

Numerical study of a mathematical model of the controlled helicopter ditching dynamics

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Increase of reliability and safety of operation of helicopters when flying over sea has special relevance nowadays due to development of offshore fields of oil and gas.

For solving such a problem when producing a helicopter it is required to develop the special design measures and guidelines for crew safety in case of a helicopter ditching and maintaining the buoyancy of helicopter during time, which is sufficient for evacuating the people from inside. It is evident that in this case one of the most important safety factors is the proper piloting the helicopter at its ditching, precluding the possibility of its turning and flooding. Rationale of the safe methods of piloting, especially in conditions of excitement, is a complicated scientific and technical task. For this purpose, in particular, it is required to perform numerical modeling of ditching process taking into account all the factors that affect it. Conducting such research requires the creation of a mathematical model of the spatial movement of the helicopter during ditching, which should take into account the hydrodynamic forces generated by the elements of Emergency Flotation System (EFS), as well as forces and moments generated by main rotor based on pilot's control actions. This mathematical model is being developed by specialists of "Kazan Helicopters" JSC now.

The results of scientific research carried out by teams of Central Aerohydrodynamic Institute named after Zhukovsky N.E. and Kazan State Technical University named after Tupolev A.N. were brought for its creation

This paper presents the results obtained on the basis of analysis of the controlled ditching dynamics of single-rotor ANSAT helicopter equipped with EFS and passed the certification procedure as per АП-29 (FAR-29) standards in 2005 (see

Figure 1). The main feature of this mathematical model is taking into account the whole range of power factors (forces and moments) on the main rotor hub, created by aeroelastic rigid main rotor during ditching and EFS elements entry into the water.



Figure 1 – ANSAT Helicopter with Emergency Flotation System (EFS)

The developed computational model assumes that the fuselage bottom does not generate great hydrodynamic forces, which will influence on water landing significantly. To simplify the calculation and testing of the methods at this stage of investigation the hydrodynamic forces are taken into account only for EFS elements.

For convenience of presentation the article is divided into three sections in accordance with stages of creating a mathematical model of helicopter ditching.

1 Calculation of hydrodynamic forces and moments at steady gliding of cylinder

The values of the hydrodynamic loads on the EFS elements basically are possible to be calculated with the involvement of well-known finite element specialized software packages. However, such software is not always able to take into account the whole range of features of the hydrodynamic loading of bodies immersed into water (for example, counter rise of water and increase its added mass, etc.). Due to this fact, at development of a mathematical model of the ANSAT helicopter

ditching, the approximate theory of submersion and cylinder gliding is used to determine the hydrodynamic loads on the EFS elements. This theory is developed by research scientists of Central Aerohydrodynamic Institute [1], [2], [3].

It is assumed that the interaction with water occurs only on the surface of the EFS element (hereinafter - float), the middle part of which is a circular cylinder, and the tail and nose parts approach the spherical shape.

At this stage of investigation due to short length of float non-cylindrical parts it is considered that their form is cylindrical.

When calculating the hydrodynamic forces we will use the method of plane sections, normal to axis of float and still in the absolute coordinate system. It is considered that fluid flows only in the plane of layers, and the longitudinal flow is absent. Then in each of the plane layers, when float is passing through it, there will be flow, which is similar to cylinder submersion into fluid with free surface. The total hydrodynamic load will be determined by integrating of all elementary sections at each fixed time moment, and the elementary hydrodynamic force acting in the plane sections will be determined only by the instantaneous value of the kinematic parameters of helicopter - its vertical and horizontal components of velocity, angular velocity and linear and angular accelerations.

Let us consider the forces that act on the cylinder, submerging into fluid at a constant velocity along the normal to the free surface. The basis of the approximate theory of this process is a method for determining the kinematics of movement of the free surface towards the body and the value of body wetted $2c$ width, corresponding to each value h in relation to free surface (the method of Wagner). It uses cross-flow velocity potential of expanded plate with a variable width $2c$. As a result of counter rise of water, the width $2c$ is greater than the geometrical width $2c_0$ of segment, cut off by the undisturbed free surface (see Figure 2).

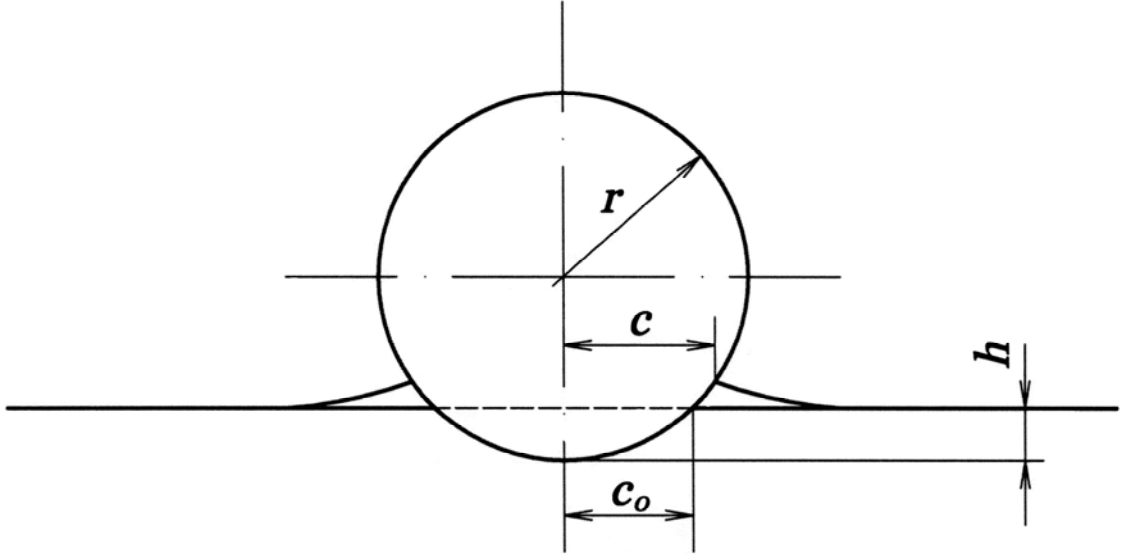


Figure 2

The dependence $2c$ versus h is determined by the well-known equation of Wagner, whose solution is the following expression:

$$h = \frac{2}{\pi} \int_0^c \frac{y(x)}{\sqrt{c^2 - x^2}} dx, \quad (1)$$

where $y = y(x)$ – profile equation in the coordinate system shown in Figure 2.

For a circular cylinder of radius r , this equation is as follows:

$$y = r - \sqrt{r^2 - x^2} \quad (2)$$

In this case, (1) can be represented as a power series:

$$\frac{h}{r} = \frac{1}{4} \left(\frac{c}{r} \right)^2 + \frac{3}{64} \left(\frac{c}{r} \right)^4 + \frac{5}{256} \left(\frac{c}{r} \right)^6 + \dots \quad (3)$$

The integral (1) can also be reduced to complete elliptic integral of the 2nd kind:

$$\frac{h}{r} = 1 - \frac{2}{\pi} E \left(\frac{c}{r} \right), \quad (4)$$

or can be determined by the numerical method directly.

