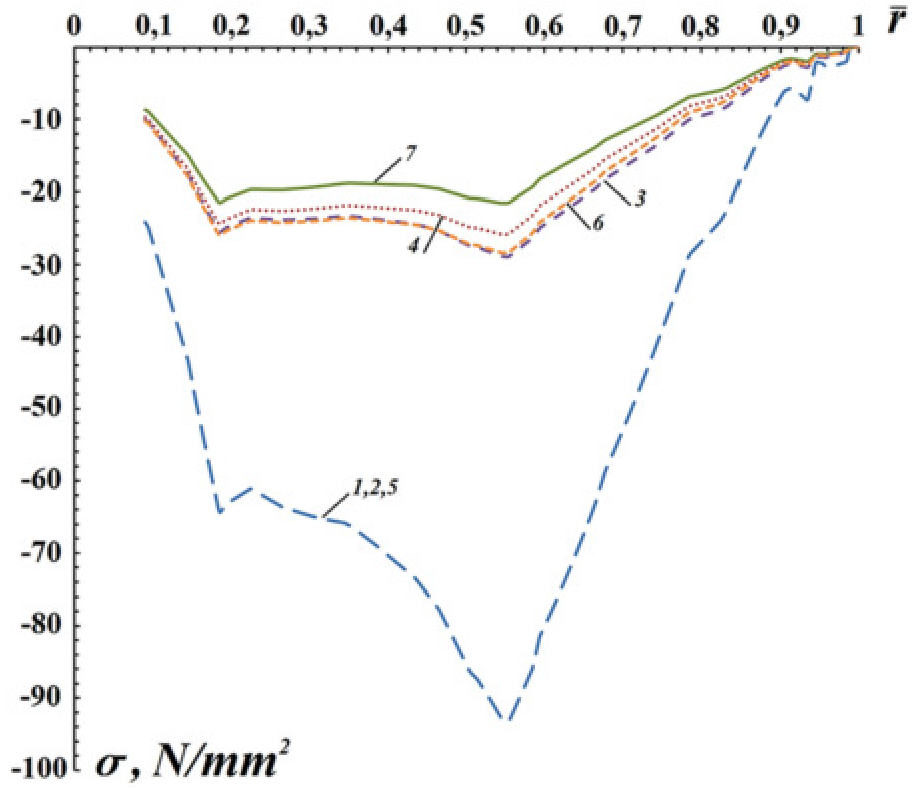


Figure 4: Stress distributions along the blade length corresponding to the greatest deflections of the blade end for the specified calculation cases.

