ID 182

Computational investigation of dynamics of controlled landing of the helicopter equipped with skid landing gear

Alimov S.A., Girfanov A.M., Mikhailov S.A., Nedelko D.V.

At the present time the helicopter is one of the elements of transport infrastructure of megalopolises, business and production corporations. It is used to perform a variety of transport operations, such as monitoring of ecological areas and engineering facilities, liquidation of emergencies and providing of urgent medical care at a long distance. The lightweight multipurpose helicopter is the most suitable type of the aircrafts to solve these tasks.

In helicopters design, the use of rigid rotors has been spread rather widely due to several technical advantages, including exploitation convenience and simplicity of such type plugs . Most often, such rotors are used in light helicopters construction, which are normally equipped with skid-equipped landing gear. And the exploitation advantages of such helicopter design require a rather detailed and knowledge-intensive development of the design method for devices of the abovestated type (pivotless plug and skid-equipped landing gear).

Also very important in this case is the methodical development of exploitation safety maintenance in terms of performing safe auto-rotation landing. It is essential to maintain the appropriate level of safety using both the relevant construction solutions in the part of the chassis' energy absorbing characteristics, and the authoritatively reasoned auto-rotation execution method, with regard to constructive peculiarities of the pivotless rigid rotor.

The helicopter's skid-equipped landing gear is usually the key component in investigation of different helicopter landing conditions, including during auto-rotation of the main rotor. It is apparent that in this case only correct pilot actions can provide safe landing. So, the problem of modeling helicopter's guided landing can be topical up to this moment.

Helicopter movement over distances, under the effect of external inertial forces and torques, is traditionally introduced as progressive advance and angular rotation in the three-dimensional Euclidean space of the helicopter center of mass:

$$\begin{aligned}
& m\left(a_{xg}\cos\vartheta\cos\psi+\left(a_{yg}+g\right)\sin\vartheta-a_{zg}\cos\vartheta\sin\psi\right)=P_x; \\
& m\begin{pmatrix} a_{xg}\left(\sin\psi\sin\gamma-\sin\vartheta\cos\psi\cos\gamma\right)+\left(a_{yg}+g\right)\cos\vartheta\cos\gamma+ \\ +a_{zg}\left(\cos\psi\sin\gamma+\sin\vartheta\sin\psi\cos\gamma\right) \end{pmatrix}=P_y; \\
& m\begin{pmatrix} a_{xg}\left(\sin\vartheta\cos\psi\sin\gamma+\sin\psi\cos\gamma\right)-\left(a_{yg}+g\right)\cos\vartheta\sin\gamma+ \\ +a_{zg}\left(\cos\psi\cos\gamma-\sin\vartheta\sin\psi\sin\gamma\right) \end{pmatrix}=P_z,
\end{aligned} \tag{1}$$

where g is the downward acceleration; a_{xg}, a_{yg}, a_{zg} are the dynamic parameters, introduced in the earth referenced coordinate system; ϑ, ψ, γ are the commonly known angles of tangage, fishtailing and banking respectively. The forces P_x, P_y and P_z determine the projections of outside forces vector in the system of coordinates connected with the helicopter's longitudinal datum line.

Let us also introduce the torques equilibrium equation M_x, M_y, M_z in relation to the center of mass. Let us assume that, during one rotation, the mass of helicopter remains constant, then we may write the equations of moments as follows:

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

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

The projections of the angular velocity vector of the helicopter movement on the fixed axis may be determined using kinematic proportions:

$$
\begin{aligned}
\Omega_x &= \dot{\gamma} + \dot{\psi}\sin\vartheta, \\
\Omega_y &= \dot{\psi}\cos\vartheta\cos\gamma + \dot{\vartheta}\sin\gamma, \\
\Omega_z &= \dot{\vartheta}\cos\gamma - \dot{\psi}\cos\vartheta\sin\gamma.
\end{aligned} \tag{3}
$$

Then, if we make differentiation with the time of expression (3), we can get proportions for determining the amounts of local derivatives with time from angular speeds:

$$
\begin{aligned}
\dot{\Omega}_x &= \ddot{\gamma} + \ddot{\psi}\sin\vartheta + \dot{\psi}\,\dot{\vartheta}\cos\vartheta, \\
\dot{\Omega}_y &= \ddot{\psi}\cos\vartheta\cos\gamma - \dot{\psi}\,\dot{\vartheta}\sin\vartheta\cos\gamma - \dot{\psi}\,\dot{\gamma}\cos\vartheta\sin\gamma + \\
&\quad + \ddot{\vartheta}\sin\gamma + \dot{\vartheta}\dot{\gamma}\cos\lambda, \\
\dot{\Omega}_z &= \ddot{\vartheta}\cos\gamma - \dot{\vartheta}\dot{\gamma}\sin\gamma - \ddot{\psi}\cos\vartheta\sin\gamma + \dot{\psi}\,\dot{\vartheta}\sin\vartheta\sin\gamma - \\
&\quad - \dot{\psi}\,\dot{\gamma}\cos\vartheta\cos\gamma.
\end{aligned} \tag{4}
$$

In this case, no such common failure occurs as divide-by-zero resulting from the use of classical algorithms based on the Eulerian coherent transition angles. Then, solving the differential equations of the helicopter center of mass movement dynamics is possible using any method of numerical integration.