Based on (1) - (3) it is easy to picture the behavior of wetted boundary of the cylinder in a function of its dive. Figure 3 shows the calculated dependence of c/r versus h/r . The calculation shows that $c/r = 1$ at $h/r = 0.33$, i.e. the value of $h/r = 0.33$

is the limit. The following dependence is also of special interest: the dependence of the ratio of wetted half-width “ c ” to the geometrical width, which corresponds to half chord of the segment, formed by the intersection of the cylinder with the undisturbed level of free surface c_0 . It is clear that for small values of h/r the value c/c_0 is close to $\sqrt{2}$ that results directly from (2) and (3). With increasing of h/r value the c/c_0 ratio varies slightly and to the point where h/r reaches 0.33, decreases to 1.34.

At immersion $h \approx 0.33r$, the wetted width $2c$ is equal to the cylinder diameter $2r$. This approach makes it possible to solve the task only at $h < 0.33r$. At great h values the jets are separated from cylinder surface and there is a transition to the cavitation stage of its flow.

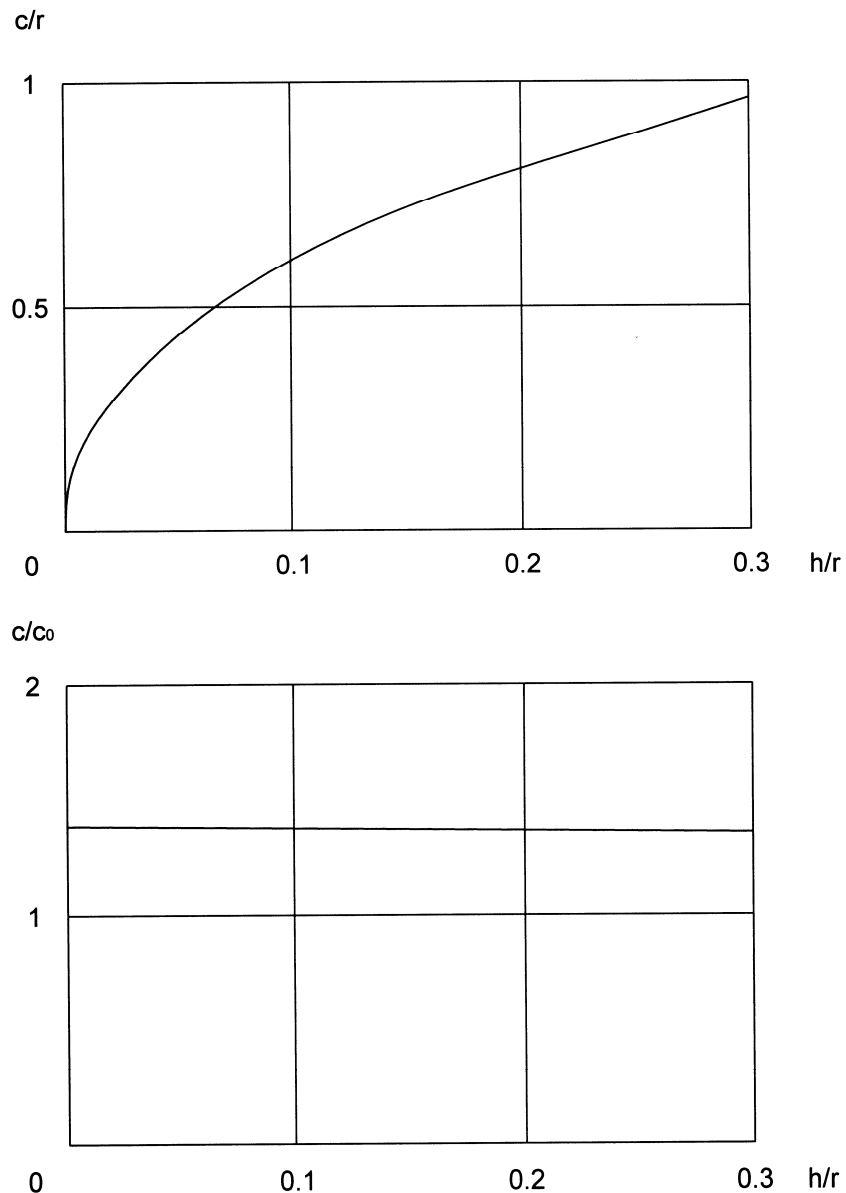


Figure 3

Due to the fact that at continuous immersion of profile into fluid the important role belongs to behavior of free boundaries, in particular, to formation of jets, the fluid motion quantity, obtained from a "shock" task, not in all cases correspond to the real flows. The error increases with increase of slope of the body surface in the area of spray jets' formation. Logvinovich G.V. [10] offered to determine the force by using the Cauchy – Lagrange integral, but at that he modified the form of the velocity potential on the plate surface, which represents the wetted body surface, and the limits of integration, limiting their range by positive pressures on the plate.

Under these conditions, we used the Cauchy – Lagrange integral, keeping a term in it, which is proportional to the square of the absolute fluid velocity. As a result, we obtain the following expression for the hydrodynamic force:

$$f = \pi \rho V_n^2 c \frac{dc}{dh} \left[1 - \frac{1}{\pi} \frac{dh}{dc} \left(1 + \ln 4 \frac{dc}{dh} \right) \right] \quad (5)$$

Defining c and $\frac{dh}{dc}$ in (1), (2) and substituting these values in (5), we obtain the dependence of the force f versus cylinder immersion. For calculations in this paper we used approximation dependence obtained by the calculation results of the curve of

$$f(h/r): f = 2\pi \rho V_n^2 r \varphi \left(\frac{h}{r} \right)$$

Now let us consider the case of steady cylinder gliding on the fluid surface with constant angle and dipping its transom into constant depth with respect to the undisturbed free surface level (see Figure 4). We use above-mentioned method of plane sections, which are normal to cylindrical body axis. It should be strictly noted that such a flow diagram is justified theoretically within the theory of thin body only under certain conditions fulfilling with respect to geometric characteristics of the contact area of body with fluid. In this case, these conditions are not met in front part of the contact zone, because the presence of a cusp is required, and in the case of cylinder gliding the contact area in plan is a near-elliptical shape. However, despite this violation of mathematical aspects of the issue the method of plane sections provides accuracy, which is enough for practice when determining the lifting capacity of gliding cylinder.

