ON THE DESIGN OF A HELICOPTER ROTOR BLADES EXPOSED TO THE WIND FLOW

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Abstract

The paper presents methods for calculating bending stresses in the rotor blade of a helicopter blown by a wind flow. The data obtained using the methods set out in this paper can be used in the design of the rotor blades and the determination of safe operation to ensure the required reserves for operational wind speeds. For the problem in the linear formulation, convenient calculation formulas for calculating deflections, angles of rotation and bending moments (stresses) directly through their values for the "rigid" blade are obtained. For the problem in the nonlinear formulation, a simple-to-implement computational scheme for solving the initial nonlinear equation of loading of the blade based on the method of successive perturbations of the parameters of V. V. Petrov is obtained. The results of calculations made for the tested rotor blades of the helicopter.

1. INTRODUCTION

One of the main problems facing the designer when creating a helicopter, still remains to ensure the strength of the rotor blade. When creating large diameter rotors, this problem is solved especially hard. The magnitude of the loads at which the destruction occurs, there are residual deformations or disturbed functioning of the blade should be greater than the maximum load possible in operation. Previously, when designing the rotor blades, in terms of ensuring static strength, limited its calculation under the influence of forces of its own weight. At the same time in the operation of helicopters, there are cases of damage to the units of the main and tail rotor after exposure to the storm wind.

These phenomena are possible due to the low intrinsic stiffness of the rotor blades, which makes them very sensitive to wind loading. Designers in the design of rotorcraft need to take measures to ensure protection from the effects of wind flow.

According to paragraph 29.675 b advisory circular AC 29-2C [1], which provides procedures for determining compliance with the requirements of the airworthiness, the design of the carrier system it is necessary to avoid overloading the stops and blades in terms of wind gusts in the parking lot or the thread of the rotor is close taxiing rotary-wing apparatus.

Therefore, from a practical point of view, when considering the impact of the wind on the non-rotating rotor blade of a helicopter in a parking lot, it is important to determine the most dangerous direction and the maximum permissible wind speed for the unmoored rotor blade at a given position of the helicopter in the parking lot. In [2], the most dangerous directions and the minimum critical speeds of the wind flow for the non-rotating rotor blade at a given position of the helicopter in the parking lot are determined. They are implemented on the modes of oblique blowing with negative sliding angles - when the blade end is located towards the wind flow. The minimum critical speed is achieved at a slip angle of -45˚. Therefore, increased stress values should be expected at these positions of the blade. The results of the calculation of the critical speed for the test blade are shown in figure 1.

The existence of the phenomenon of buckling in the bending of the blade under the influence of wind, as well as the fact that the calculated critical speeds were relatively small, confirm the need to calculate the stresses in the blade exposed to wind. Therefore, designers in the design of rotorcraft need to take measures to ensure protection from the effects of wind flow.

2. MODELLING

2.1. Problem statement

Determine the tension in unmoored the blades of the rotor is inhibited when blowing the helicopter parked, a horizontal wind flow. 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. Flow diagram of the rotor blade is shown in figure 2.

The range of variation of the azimuthal angle, limit area from 0˚ to 180˚, counting it's 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˚.

2.2. Basic assumption

When determining the stresses in the unmoored 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 (rod) of variable cross-section. The parameters of this beam will be considered continuously distributed along the length of the blade. In addition, we use the following assumptions.

1 Wind is considered as a steady flat-parallel horizontal flow.

2 The plane of the least stiffness of the blade coincides with the plane of the swing. Therefore, the blade will bend only under the action of forces acting in this plane.

3 When determining the loads in the plane of the swing torsional deformation of the blade is not taken into account.

4 We consider the usual type of rotor with hinged blades, and the distance to the horizontal hinge is not neglected. Also, friction forces in the blade suspension hinges are not taken into account.

5 The blade desalvatore and hanging on the focus limiter of overhang, with a design scheme corresponds to a beam rigidly clamped left end and free right.