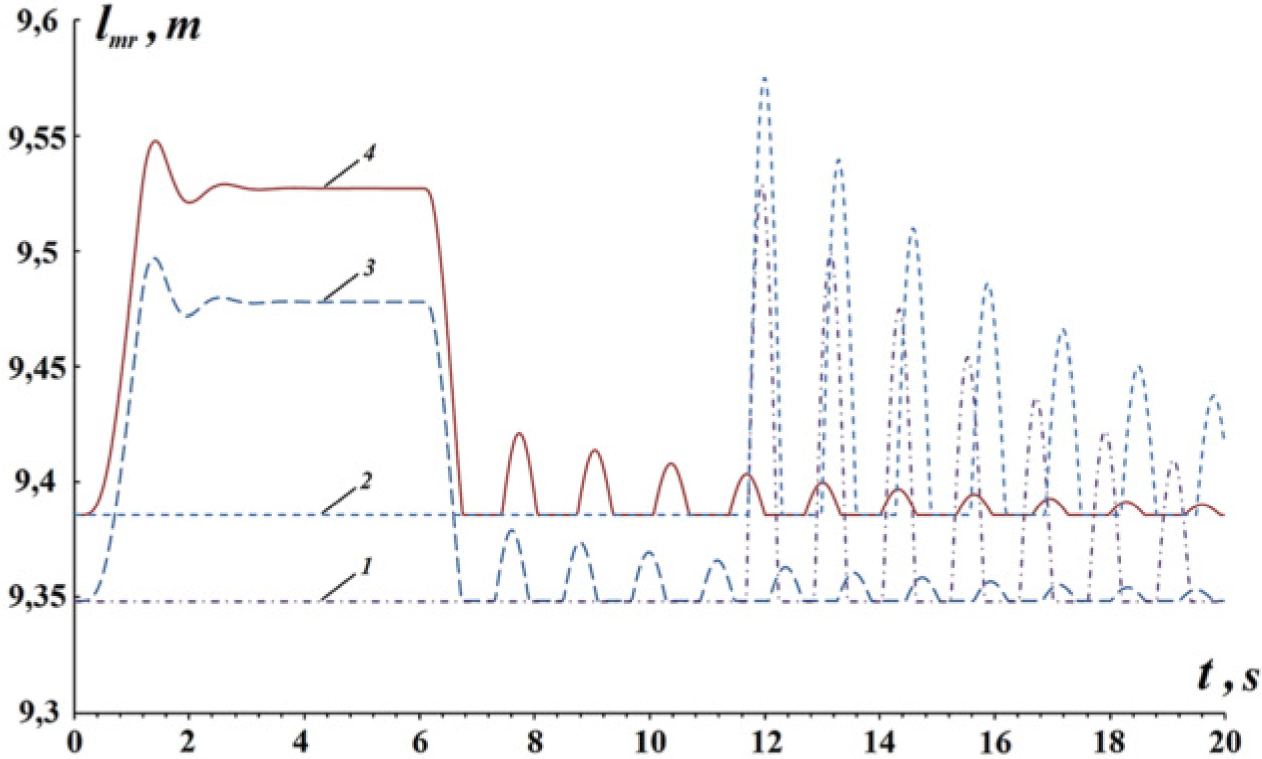


Figure 5: Dependences of changes in the mooring cable length on time for the specified calculation cases.

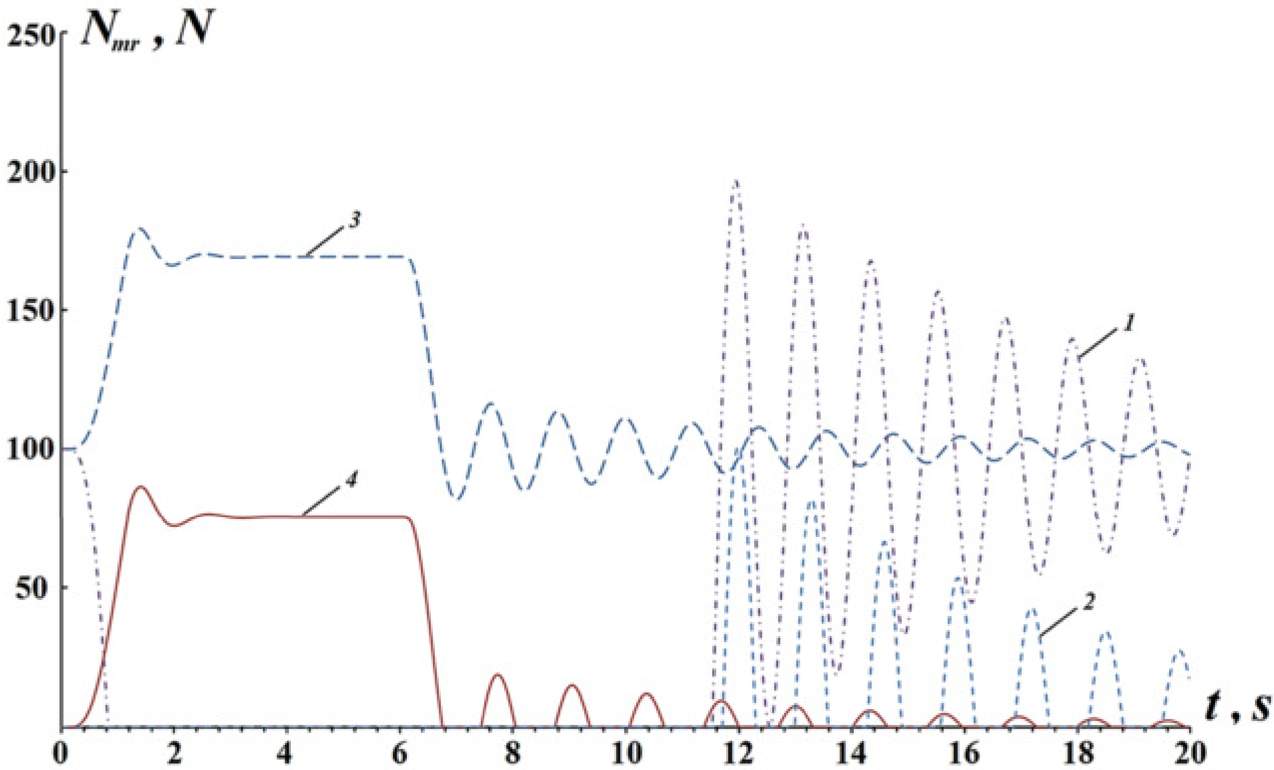
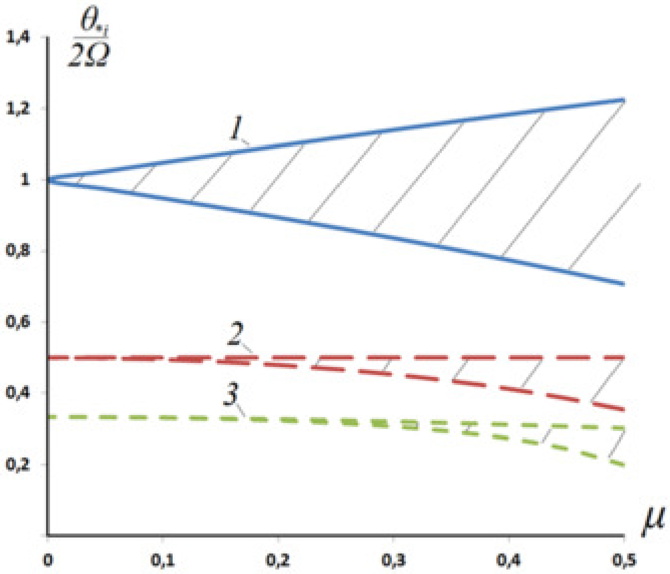
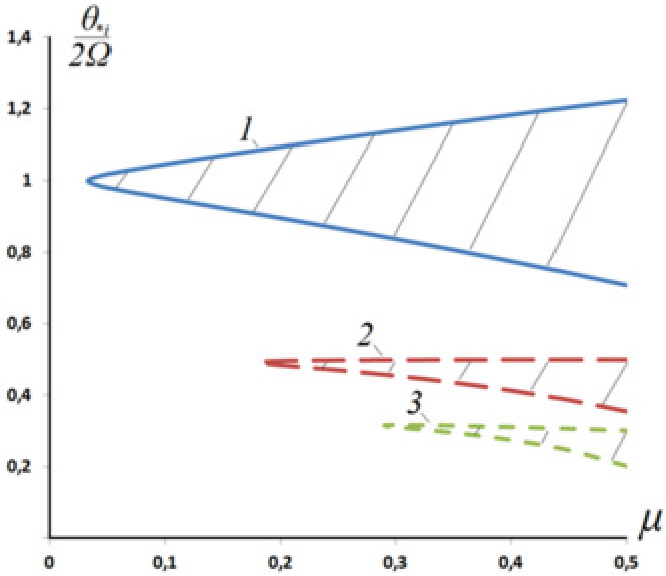