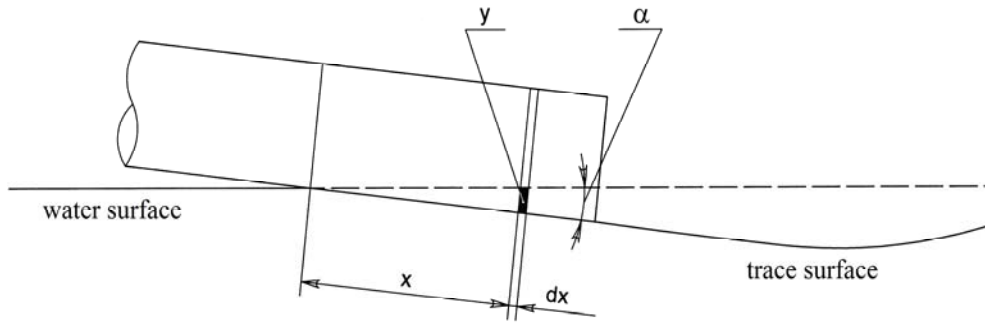


Figure 4

The elementary lifting force, acting in the section with thickness dx will be:

$$dF_G = 2\pi\rho V_n^2 r \varphi\left(\frac{h}{r}\right) dx$$

Value of normal velocity V_n with steady gliding is as follows:

$$V_n = V\alpha,$$

where V is velocity of body movement.

In actual conditions of aircraft landing on water the normal velocity V_n depends on kinematics of its movement. During ditching there are changes of attack angle α , aircraft velocity V , there is addition of angle velocity ω , resulting in appearance of normal velocity component ωx_n , where x_n is distance of this plane layer from helicopter CG.

At $\frac{y}{r} > 0,33$ the cavitational flow of cylinder is formed with velocity V_n , which results in force that affects the cylinder unit of length

$$f_k = C_k \frac{\rho V_n^2}{2} 2r, \quad (6)$$

where C_k is coefficient of cylinder cavitation drag.

In each plane section at $\bar{y} > 0.33$ there will be force:

$$dF_k = C_k \rho V^2 r \alpha^2 dx. \quad (7)$$

There is reason to consider that C_k depends a little on the immersion of the cylinder. In this case, at steady gliding the force distribution along the cylinder length can be considered as uniform, and the coefficient C_k as of 0.5 approximately.

The Archimede's buoyant force, acting in the section with thickness dx is equal to $dF_A = S\rho g dx$, where S is area of float section part submerged in relation to undisturbed fluid level, g is gravity acceleration.

In addition to forces, which depend on submersion velocity, in actual conditions of landing, in each elementary section there will be also the forces, proportional to acceleration $\dot{V}_n = \ddot{y}$, acting in the section. Let us consider that elementary force is equal to product of acceleration by added mass, corresponding to the section. We assume that the added mass is equal to half of added mass of cylinder, located in unbounded fluid, with diameter, which is equal to wetted width of the section $2c$. The added masses are determined as follows:

$$m^* = \frac{1}{2}\rho\pi c^2 \text{ at } \frac{y}{r} \leq 0,33 \quad (8)$$

$$m^* = \frac{1}{2}\rho\pi r^2 \text{ at } \frac{y}{r} > 0,33 (c = r).$$

The drag force, acting on float, depends on helicopter movement dynamics and changes at landing. This force is determined by some factors. The total lifting force, which is equal to float wetted length integral from differential expressions for hydrodynamic force, directs along normal to float longitudinal axis. The projection of this force onto helicopter speed vector direction gives drag, whose physical bases are induction, spray and wave components.

Friction drag can be determined by simple method, used in shipbuilding. Surface of body moving in water is changed by plane plate of the same area S and with the same length L , as the actual body surface. In this case there is keeping of the Reynolds number, which is typical to this object movement. Because in this case the velocity and dimensions of body surface part, contacting with water, ensure (at least at initial stage of landing, which is the most dangerous) existence of turbulent boundary layer, we can use well-known dependence for friction force coefficient [9]:

$$C_f = 0,445(\lg Re)^{-2,58},$$

where $Re = \frac{VL}{\nu}$, ν is kinematic viscosity of water. For example, with landing speed of 15 m/s and length of washed-off part $L=5$ m the coefficient C_f is approximately 0.003.

The friction drag force will be as follows:

$$F_f = C_f \frac{\rho V^2}{2} S \quad (9)$$

The above calculation method is for the landing of gliding type with nose-up of helicopter as shown in Figure 5. The case of landing with a negative pitch angle requires special consideration, but we can assert beforehand that such regimes of landing are extremely dangerous and undesirable.

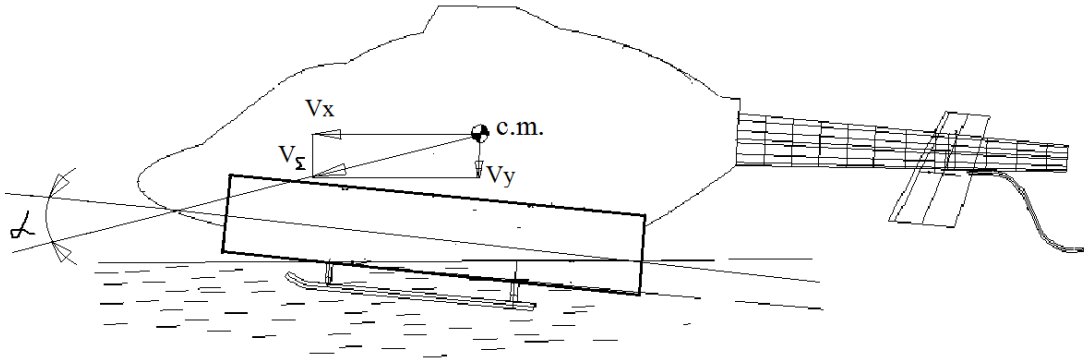


Figure 5

2 Method of taking into account the forces and moments, generated by main rotor

The aerodynamic load on the blades of aeroelastic main rotor is determined by the element-impulse theory. The elastic deformations of the blade are taken into account on the basis of geometrically nonlinear theory of spatially deformed rods of

wing profile. At that in order to take into account the actual flow velocities at blade elements with rapid change of transient ditching regime the following calculation scheme is adopted (See Figures 6 and 7).

This method is developed by research scientists of Kazan State Technical University named after Tupolev A.N.