In this work, let us use the reverse method of numerical integration for time using cubic spline. We shall take the dynamic parameters as main indeterminates, then the other indeterminate parameters of translational and rotary motion of the center of mass will be built up based on the formulas, determined by the cubic spline. Then, at the next time step $j+1$ we shall have:

$$
\begin{aligned}
V_{xg(j+1)} &= V_{xg(j)} + \frac{1}{2}\left(a_{xg(j+1)} + a_{xg(j)}\right)\Delta t_j; \\
V_{yg(j+1)} &= V_{yg(j)} + \frac{1}{2}\left(a_{yg(j+1)} + a_{yg(j)}\right)\Delta t_j; \\
V_{zg(j+1)} &= V_{zg(j)} + \frac{1}{2}\left(a_{zg(j+1)} + a_{zg(j)}\right)\Delta t_j;
\end{aligned} \tag{5}
$$

$$\dot{\gamma}_{j+1} = \dot{\gamma}_j + \frac{1}{2}\left(\ddot{\gamma}_{j+1} + \ddot{\gamma}_j\right)\Delta t_j;$$

$$\dot{\psi}_{j+1} = \dot{\psi}_j + \frac{1}{2}\left(\ddot{\psi}_{j+1} + \ddot{\psi}_j\right)\Delta t_j; \qquad (6)$$

$$\dot{\vartheta}_{j+1} = \dot{\vartheta}_j + \frac{1}{2}\left(\ddot{\vartheta}_{j+1} + \ddot{\vartheta}_j\right)\Delta t_j;$$

$$\gamma_{j+1} = \gamma_j + \dot{\gamma}_j \cdot \Delta t_j + \frac{1}{6}\left(2 \cdot \ddot{\gamma}_j + \ddot{\gamma}_{j+1}\right) \cdot \Delta t_j^2;$$

$$\psi_{j+1} = \psi_j + \dot{\psi}_j \cdot \Delta t_j + \frac{1}{6}\left(2 \cdot \ddot{\psi}_j + \ddot{\psi}_{j+1}\right) \cdot \Delta t_j^2; \qquad (7)$$

$$\vartheta_{j+1} = \vartheta_j + \dot{\vartheta}_j \cdot \Delta t_j + \frac{1}{6}\left(2 \cdot \ddot{\vartheta}_j + \ddot{\vartheta}_{j+1}\right) \cdot \Delta t_j^2,$$

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

Consequently, in order to determine the flight trajectory of the helicopter, we should set the initial conditions (already known to us) in the beginning of the time period. For example, we may set as initial any habitual mode of the helicopter flight, and then, for determining the indeterminates at the next step, we can use the Newton's method for resolving the systems of algebraic equations.

Hence only forces and torques created by the main rotor, and the reactions of the skid will remain indeterminate at the next step. Let us examine a little closer the mathematical models used for resolving the set task.

A model of skid-equipped landing gear is actually a dimensional, statically indeterminate rod construction which works in the conditions of considerable (up to 40-50%) geometrical nonlinearity, as well as considerable physical nonlinearity of the springs material, which obeys the set law of plastic deformation, yet does not reach the level of destruction. A numerical model of skid-equipped landing gear allows modeling the helicopter landing with vertical and horizontal components of landing velocity, as well as with forces of longitudinal friction which emerge during landing. The geometrical nonlinearity of the chassis construction is based on the theory of large displacements, developed into the geometrical nonlinear theory of the outboard profile rods polydimensional deformation, adapted for the rods of tubular section.

In order to resolve the task with dimensional warping of the statically indeterminate skid construction, we have used the forces method, the main system of which was achieved by introducing required indeterminates in the form of concentrated forces and torques $\hat{X}_i$, where i is the static redundancy degree in the system. Generally speaking, the amended system of equations for the mathematical model of skid-equipped landing gear warping will be as follows:

$$\begin{cases} F_I(\vec{X}_I, \vec{P}) = 0; \\ F_{II}(\vec{X}, \vec{P}) = 0; \\ \Delta_1(\hat{X}_1, \hat{X}_2, ..., \hat{X}_{12}, \vec{X}_I, \vec{X}_{II}, \vec{P}) = 0; \\ \Delta_2(\hat{X}_1, \hat{X}_2, ..., \hat{X}_{12}, \vec{X}_I, \vec{X}_{II}, \vec{P}) = 0; \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \Delta_{12}(\hat{X}_1, \hat{X}_2, ..., \hat{X}_{12}, \vec{X}_I, \vec{X}_{II}, \vec{P}) = 0; \\ Y_1^{\alpha}\left(R_1,\ R_2,\ R_3,\ R_4\right) = 0; \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ Y_4^{\alpha}\left(R_1,\ R_2,\ R_3,\ R_4\right) = 0, \end{cases} \qquad (8)$$

where the generalized load parameter $\vec{P}$ contains the rates of reactions R_i and the correspondent friction forces. A more detailed scheme of resolving this task is given in the works [1, 2].

Verification of the calculated skid model was performed by means of comparison of the calculations results within special software performing the finite elements technique, and the results of natural drop work tests of the skids.