3. METHODS

3.1. Stress calculation method based on linear loading model

The bending of the rotor blade in the sweep plane is described by a well-known differential equation of the following form [3]:

(1) $$(EIy'')'' = Y_n - mg.$$

The magnitude of the aerodynamic force Y_n depends on the deformation of the blade and varies in the azimuth of the blade rotation. Linear aerodynamic force acting on the blade in the plane of the sweep with oblique blowing, according to [2,4-6], is determined by the expression:

(2) $$Y_n = \frac{\rho V^2}{2} C_n^{\alpha} b \alpha \cos \chi^2.$$

The expression for the linear aerodynamic force can be used both when blowing the blade from the leading edge and from the rear. To calculate the angles of attack of sections when blowing the blade from the trailing edge, it is enough to change the signs of the angles of relative twist of the blade, as well as the angle of installation of the profile to the reverse.

Substituting the expression (2) in the right part of the expression (1), and making algebraic transformations, we obtain the following differential equation of the blade bending:

(3) $$(EIy'')'' - wy' tg \chi = w\alpha_r - mg,$$

$$w = \frac{\rho V^2}{2} C_n^{\alpha} b \cos \chi^2,$$

$$\alpha_r = \theta_0 + \Delta\varphi_t + \beta_0 tg \chi - \gamma \frac{\cos \psi}{\cos \chi} - \Delta\alpha_v.$$

Equation (3) allows a reduction of order by replacing a variable $\theta = y'$. Then equation (3) will take the form:

(4) $$(EI\theta')'' - w\theta tg \chi = w\alpha_r - mg.$$

Equation (4) is a third-order linear inhomogeneous equation with variable coefficients. To solve equation (4), we apply the method of B. G. Galerkin [7-9]. Imagine the function of the angles of rotation of the elastic axis of the blade θ, as the sum of a certain number of tones:

(5) $$\theta = \sum_j \delta_j \theta^{(j)}.$$

Substitute expression (5) in (4), and all terms of equation (4) are alternately multiplied by $\theta^{(j)}$ (where *j*=0,1,2...*n*) and integrated by radius. Due to the orthogonality of the blade bending forms, equation (4) decomposes into *n* independent equations of the form:

(6) $$P_j \delta_j = A_j.$$

Here: $$P_j = \int_0^R (EI\theta^{(j)\prime})'' \theta^{(j)} dr - \int_0^R w\theta^{(j)2} tg\,\chi dr,$$

$$A_j = \int_0^R w\alpha_r \theta^{(j)} dr - \int_0^R mg\theta^{(j)} dr.$$

It is known that the values included in equation (6) have a certain physical meaning. The value of P_j is the potential energy accumulated by the blade during its bending in the form of *j-th* tone; and the integrals A_j, standing on the right side of equation (6) – the algebraic sum of the aerodynamic forces and forces of its own weight. Solving equation (6) with respect to the deformation coefficient δ_j, we obtain:

(7) $$\delta_j = \frac{A_j}{P_j} = \frac{\int_0^R w\alpha_r \theta^{(j)} dr - \int_0^R mg\theta^{(j)} dr}{\int_0^R (EI\theta^{(j)\prime})'' \theta^{(j)} dr - \int_0^R w\theta^{(j)2} tg\,\chi dr}.$$

From (7) it can be seen that the coefficient δ_j depends on the direction and speed of the wind flow. In [2] it is shown that at a critical value of the wind flow velocity, a static loss of stability of the blade occurs. Here, the condition of loss of stability is the reversal of the denominator of expression (7) to zero. This equality gives:

(8) $$\int_0^R (EI\theta^{(j)\prime})'' \theta^{(j)} dr - \int_0^R w_{cr}\theta^{(j)2} tg\,\chi dr = 0,$$

(9) $$w_{cr} = q_{cr} C_n^{\alpha} b \cos\chi^2.$$

But the critical velocity head at a given direction of blowing, according to [2] is determined by the expression:

(10) $$q_{cr} = -q_{cr}^{\min} \frac{1}{\sin 2\chi}.$$

Substituting (9) in (8), taking into account (10) we obtain:

(11) $$\int_0^R C_n^{\alpha} b\theta^{(j)2} dr = -\frac{2}{q_{cr}^{\min}} \int_0^R (EI\theta^{(j)\prime})'' \theta^{(j)} dr.$$

Substituting (11) into (7) gives:

(12) $$\delta_j = \frac{\int_0^R w\alpha_r \theta^{(j)} dr - \int_0^R mg\theta^{(j)} dr}{\left(1 + \frac{q \sin 2\chi}{q_{cr}^{\min}}\right) \int_0^R (EI\theta^{(j)\prime})'' \theta^{(j)} dr}.$$