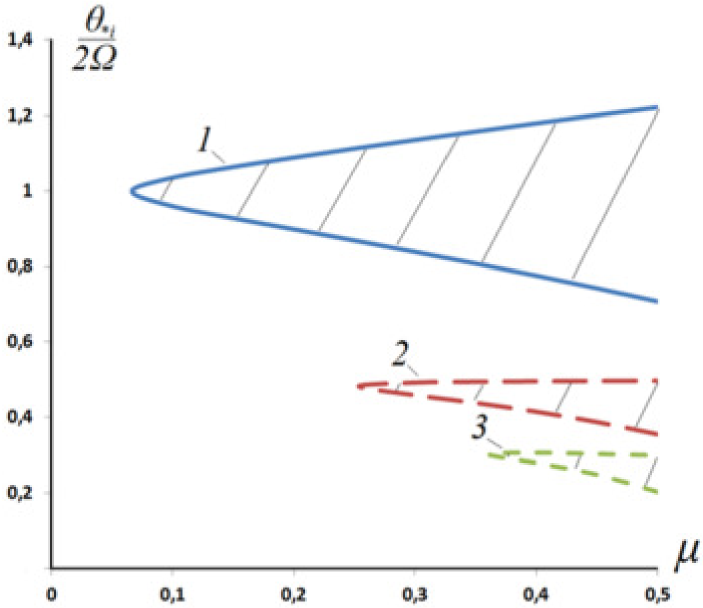
Figure 6: Dependences of changes in the mooring cable tension force on time for the specified calculation cases.



a) $\varepsilon = 0$



b) $\varepsilon = 0.1$



c) $\varepsilon = 0.2$

Figure 7: Location of the regions of dynamic instability:
1 - the main region, 2 - the second region, 3 - the third region.