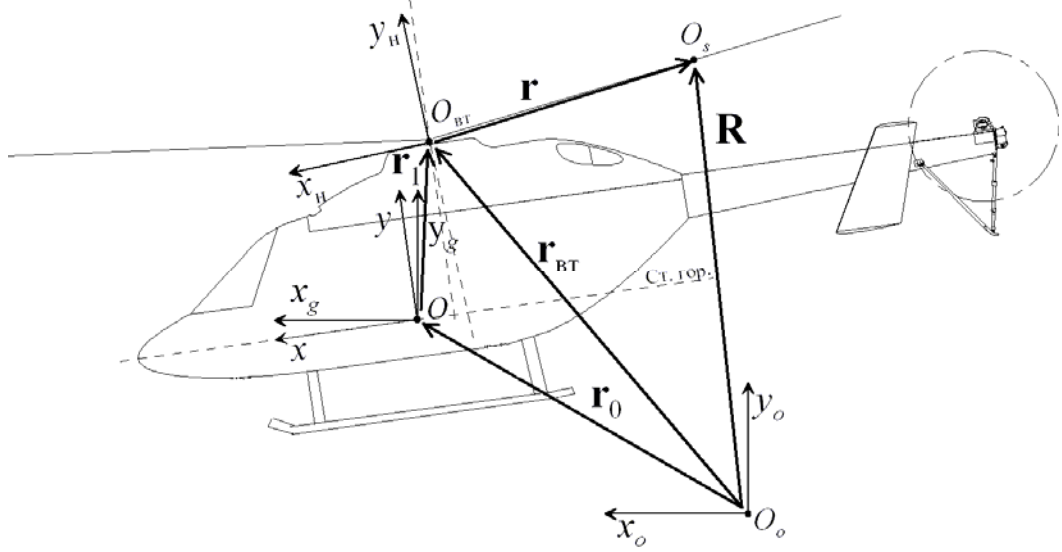


Figure 6

Calculation of velocities and speeds MR blade element is performed by the following formulas:

$$\frac{d\mathbf{R}}{dt} = \mathbf{U}_0 + \mathbf{\Omega}_0 \times \mathbf{r}_1 + \dot{\mathbf{r}} + \mathbf{\Omega} \times \mathbf{r}, \quad (9)$$

$$\begin{aligned} \frac{d^2\mathbf{R}}{dt^2} = & \dot{\mathbf{U}}_0 + \mathbf{\Omega}_0 \times \mathbf{U}_0 + \dot{\mathbf{\Omega}}_0 \times \mathbf{r}_1 + \mathbf{\Omega}_0 \times (\mathbf{\Omega}_0 \times \mathbf{r}_1) + \\ & + \ddot{\mathbf{r}} + \dot{\mathbf{\Omega}} \times \mathbf{r} + 2\mathbf{\Omega} \times \dot{\mathbf{r}} + \mathbf{\Omega} \times (\mathbf{\Omega} \times \mathbf{r}), \end{aligned} \quad (10)$$

where $\mathbf{U}_0$ is a vector of movement speed of helicopter mass center when rotating with angle velocity $\mathbf{\Omega}_0$, and $\mathbf{\Omega}$ is a vector of angle velocity rotation of “moving” axes, connected with rotor blade, in relation to inertial system of axes. Coordinate system $x_0O_0y_0$ is connected with water surface.

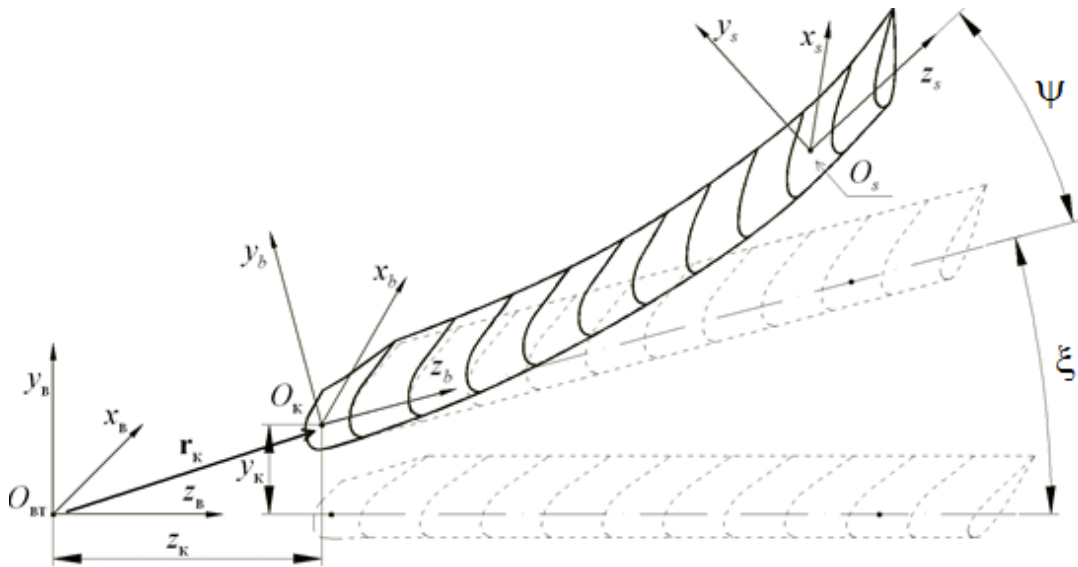


Figure 7

To solve the task of calculation of loads, generated by aeroelastic rigid main rotor of helicopter, there is admission that in each time moment the elastic-flapping movement of blades, forces and moments correspond to their instantaneous values. At this stage of investigation it allows using the model of aeroelastic calculation of main rotor [4], wherein modeling of elastic characteristics of blade in space is conducted by means of geometrically nonlinear theory of spatially deformed rods of wing profile [5]. Use of this theory allows obtaining the system of integro-differential equations of aeroelastic fluctuations of MR blades. It is impossible to solve this system analytically so, that it was taken. That is why the integrant matrixes on the basis of interpolation by “strained” splines are used for reducing to matrix algebraic form. The numeric solution of obtained algebraic equations is made by means of the Newton’s method.

Integration of equations of MR blade movement for time is performed by method, based on use of decomposition of bending and torsion oscillations of blade into trigonometric series of Fourier. At quasisteady regimes the angle functions $\xi(r, \psi)$; $\eta(r, \psi)$; $\zeta(r, \psi)$, determining the position of elastic line of blade, are periodical; this fact allows to decompose them into series of Fourier according to azimuth (time):

$$\begin{aligned}
\xi &= \alpha_0^\xi + \sum_{k=1}^{\infty} (\alpha_k^\xi \cdot \cos k\psi_H + b_k^\xi \cdot \sin k\psi_H); \\
\eta &= \alpha_0^\eta + \sum_{k=1}^{\infty} (\alpha_k^\eta \cdot \cos k\psi_H + b_k^\eta \cdot \sin k\psi_H); \\
\zeta &= \alpha_0^\zeta + \sum_{k=1}^{\infty} (\alpha_k^\zeta \cdot \cos k\psi_H + b_k^\zeta \cdot \sin k\psi_H);
\end{aligned} \tag{11}$$

where: $a_o^\xi, a_k^\xi, b_k^\xi$, $a_o^\eta, a_k^\eta, b_k^\eta$, $a_o^\zeta, a_k^\zeta, b_k^\zeta$ are coefficients of decomposition; $\psi_H = \omega \cdot t$ is azimuth of MR blade; ω is angle velocity of rotor revolution; t is time; k is harmonics of decomposition.

It is evident that with known coefficient values of decomposition it is possible to calculate not only flexures in every point of blade, but also velocity and acceleration of node points.