Let us turn to the bending equation of a hypothetical "rigid" blade, whose deflections do not change the angles of attack of the sections. By excluding the term containing θ from equation (4), we obtain:

(13) $$(EI\theta_r')'' = w\alpha_r - mg,$$

(14) $$\theta_r = \sum_j \delta_{r_j} \theta^{(j)}.$$

Doing the same for (4) calculations, we obtain the following expression for the deformation coefficient of the "rigid" blade:

(15) $$\delta_{r_j} = \frac{\int_0^R w\alpha_r \theta^{(j)} dr - \int_0^R mg\theta^{(j)} dr}{\int_0^R (EI\theta^{(j)\prime})'' \theta^{(j)} dr}.$$

Comparing (12) and (15), we obtain the following important relation:

(16) $$\delta_j = \frac{\delta_{r_j}}{1 + \frac{q \sin 2\chi}{q_{cr}^{\min}}}.$$

Note that the sign of the second term in the expression (16) is determined by the sign of the sliding angle χ, i.e. the direction of blowing the blade. For blowing modes with a negative angle χ, the denominator decreases with increasing speed head and at $q = q_{cr}^{\min} / \sin 2\chi$ turns to zero. In this case, the deformation of the elastic blade, in comparison with the deformation of the "rigid" blade, increases and in the limit, at a velocity head corresponding to the minimum critical at a given χ, turns to infinity. For blowing with positive angles opposite picture is observed – the elasticity of the blade reduces strain.

The resulting ratio (16) avoids the need to integrate the original equation (3). We introduce the concept of load increase factor:

(17) $$K_w = \frac{\delta_j}{\delta_{r_j}} = \frac{1}{1 + \frac{q \sin 2\chi}{q_{cr}^{\min}}},$$

which shows how many times the actual deflection of the elastic blade is greater than (less than) the deflection obtained under the condition of neglect of additional aerodynamic loads caused by elastic deformations of the blade. Then we can write:

$$\delta_j = K_w \delta_{r_j}. \tag{18}$$

Substituting (18) in (4), taking into account (14), we obtain:

$$\theta = K_w \sum_j \delta_{r_j} \theta^{(j)} = K_w \theta_r, \tag{19}$$

where θ_r is the function of the angles of rotation of the elastic axis of the "rigid" blade, which is the solution of equation (13). Integrating equation (13) three times, we obtain:

$$\theta_r = \frac{\rho V^2}{2} \cos\chi^2 \int_0^r \frac{1}{EI} \int_r^R \int_r^R C_n^\alpha b \alpha_r dr^3 - \int_0^r \frac{1}{EI} \int_r^R \int_r^R mgdr^3. \tag{20}$$

Knowing that $\theta = y'$, $M = EIy'' = EI\theta'$ and taking into account (19), we obtain:

$$y = K_w y_r, \quad M = K_w M_r,$$

$$y_r = \frac{\rho V^2}{2} \cos\chi^2 \int_0^r \int_0^r \frac{1}{EI} \int_r^R \int_r^R C_n^\alpha b \alpha_r dr^4 - \int_0^r \int_0^r \frac{1}{EI} \int_r^R \int_r^R mgdr^4, \tag{21}$$

$$M_r = \frac{\rho V^2}{2} \cos\chi^2 \int_r^R \int_r^R C_n^\alpha b \alpha_r dr^2 - \int_r^R \int_r^R mgdr^2.$$

Thus, expressions are obtained for calculating deflections, angles of rotation and bending moments (stresses $\sigma = M/W$, W – moment of resistance to the bending of the section) directly through their values for the "rigid" blade.

3.2. Stress calculation method based on nonlinear loading model

The need to consider the problem of wind loading of the blade in a nonlinear formulation is mainly due to two facts. The non-rotating rotor blade by its characteristics refers to a flexible rod having deflections within the elastic deformations of the material commensurate with their length [10]. The aerodynamic load, normal to the blade axis, is a tracking load – its direction changes with the change in the angles of rotation of the blade axis during bending.