The landing surface is set as hard warp-free analytical subspace. During the contact of the elastomeric skids, reactive forces emerge (Figure 1) which prevent the helicopter from vertical downward movement.

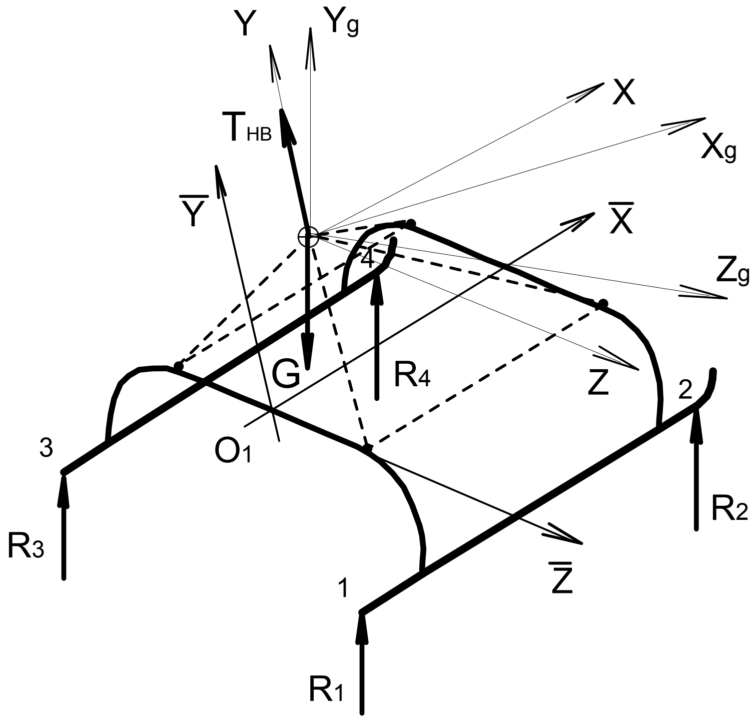

Figure 1 – The basic coordinates systems connected with the skid

The model of the helicopter movement during landing allows seeing the initial wheels-on of the chassis on the landing site, with any part of either right or left skid. In order to simplify the calculation model, we shall assume that the reaction of the landing site is applied to the two front or two rear endpoints of skids.

The current requirements of strength standards have been created based on many years of design experience, tests and exploitation of helicopters with a classical pivot rotor. The emergence of new helicopters with pivotless main rotor leads us to the necessity to clarify some calculation cases and helicopter load conditions during both flight and landing.

In order to resolve the task of calculating loads of the helicopter's aeroelastic pivotless main rotor, we shall assume that at each moment of time, the elastic flapping movement of the blades, forces and torques of the main rotor correspond to their instant amounts. At this stage of research, such assumption allows us to use the model of aeroelastic calculation for the main rotor [3] where the blade's elastic characteristics modeling over distance is performed using the geometrically nonlinear theory of the dimensionally warped rods of the outboard profile [4].

Application of this theory allows us to get a system of integro-partial differential equations for aeroelastic overswinging of the main rotor blades. This system can't be resolved analytically in its initial form. So, for its contraction to the matrix algebraic form, we apply integrating matrixes based on the interpolation by the "stressed" splines. The thus received algebraic equations are solves by the Newton's method.

Time integration of the motion equations of the main rotor blades is conducted using a technique employing Fourier series expansion of bending and torsional overswingings of the blade. In quasi-habitual modes, the angular functions ξ(r,ψ); η(r,ψ); ζ(r,ψ), which determine the position of the blade's elastic line, are periodical, which allows us to expand them into a Fourier in azimuth (of time):

$$\begin{aligned} \xi &= \alpha_0^{\varsigma} + \sum_{k=1}^{\infty}\left(\alpha_k^{\xi}\cdot\cos k\psi_{\text{н}} + b_k^{\xi}\cdot\sin k\psi_{\text{н}}\right); \\ \eta &= \alpha_0^{\eta} + \sum_{k=1}^{\infty}\left(\alpha_k^{\eta}\cdot\cos k\psi_{\text{н}} + b_k^{\eta}\cdot\sin k\psi_{\text{н}}\right); \qquad (9) \\ \zeta &= \alpha_0^{\varsigma} + \sum_{k=1}^{\infty}\left(\alpha_k^{\xi}\cdot\cos k\psi_{\text{н}} + b_k^{\xi}\cdot\sin k\psi_{\text{н}}\right); \end{aligned}$$

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 the expansion indexes; $\psi_{\text{н}} = \omega \cdot t$ is the azimuth of the main rotor blade; ω is the angular velocity of the rotor's rotation; t is the time; k is the expansion harmonics.

It's obvious that, given coefficients of expansion, it's possible to calculate both the deflection in any point of the blade and the velocities and accelerations of the node points.

The aerodynamic load at the blades is calculated based on the elemental impulse theory using the profile's circular polar. Inductive velocities are calculated using the formulas introduced in the work [5]. They are based on the results of the classic vortex theory of the main rotor, and allow us to consider the first harmonics of the velocities' field distortion.