The aerodynamic load on blades is calculated on the basis of element-impulse theory with use of circular polar of profile. The inductive velocities are calculated by formulas, given in the paper [6]. They are based on results of classic MR vortex theory and allow taking into account the first harmonics of velocity field nonuniformity.

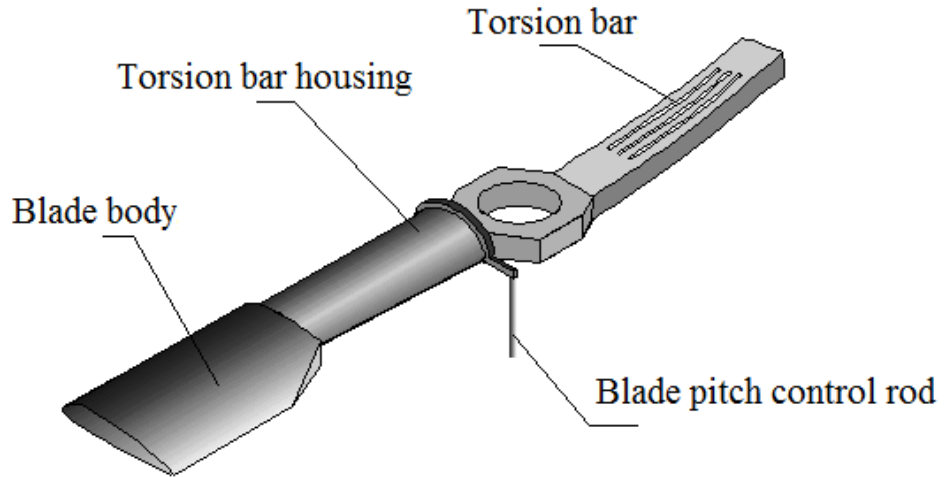


Figure 8

The main rotor of ANSAT helicopter is a rigid rotor, wherein the axial, horizontal and vertical hinges are replaced by elastic torsion (see Figure 8). This fact is taken into account in used theory of calculation model of aeroelastic main rotor.

The helicopter ditching mathematical model being developed takes into account all above-mentioned features of calculation of loads on aeroelastic main rotor.

However, nowadays we investigate an issue concerning the adequate consideration of field of inductive velocities for rotor, located over the water surface. Before solving this issue in the present paper there are results, obtained at establishment on MR hub of concentrated forces and moments, previously determined at helicopter ditching regime (till contact with water surface) as per above-described method.

3 Mathematical model of helicopter movement during entry of EFS elements into water

As per requirement of i. 29.563 АП-29, during landing impact the MR thrust should be applied to helicopter CG and should be equal to $2/3$ of its weight. At that the vertical velocity of helicopter descent is 1.5 m/s , and the horizontal velocity in the moment of contact with water is 56 km/h .

It is known, that rigid main rotor has higher moment characteristics, than the classic hinged rotor. That is why this paper presents modeling of landing impact with consideration of not only MR thrust, but also other components of spatial loading. The general scheme of helicopter loading during ditching is given in Figure 9.

The method of solving the task of helicopter spatial movement during ditching is similar to the method of earlier solved task of modeling the autorotation landing of helicopter at ground and at its solving they used the similar way [7].

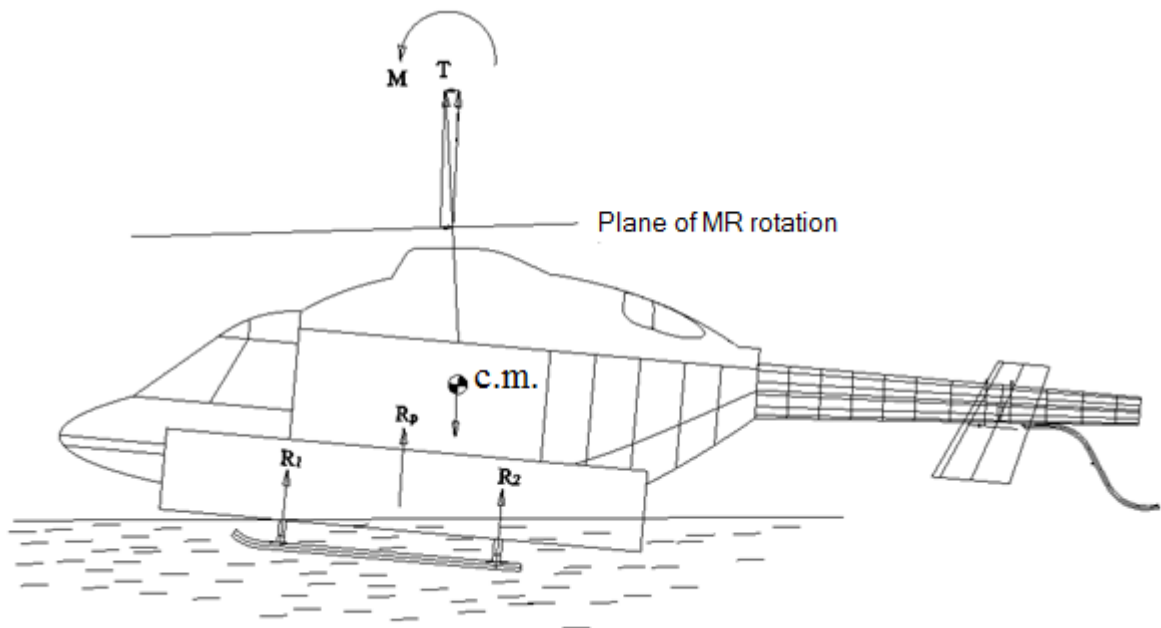


Figure 9

Helicopter movement in space under action of external and inertial forces and moments is traditionally given as forward movement and angle rotation in 3D Euclidean space of helicopter mass center:

$$\begin{aligned}
 m(a_{xg} \cos \vartheta \cos \psi + (a_{yg} + g) \sin \vartheta - a_{zg} \cos \vartheta \sin \psi) &= P_x; \\
 m \left(a_{xg} (\sin \psi \sin \gamma - \sin \vartheta \cos \psi \cos \gamma) + (a_{yg} + g) \cos \vartheta \cos \gamma + \right. & \\
 \left. + a_{zg} (\cos \psi \sin \gamma + \sin \vartheta \sin \psi \cos \gamma) \right) &= P_y; \quad (12) \\
 m \left(a_{xg} (\sin \vartheta \cos \psi \sin \gamma + \sin \psi \cos \gamma) - (a_{yg} + g) \cos \vartheta \sin \gamma + \right. & \\
 \left. + a_{zg} (\cos \psi \cos \gamma - \sin \vartheta \sin \psi \sin \gamma) \right) &= P_z,
 \end{aligned}$$

where g is acceleration of free fall; a_{xg}, a_{yg}, a_{zg} are dynamic parameters, given in the Earth coordinate system; ϑ, ψ, γ are well-known angles pitch, yawing and roll correspondingly. The forces P_x, P_y and P_z determine vector projections of external forces in connection with helicopter FWL of coordinate system.