The nonlinear integro-differential equation of the rotor blade under wind loading has the form [11]:

$$EI \frac{y''}{(1+y'^2)^{3/2}} = -\int_r^R \int_r^R mgdr^2 + \int_r^R \int_r^R Y_n (1 - \frac{y'^2}{2}) dr^2 + \int_r^R Y_n y'(y_l - y) dr. \tag{22}$$

The method of successive perturbations of V. V. Petrov's parameters is increasingly used to solve nonlinear problems of the theory of elasticity, which include the problem of complex bending of the blade [12-17]. In this method, based on the consideration of static loading as a process that develops with a monotonous increase in the loading parameter, the interval of load change by gradual application of its small increments is divided into steps, for each of which the boundary value problem for linearized equilibrium equations is solved. The thus obtained deformed state of the system at the current step is taken as the initial one for the next loading step. However, the linearization procedure, based mainly on physical representations, introduces inevitable errors that accumulate as the loading parameter increases. To improve the accuracy of the solution by the method of successive perturbations of the parameters in this paper, the iteration process of the solution for error correction at each loading step is used.

Traditionally, the method of successive parameter perturbations is used to solve problems in which only one loading parameter λ is considered.

In General, if you have k loading parameters, you can use the following computational scheme. The step-by-step loading procedure is based on the initial equilibrium equation (22). The loading process is divided into k loading stages. Each stage of loading will be characterized by the loading parameter λ_k and the function of the influence of the loading parameter F_k, for k =1..*m*. Inside each k stage of loading will break the interval [0, λ_k] changes the load on n_k (for definiteness equal) levels of loading, and will apply the load step by step in small increments $\Delta\lambda_k = \lambda_k / n_k$. Let for some i loading step at $\Delta\lambda_{k,i} = \lambda_{k,i-1} + \Delta\lambda_k$ the exact solution of the original equation is known. This makes it possible to calculate the influence functions F_k, included in the original equilibrium equation of the loading process, as free terms. In this case, this equation is reduced to a linear differential equation with respect to an unknown function:

$$y_i'' = \sum_{k=1}^m F_k (y_{i-1}', y_{i-1}, r). \tag{23}$$

From which, taking into account boundary conditions, after a single integration is the function y_i'; after a double - y_i, the current loading step.

Next, we will look for refined functions y_i and y_i' corresponding to the i step of loading. Why build an iterative process in which the found on the i step of loading function are the initial approximation to find their exact (with accuracy ε) values. Then for j iteration, according to equation (23) we have:

$$y'_{i,j} = \int_0^r \sum_{k=1}^m F_k(y'_{i,j-1}, y_{i,j-1}, r)dr + C_1,$$

$$y_{i,j} = \int_0^r y'_{i,j}dr + C_1 r + C_2.$$

The constants C_1 and C_2 are from boundary conditions. The condition for termination of iterations is the equality of deflections of the end section of the blade, on two adjacent iterations, with an accuracy of ε:

$$\left| y_{l_{i,j}} - y_{l_{i,j-1}} \right| < \varepsilon,$$

(24)
$$y_{l_{i,j}} = \int_0^l \sin y'_{i,j}dr, \quad y_{l_{i,j-1}} = \int_0^l \sin y'_{i,j-1}dr.$$

After fulfilling the conditions (24) repeats the above-described calculation procedure the functions of the deflections and angles of rotation of the elastic axis of the blade in the loading parameter for the $i+1$ step loading, etc. to achieve a given value of λ_k, and then transition to the next stage of loading. The calculations continue until the specified λ_m value of the last loading stage is reached.

Separately, we note the need for an iterative process to account for changes in the influence functions F_k,..., F_1, due to additional deformation of the blade per loading step. And also to clarify them before the $i+1$ step, because the influence of the loading parameter $\lambda_{k,i}$, can change them.

The representation of static loading as a process allows us to divide the problem of complex bending of the blade under the influence of wind into two stages corresponding to the actual loading picture: - transverse bending under the action of its own mass; - longitudinal and transverse bending of the blade under wind loading. Based on the general bending equation (22), we obtain the equations corresponding to each of the loading stages.

First stage: $y'' = F_1$. Second stage: $y'' = F_1 + F_2$.