Joining the introduced mathematical models within the frame of one software complex allows efficient resolving of modeling tasks considering the loads created by the main rotor. Use of this software complex will enable elaboration of optimal guided landing technique in standard and critical conditions at the design stage of new helicopter and provide estimation of required energy absorption of the skid landing gear.

In this work, the authors introduce the calculation research results of the two first landing blows of a skid-equipped helicopter to the flight landing strip, considering the different matches of forces and the lateral moment created by the pivotless main rotor. In order to simplify the research scheme, at this stage we assumed that in the most cases, the loads at the main rotor remain constant over the landing impact.

According to FAR-29, during the landing impact the push force of the main rotor must be applied to the helicopter gravity center, and equals to 2/3 of the helicopter weight at absorption of the exploitation work (para. 29.473(a)). The initial load calculating case is as follows:

- Load case 1: T_{HB} = 2/3 G = 2200 daN; H = 0.3 m; V_y = 0 m/s,

where H is the distance between the lower surface of the skid, and the flight landing strip, at the initial moment of time.

Considering that the helicopter's main rotor has not only the push force $T_{HB,}$ but also the controlling torque (M_z) in relation to the lateral axis, there can also be the following cases of load:

- Load case 2: T_{HB} = 2200 daN; M_z = 248.7 daN m; H = 0.3 m; V_y = 0 m/s;
- Load case 3: T_{HB} = 2200 daN; M_z = -248.7 daN m; H = 0.3 m; V_y = 0 m/s.

During landing, a situation may occur when the pilot, right before touching the landing strip, pulls the main rotor body backward in order to reduce the longitudinal velocity and thus creates a backward main rotor push force. Let us assume that the angle of pulling the main rotor is equal to 5 degrees, then the initial data for calculation will be as follows:

- Load case 4: $T_{НВ}$ = 2191.6 daN; H = -191.7 daN; M_z = 503 daN m; H = 0.3 m; V_y = 0 m/s.

We also additionally examine the case when the pilot gradually reduces the main rotor's push force $T_{НВ}$:

- Load case 5: $T_{НВ}$ lowers from 2200 daN to 1100 daN during 1 second, further on $T_{НВ}$ = const = 1100 daN; H = 0.3 m; V_y = 0 m/s.

For the created calculation cases, there can be the following variants of landing a helicopter with pivotless main rotor:

- Load case 1 is correspondent to requirements of para. 29.473(a) of the Aviation rules (Part 29);
- Load case 2 is correspondent to a situation when the pilot, right before touching the landing strip, pulls the main rotor's body backward in order to reduce longitudinal speed, and thus creates a backward main rotor push force;
- Load case 3 is correspondent to vertical landing with the controlling torque in relation to the helicopter's lateral axis;
- Load case 4 is correspondent to a situation when the pilot gradually reduces the main rotor's push force twice.

The calculation results are shown in Figures 2 – 11 as time dependences of the helicopter movement parameters and skid load parameters.

The examined parameters of the helicopter movement are:

- $Y_{c.m.}$, m – movement of the helicopter center of mass along the Y axis;
- a_y, m/s^2 – acceleration in the helicopter center of mass along the Y axes;
- ϑ, degrees – the helicopter pitch attitude.

The examined parameters of the helicopter's skid load are:

- R_1, daN is the reaction on the right console of the skid's rear spring;
- R_2, daN is the reaction on the right console of the skid's front spring.

As it has been already told before, the calculation results are introduced for two landing blows during the helicopter's landing. For convenience of the analysis, the results are divided into two groups, for each of which there is a calculation for the Load Case 1, according to the requirements of FAR-29.

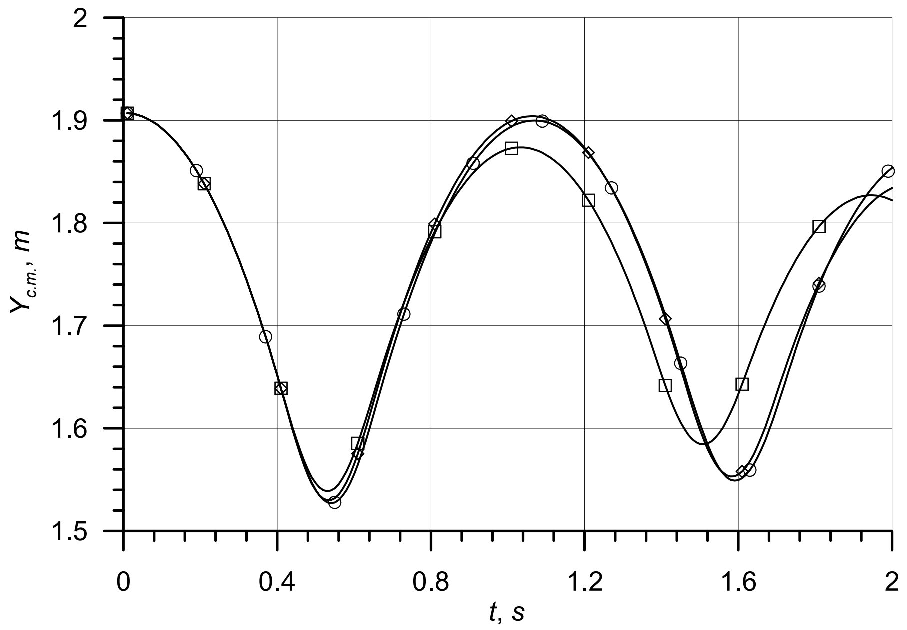

Figure 2 – Moving of the helicopter center of mass during landing
(◇ - load case 1; ○ - load case 2; ◘ - load case 3)