Let us present the equations of balance of M_x, M_y, M_z moment in relation to mass center. Let us admit that the helicopter mass does not change with one MR revolution; so the moment equations can be written as follows:

$$\begin{aligned}
 J_x \dot{\Omega}_x - J_{zx} \cdot \Omega_x \Omega_y + J_{yx} \cdot \Omega_x \Omega_z + (J_z - J_y) \cdot \Omega_z \Omega_y - J_{zy} \cdot \Omega_y^2 + J_{yz} \cdot \Omega_z^2 &= M_x, \\
 J_y \dot{\Omega}_y - J_{xy} \cdot \Omega_y \Omega_z + J_{zy} \cdot \Omega_y \Omega_x + (J_x - J_z) \cdot \Omega_x \Omega_z - J_{xz} \cdot \Omega_z^2 + J_{zx} \cdot \Omega_x^2 &= M_y, \quad (13) \\
 J_z \dot{\Omega}_z - J_{yz} \cdot \Omega_z \Omega_x + J_{xz} \cdot \Omega_z \Omega_y + (J_y - J_x) \cdot \Omega_x \Omega_y - J_{yx} \cdot \Omega_x^2 + J_{xy} \cdot \Omega_y^2 &= M_z,
 \end{aligned}$$

where $[\mathbf{J}] = \begin{bmatrix} J_x & -J_{xy} & -J_{xz} \\ -J_{yx} & J_y & -J_{yz} \\ -J_{zx} & -J_{zy} & J_z \end{bmatrix}$ is tensor of helicopter inertia.

It is possible to determine helicopter movement angle velocity vector on the axis of connected coordinate system with use of kinematic ratios:

$$\begin{aligned}
\Omega_x &= \dot{\gamma} + \dot{\psi} \sin \vartheta, \\
\Omega_y &= \dot{\psi} \cos \vartheta \cos \gamma + \dot{\vartheta} \sin \gamma, \\
\Omega_z &= \dot{\vartheta} \cos \gamma - \dot{\psi} \cos \vartheta \sin \gamma.
\end{aligned} \tag{14}$$

So upon differentiation for time of expression, we can get ratios for determination of local derivatives values for time from angle velocities:

$$\begin{aligned}
\dot{\Omega}_x &= \ddot{\gamma} + \ddot{\psi} \sin \vartheta + \dot{\psi} \dot{\vartheta} \cos \vartheta, \\
\dot{\Omega}_y &= \ddot{\psi} \cos \vartheta \cos \gamma - \dot{\psi} \dot{\vartheta} \sin \vartheta \cos \gamma - \dot{\psi} \dot{\gamma} \cos \vartheta \sin \gamma + \\
&\quad + \ddot{\vartheta} \sin \gamma + \dot{\vartheta} \dot{\gamma} \cos \gamma, \\
\dot{\Omega}_z &= \ddot{\vartheta} \cos \gamma - \dot{\vartheta} \dot{\gamma} \sin \gamma - \ddot{\psi} \cos \vartheta \sin \gamma + \dot{\psi} \dot{\vartheta} \sin \vartheta \sin \gamma - \\
&\quad - \dot{\psi} \dot{\gamma} \cos \vartheta \cos \gamma.
\end{aligned} \tag{15}$$

In this case the known disadvantage of using standard algorithms, based on angles of Euler's sequential transition, results in zero divide, is absent, and therefore solution of differential equations of helicopter mass center movement dynamics is available by any method of numerical integration.

In this article we use the inverted method of numerical integration for time by means of cubic spline. Let us take the dynamic parameters as main unknowns, so other unknown parameters of forward and torsion movement of mass center will be build on the basis of expressions determined by cubic spline, therefore in the following time step $j+1$ we will obtain the following:

$$\begin{aligned}
V_{xg(j+1)} &= V_{xg(j)} + \frac{1}{2}(a_{xg(j+1)} + a_{xg(j)})\Delta t_j; \\
V_{yg(j+1)} &= V_{yg(j)} + \frac{1}{2}(a_{yg(j+1)} + a_{yg(j)})\Delta t_j; \\
V_{zg(j+1)} &= V_{zg(j)} + \frac{1}{2}(a_{zg(j+1)} + a_{zg(j)})\Delta t_j;
\end{aligned} \tag{16}$$

$$\begin{aligned}
\dot{\gamma}_{j+1} &= \dot{\gamma}_j + \frac{1}{2}(\ddot{\gamma}_{j+1} + \ddot{\gamma}_j)\Delta t_j; \\
\dot{\psi}_{j+1} &= \dot{\psi}_j + \frac{1}{2}(\ddot{\psi}_{j+1} + \ddot{\psi}_j)\Delta t_j; \\
\dot{\vartheta}_{j+1} &= \dot{\vartheta}_j + \frac{1}{2}(\ddot{\vartheta}_{j+1} + \ddot{\vartheta}_j)\Delta t_j;
\end{aligned} \tag{17}$$

$$\begin{aligned}
\gamma_{j+1} &= \gamma_j + \dot{\gamma}_j \cdot \Delta t_j + \frac{1}{6} (2 \cdot \ddot{\gamma}_j + \ddot{\gamma}_{j+1}) \cdot \Delta t_j^2; \\
\psi_{j+1} &= \psi_j + \dot{\psi}_j \cdot \Delta t_j + \frac{1}{6} (2 \cdot \ddot{\psi}_j + \ddot{\psi}_{j+1}) \cdot \Delta t_j^2; \\
\vartheta_{j+1} &= \vartheta_j + \dot{\vartheta}_j \cdot \Delta t_j + \frac{1}{6} (2 \cdot \ddot{\vartheta}_j + \ddot{\vartheta}_{j+1}) \cdot \Delta t_j^2,
\end{aligned} \tag{18}$$

where Δt is time step, V_{xg}, V_{yg}, V_{zg} are velocities of mass center movement in normal earth coordinate system.

Therefore, to determine the trajectory of helicopter movement it is required to take the known initial conditions in the beginning of time interval.

The values of hydrodynamic forces and moments, that affect the EFS elements during their entry into water, are calculated on the basis of cylinder steady gliding, given in Setion 1 of present article. This theory was developed by tCentral Aerohydrodynamic Institute.

4 Parametric analysis of calculation results of helicopter ditching

As it was mentioned above, in Section 2 of present paper, before completion of examination of issue on method of revised consideration of MR inductive speed field over water surface, we perform calculations with application of concentrated forces and moments on the MR hub. The values of these forces and moments are determined by results of parametric analysis of conditions of controlled autorotation helicopter landing at ground. They are given in the paper [8]. Below are calculation results for some helicopter ditching variants.

Variant 1: Ditching as per conditions of i. 29.563 АП-29

This calculation is performed fully in accordance with requirements of i. 29.563 АП-29 concerning the use of initial conditions of helicopter entry into water. Hereinafter we examine entry into pacific water without initial angle of helicopter pitch.