Here F_1, F_2 functions of influence of parameters of loading which according to the equation (22) have the form:

$$F_1 = -\frac{(1+y'^2)^{3/2}}{EI} \int_r^R \int_r^R mgdr^2,$$

$$F_2 = \frac{(1+y'^2)^{3/2}}{EI} \left[\int_r^R \int_r^R Y_n (1 - \frac{y'^2}{2}) dr^2 + \int_r^R Y_n y'(y_l - y) dr \right].$$

Note the features of each of the stages of loading. At the first stage, the loading parameter is the proper mass of the blade. As an initial approximation, we will use the exact solution y_0 and y_0' obtained from the solution of the linear equation of the blade bending: $y'' = -\frac{1}{EI}\int_r^R \int_r^R mgdr^2.$

Deformed state of the blade under the action of its own mass will be the initial one for the next stage of loading.

In the second stage, the blade is loaded with wind load. Here, the loading parameter is the wind speed V. Peculiarity of this loading stage is the presence of a second load – mg, the value of which does not change during wind loading, but its function of influence F_1 changes. When the loading parameter reaches the specified value $\lambda_k = V$, the loading process ends.

4. NUMERICAL RESULTS

In accordance with the methods described above, programs are compiled in the algorithmic programming language Maple 18. 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. However, this type of blades is the most common.

All calculations are carried out for the alignment of the helicopter, which corresponds to a strictly vertical position of the rotor shaft, ie γ=0.

4.1.1. Features of wind loading

The results of calculations of bending moments based on linear models of loading are shown in figure 2, where: 1 – the bending of the blade under its own weight, 2 – blowout with the rear edge of the elastic blade, 3 – air cooling with the rear edge of the "rigid" blade, 4 – blowing with the front edge of the elastic blade, 5 – air cooling with the front edge of the "rigid" blade.

Common to both cases is that the dependence $M = f(\chi)$ at a positive angle of the "common step" is symmetrical with respect to the azimuth of $\psi = 180^{\circ}$ a similar dependence at a negative angle of the installation. The difference in the magnitude of the angles of the installation, for which there is a quantitative equality of the extremes of these dependencies, is due to the presence of the blade twist.

As can be seen, elasticity makes significant changes in the distribution of bending moments. The peculiarity is that for the elastic blade, in comparison with the "rigid", the maxima of the curve $M = f(\chi)$ increase slightly, while the minima decrease sharply. The latter moves in the region of angles $\chi = -45^{\circ}$ that correspond to the azimuths $\psi = 135^{\circ}$ at negative angles "collective pitch", and $\psi = 225^{\circ}$ – if positive. As the flow rate increases, this pattern becomes stronger.

From figure 2, it is also clear that the conditions of ensuring the strength of the blade are dangerous oblique blowing modes at negative sliding angles close to $\chi \approx -45^{\circ}$. The calculations performed according to the proposed method showed that the stresses from wind loading exceed the stresses from the forces of the blade's own weight and, therefore, should be taken into account in its design. The stress distributions over the radius of the blade obtained at the slip angle are shown in figure 4, the designation of the curves is preserved.

4.1.2. Influence of nonlinear factors

Comparison of bending stress distributions along the blade length calculated on the basis of linear (curve 2) and nonlinear (curve 1) loading models are shown in figure 5**.**

The results obtained on the basis of solving the linear problem give a fairly complete picture of the behavior of the rotor blade under static wind action. However, to obtain more accurate quantitative results, consideration of the nonlinear problem is required. This is due to the need to take into account various kinds of nonlinearities that appear at large deflections of the blade.

5. 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 A method for calculating bending stresses in the non-rotating rotor blades of a helicopter based on a linear loading model is proposed.

2 The coefficient of load increase is determined, on the basis of which the solution is constructed, allowing to avoid the need for direct integration of the initial differential equation of the blade bending under the influence of wind.

3 Expressions are obtained that are convenient for calculating deflections, angles of rotation and bending moments (stresses) directly through their values for the "rigid" blade.

4 A method for calculating bending stresses in the rotor blades of a helicopter based on a nonlinear model of loading under static wind action is proposed.