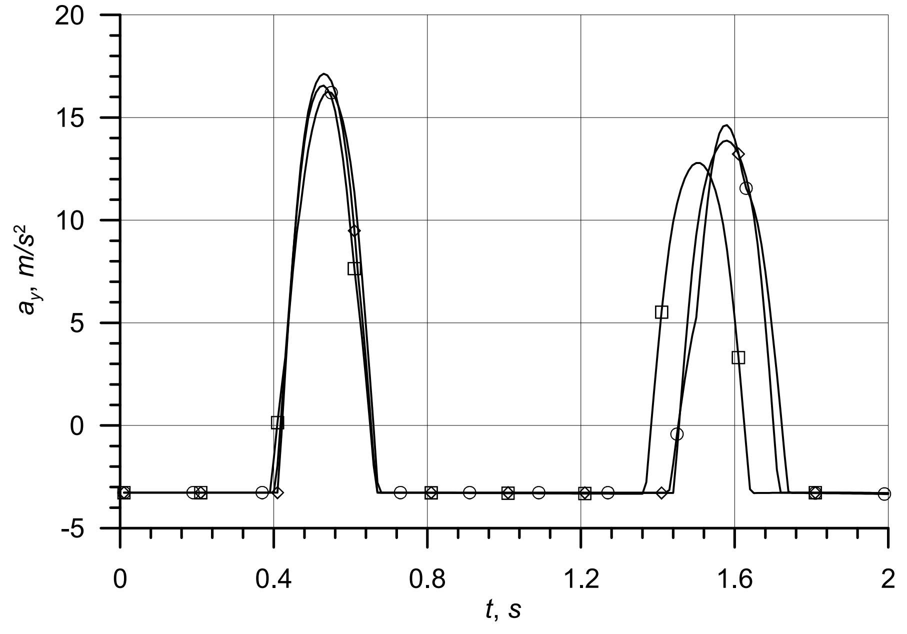

Figure 3 – Acceleration factor in the helicopter center of mass during landing
(◇ - load case 1; ○ - load case 2; ◘ - load case 3)

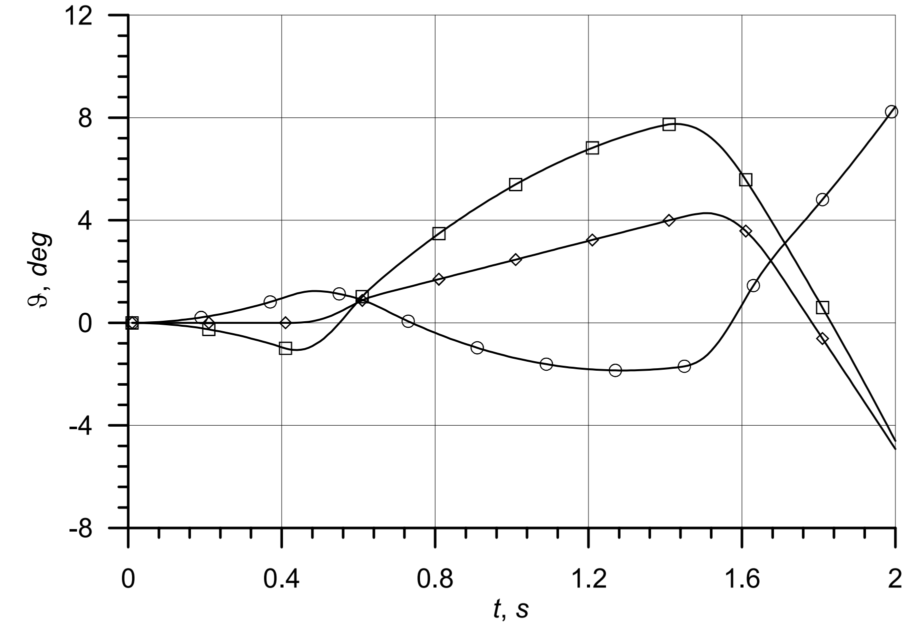

Figure 4 – The helicopter pitch attitude during landing
(◇ - load case 1; ○ - load case 2; ◘ - load case 3)