Variant 2: Consideration of longitudinal control moment on MR hub

In this variant of calculation we use value and law of change of longitudinal control moment, generated by main rotor at helicopter movement on the water with pilot's control actions. At that all other calculation conditions correspond to the first variant of calculation.

Variant 3: Consideration of decrease of MR unloading during ditching

In this calculation variant we reproduced the conditions of MR unloading decrease, which simulate decrease of its thrust after undermining at autorotation before contact with water surface. At that it is assumed that from the moment of contact with water the MR unloading value decreases up to $2/3$ to $1/3$ of helicopter weight for two seconds. The values of vertical and horizontal velocities at calculation correspond to the first variant of calculation.

Before comparative calculations we tested the calculation model as per results of experiment. The test results are given in Figures 10 and 11. For testing we used calculation, which corresponds to one of the cases of model tests of ANSAT helicopter with EFS. The comparison of results of calculation and experiment are performed as per record of overloads in mass center. The Figures 10 and 11 with the results show that the dynamic process of overload change concerning character and values is sufficiently similar to experiment; therefore we can make a conclusion about acceptable authenticity of calculation model.

Figures 12 and 13 show the comparison of test calculation results for variants 1, 2 and 3. At that the figures show the following:

- row 1 – variant of calculation No. 1;
- row 2 – variant of calculation No. 2;
- row 3 – variant of calculation No. 3.