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Figures

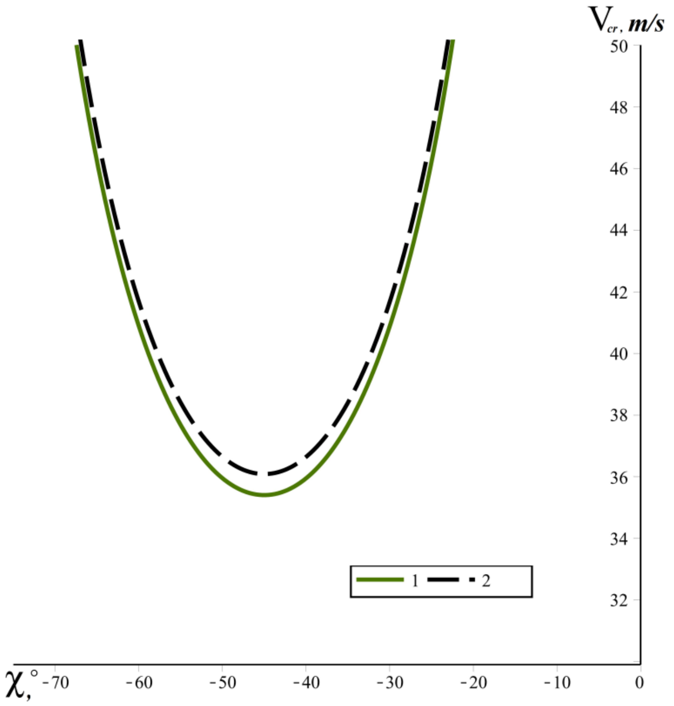


Figure 1: Change in the critical speed of the rotor test blade depending on the direction of airflow: 1-blowing from the leading edge, 2-blowing from the trailing edge.

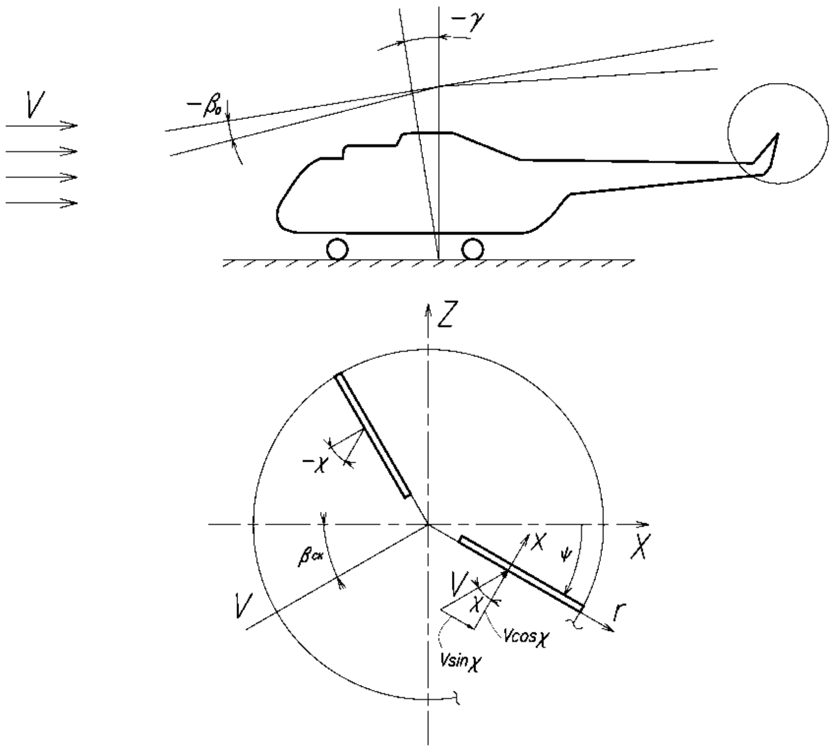
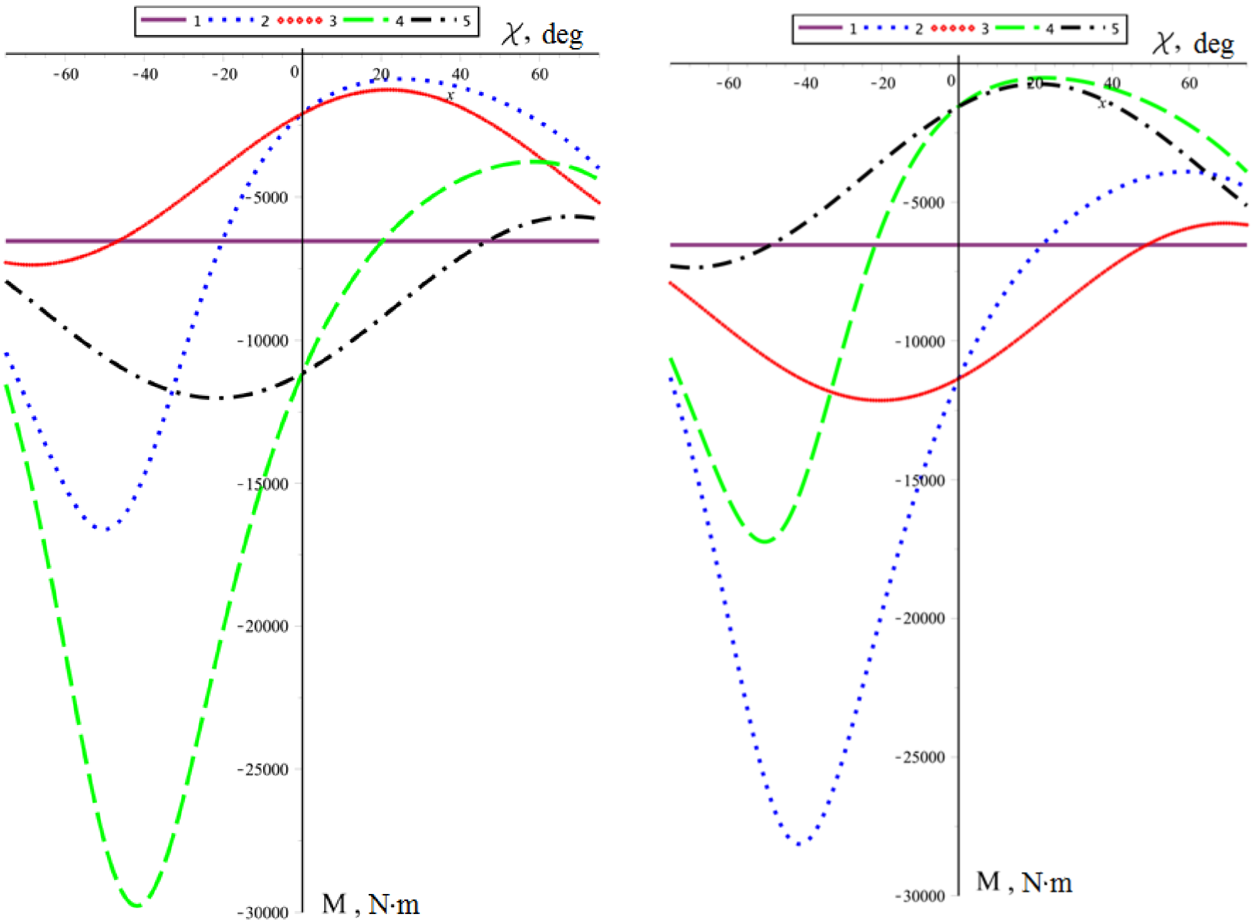