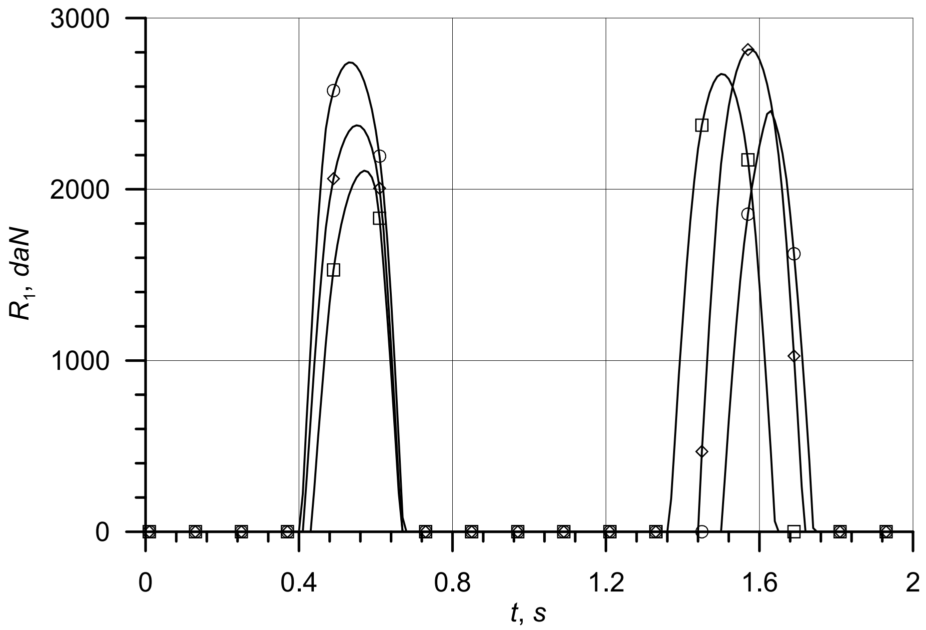

Figure 5 – Reaction on the rear spring during landing
(◇ - load case 1; ○ - load case 2; ◘ - load case 3)

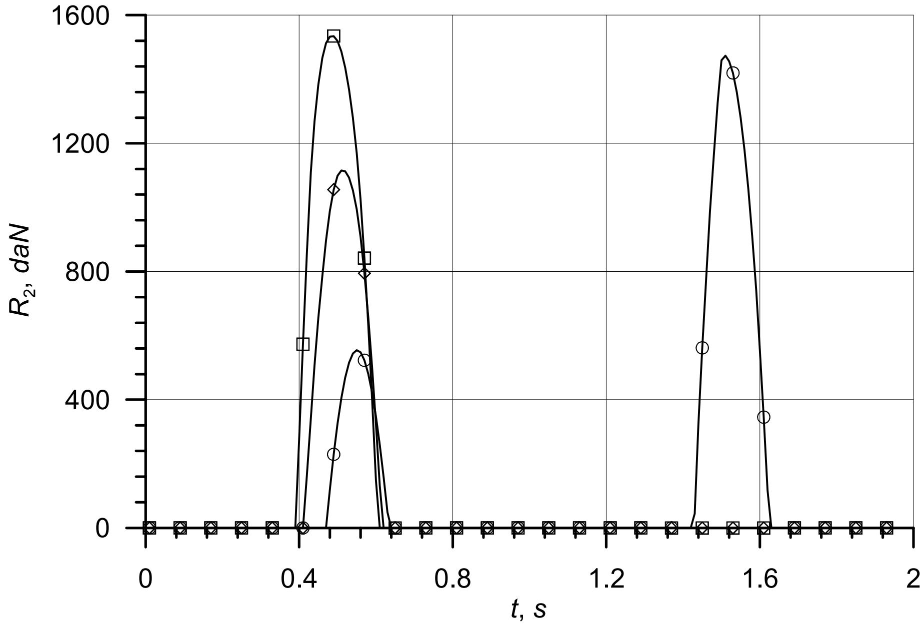

Figure 6 – Reaction on the front spring during landing
(◇ - load case 1; ○ - load case 2; ◻ - load case 3)

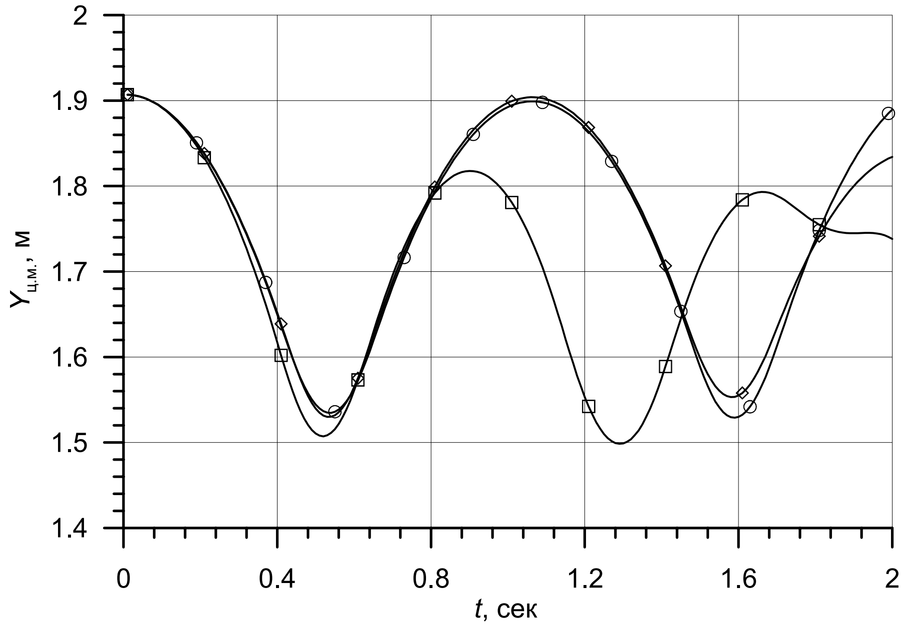

Figure 7 – Moving of the helicopter center of mass during landing
(◇ - load case 1; ○ - load case 4; ◻ - load case 5)