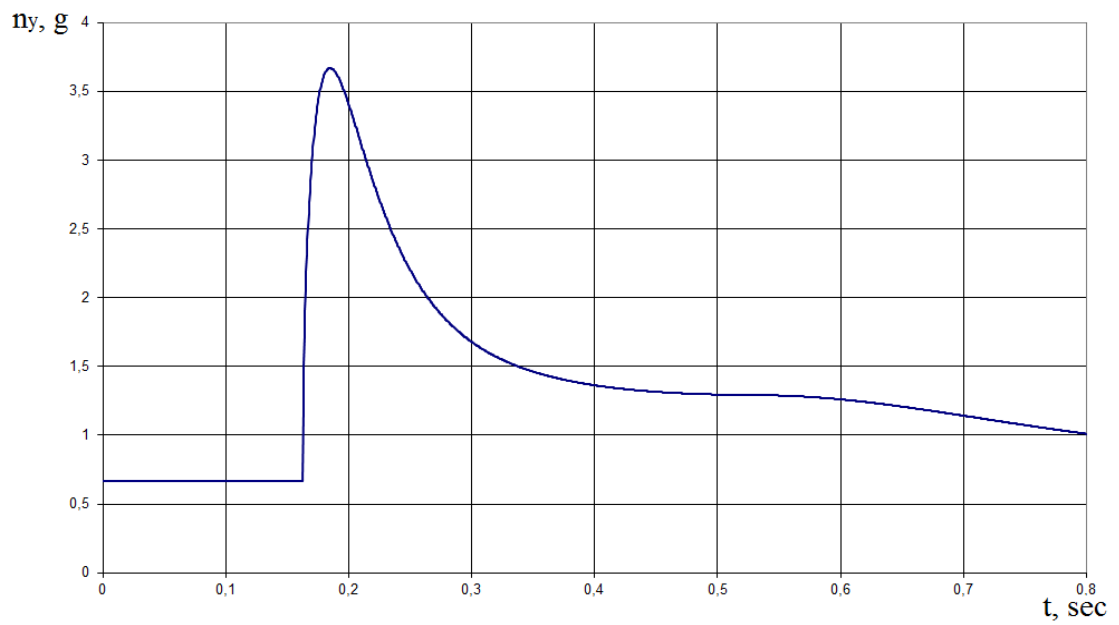


Figure 10 - Dependence of CG overload versus time - calculation

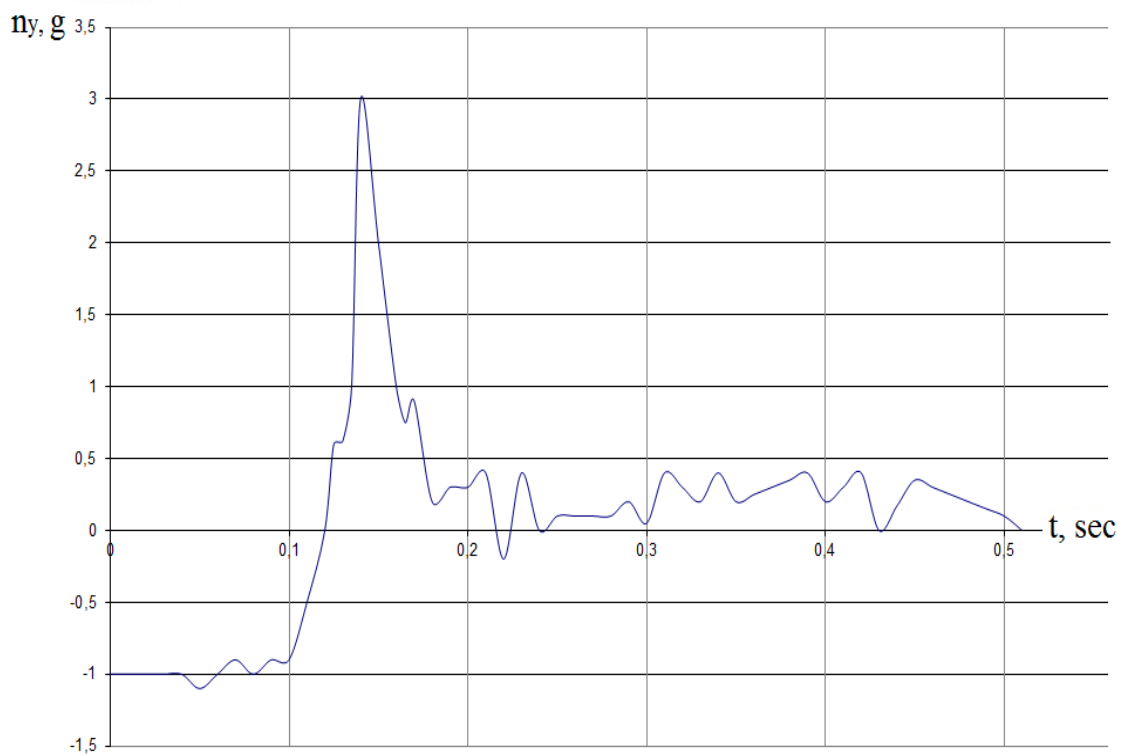


Figure 11 – Dependence of CG overload versus time - experiment

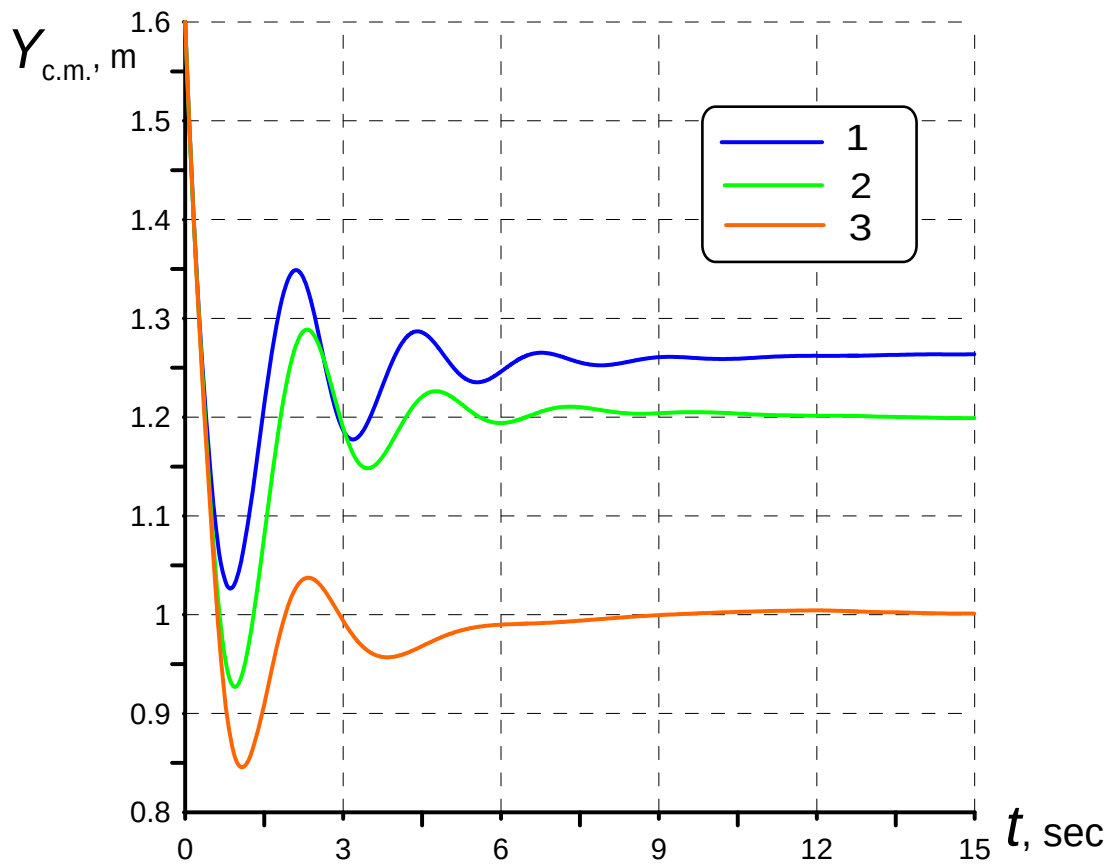


Figure 12 – Dependence of CG displacement versus time

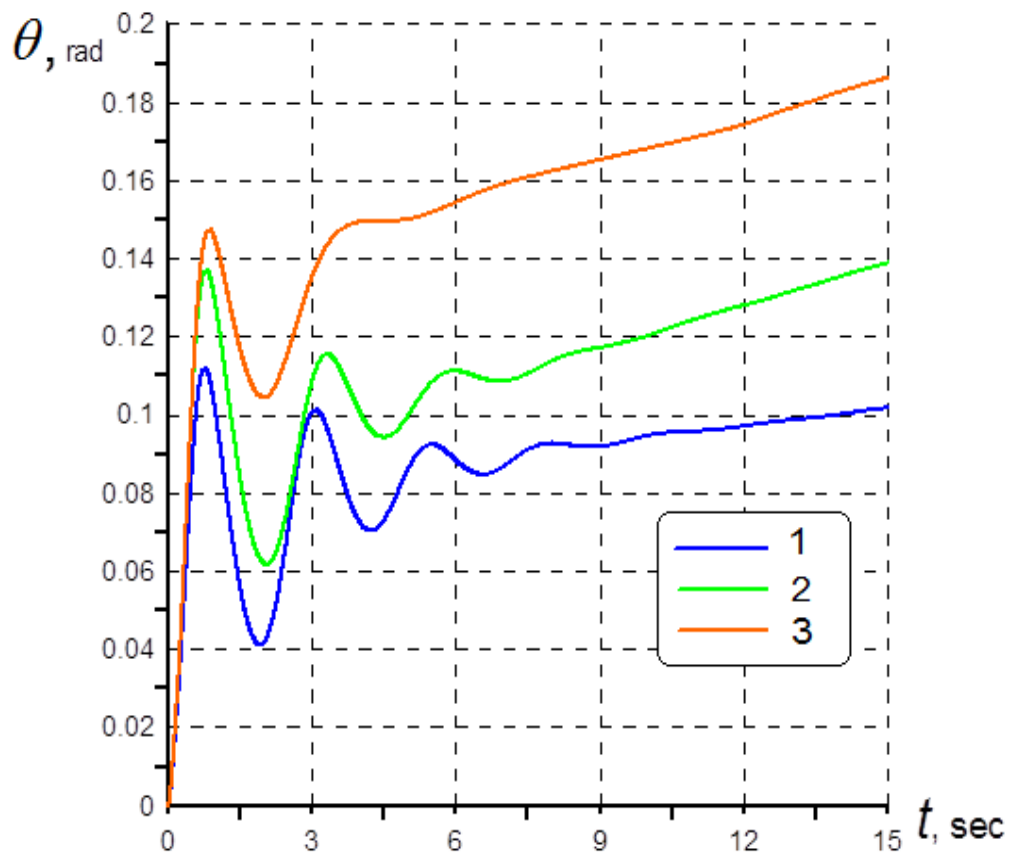


Figure 13 – Dependence of pitch angle change versus time

As you can see in comparison of calculation results, given in Figures 12, 13, the forces and moments on main rotor influence on the helicopter movement trajectory during ditching considerably. Therefore consideration of these forces and moments is required at modeling the process of controlled landing. By means of such modeling there can be selected the required parameters of helicopter control to prevent its turning and “dipping” into water at landing in condition excitement.

5 Conclusion

The results of investigation show the possibility of solving the task of modeling the dynamics of controlled helicopter ditching taking into account the loads, created by rigid main rotor and hydrodynamic loads on the EFS elements. This provides the possibility for subsequent solving the following tasks:

- the best possible method of implementation of controlled landing on water surface in standard and critical conditions;
- assessing the required level of stability and buoyancy performance of helicopter equipped with Emergency Flotation System;
- well-grounded determination of actual loads, effecting on the EFS elements and on the elements of their attachment to helicopter structure;
- assessing the possibility of dangerous proximity of revolving MR blades with water surface.

Further research for creation of mathematical model of controlled helicopter ditching will continue, including revision of calculation model for determining the loads on the EFS float with negative angles of attack during its contact with water surface, as well as calculation taking into account MR influence directly.

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