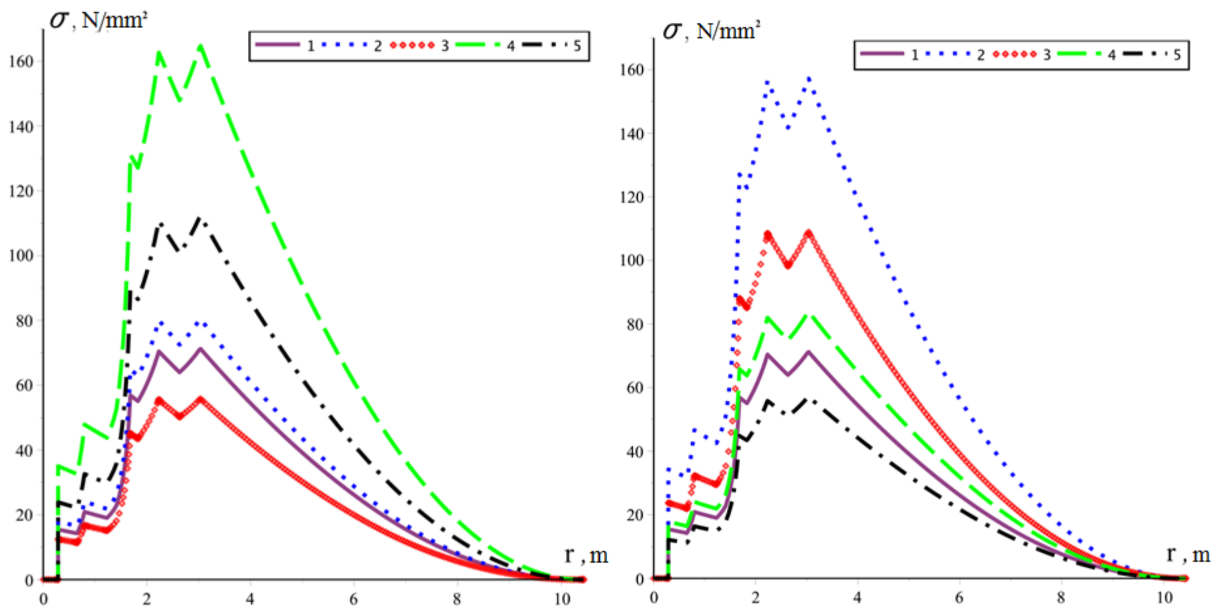
Figure 2: Flow diagram of the rotor blade when blowing the helicopter.