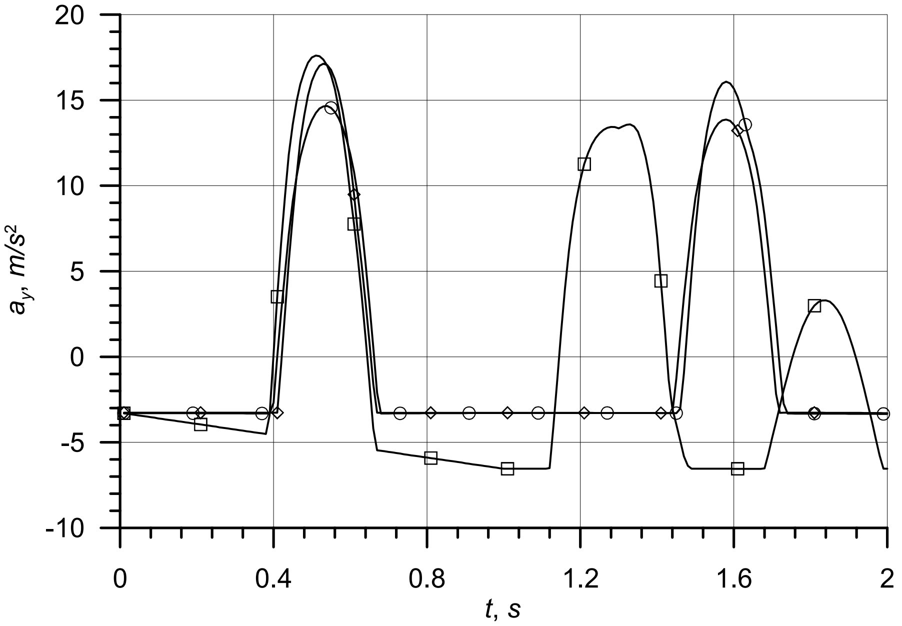

Figure 8 – Acceleration factor in the helicopter center of mass during landing (◇ - load case 1; ○ - load case 4; ◘ - load case 5)

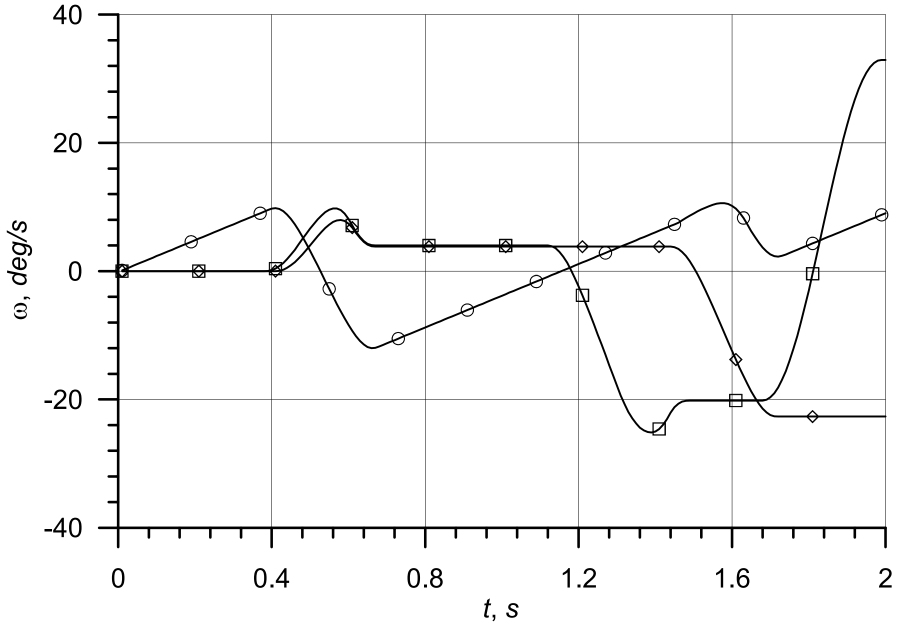

Figure 9 – The helicopter pitch attitude during landing (◇ - load case 1; ○ - load case 4; ◘ - load case 5)

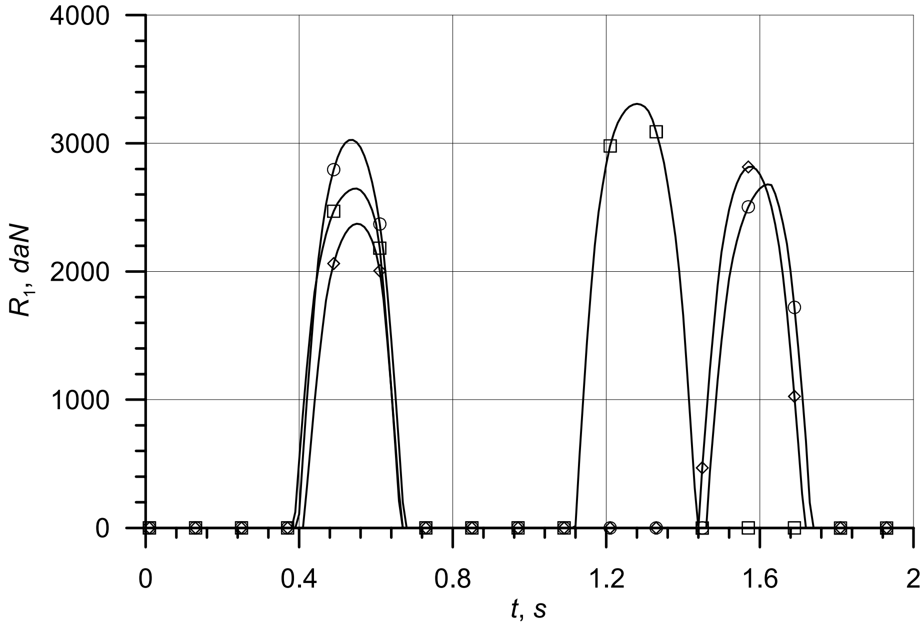

Figure 10 – Reaction on the rear spring during landing
(◇ - load case 1; ○ - load case 4; ◘ - load case 5)

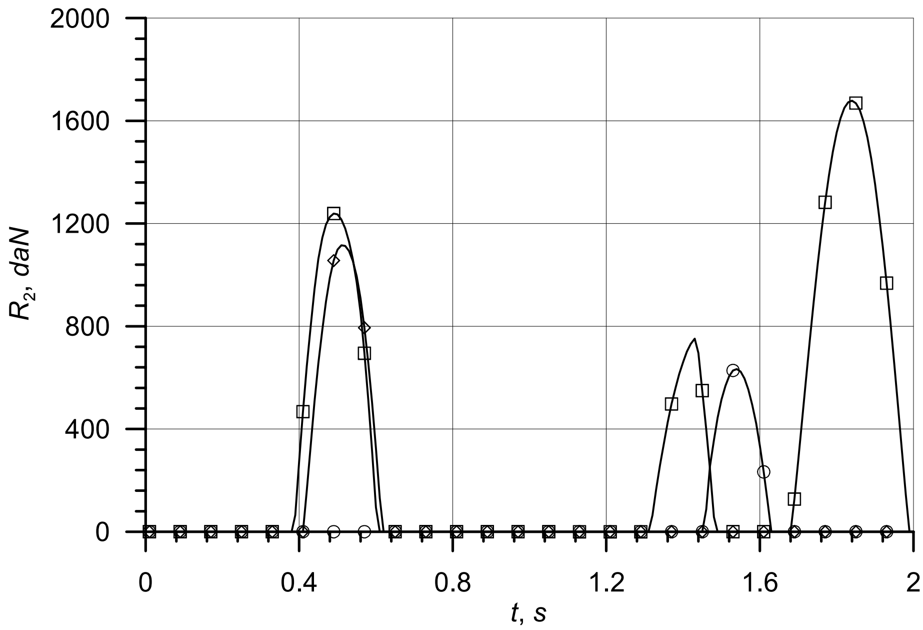

Figure 11 – Reaction on the front spring during landing
(◇ - load case 1; ○ - load case 4; ◘ - load case 5)

The aboveshown comparative charts demonstrate that the amounts of load on the main rotor exercise a significant influence on the helicopter landing process and the loading conditions of the skid-equipped landing gear. In most simulation cases, there is a significant difference in the helicopter behavior during landing compared to the conditions required by the FAR-29 norms. The analysis of the helicopter movements' character during different complexes of loads made by the main rotor, shows the possibility of helicopter nosing in some certain unfavorable landing conditions, such as axial velocity of movement or considerable forces of friction of the skids at the flight landing strip.

The abovelisted circumstances show practicability of considering all forces and torques created by the helicopter's pivotless main rotor during the auto-rotation landing. And the method invented by the authors allows to consider them very thoroughly, as well as to consider the influence of stick forces not only at general pitch, but also at cyclic pitch, which is set by the pilot through the helicopter's actuating levers.

List of references

1. Mikhailov S.A., Nedelko D.V. "Numerical modeling of load parameters for a helicopter's skid-equipped landing gear, using 3D model". Selected works. The IV Forum of Russian Helicopter Society. Moscow, 2000.

2. Mikhailov S.A., Nedelko D.V. and Shuvalov V.A. Analysis of skid landing gear landing dynamics. Abstract for Aircraft design session 26th European Rotorcraft Forum. Hague/ Netherlands. September 26-29. 2000.

3. Girfanov A.M. Mathematical model of complex dimensional warping of the main rotor blade during a helicopter autokinetic movement // Samara, The Newsletter of Samara aerocosmic state university, #4, 2009.

4. Pavlov V.A., Gainutdinov V.G., Mikhailov S.A. The theory of big and finite displacements of a rod. //The news of higher educational institutions. Aviation technique. 1985. #3. P. 55-58.

5. W.Johnson. The theory of helicopters. – Moscow: Mir, 1983. – Book 1.