a) $\theta_0 = -5^{\circ}$, $V = 28$ m/s.

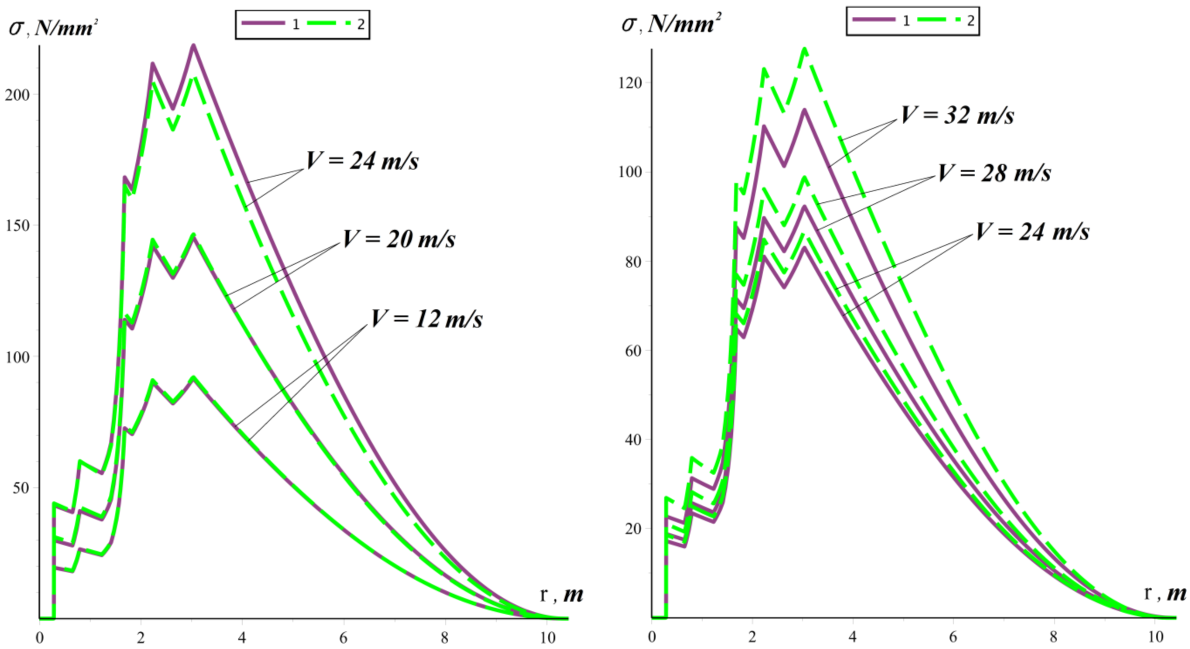
b) $\theta_0 = 5^{\circ}$, $V = 28$ m/s.

Figure 3: Changing the bending moment in the blade sealing.



a) $\theta_0 = -10^{\circ}$, $V = 20$ m/s. b) $\theta_0 = 10^{\circ}$, $V = 20$ m/s.

Figure 4: Distribution of bending stresses along the blade length.



a) blowing from the leading edge at $\theta_0 = -10^{\circ}$, $\psi = 135^{\circ}$. b) blowing from the leading edge at $\theta_0 = 10^{\circ}$, $\psi = 150^{\circ}$.

Figure 5: Distribution of bending stresses along the blade length.