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ANALYSIS OF SKID LANDING GEAR LANDING DYNAMICS

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Summary

We present the fundamentals of the analysis technique of a skid helicopter landing which takes into account all necessary design features of this landing gear type and modern-day requirements of the standard documents as to its design. We compare the results of the design studies with the experimental data and results obtained using other techniques.

Introduction

The design techniques which were used over several tens of years possessed a number of simplifications and in essence copied the traditional approach to the analysis of aircraft landing gear absorption concerning the calculation of shock-absorbing elements loads. In the framework of such an approach called "classical" in [2] the front and rear landing gear springs are simulated separately without regard for a skid and their proper deformations during landing are determined by means of preassigned calculational or experimental diagrams of springs static compression. In real service conditions, however, a helicopter can extremely seldom perform an autorotation landing in the strictly horizontal position. At the moment of ground touch the helicopter will most likely have some bank or pitch angle or their combination. In this case FAR-29 and FAR-27 require the supporting evidence for energy intensity of each landing gear element under its most unfavorable conditions.

At present the investigations of the skid landing gear helicopter landing dynamics are carried out by specialists of the leading helicopter companies [1, 2]. They are based on the application of the present-day finite element systems for the helicopter drop dynamics analysis. It is seen from the results of these studies that the structure under investigation was simulated rather accurately and we solved the problem of both overall and local strength during landing. At the same time the investigators [2] note that the analysis takes plenty of time and this methodology can be used in the case when the structural parameters have already been determined.

Further studies are needed to optimize the structural parameters of the skid landing gear from the viewpoint of using composites and searching for the most efficient structure geometry. The authors have developed a technique for the dynamic analysis of helicopter landing under various landing conditions. The basis for this technique is the consideration of main design features of the landing gear influencing its shock-absorbing capabilities. The design model of the landing gear structure makes it possible to simulate rather accurately landing gear-to-fuselage attachment conditions, to take into account friction between moving structural elements and skid-on-ground friction.

It should be noted that the general strategy of investigations [1, 2] supposes that the problem of landing gear structure strength is solved concurrently with the simulation of the helicopter landing dynamics. In the study being suggested these two problems are separated into independent ones. To design the skid landing gear it is important to determine properly and rather rapidly the level of acting loads in each landing case to provide the design strength analysis with necessary accuracy. The subsequent checking strength analysis can be carried out using the same finite element method at the rather large number of finite elements but now at the level of solving a static problem.

1. Skid Landing Gear Design Model

The main purpose of the skid landing gear is to prevent helicopter structure destruction at the hard autorotation landing, that is, to absorb landing shock energy. In this case the shock-absorbing structural landing gear elements (as a rule, they are elastic springs) can also operate under conditions of plastic material deformation when they gain large displacements. The necessity to take into account geometric and physical nonlinearity of the skid landing gear structural elements deformation as well as connection of front and rear springs with skids results in significant complication of this unit analysis and design techniques.

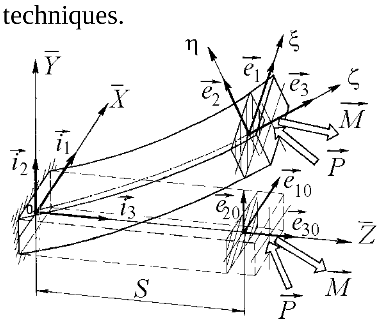


Fig.1

Here $\kappa_\xi = \dfrac{M_\xi}{EJ_\xi}$, $\kappa_\eta = \dfrac{M_\eta}{EJ_\eta}$, and $\kappa_\varsigma = \dfrac{M_\varsigma}{GJ_p}$ are the Kirchhoff-Clebsch relations; $\omega_0 = \{\omega_{01}, \omega_{02}, \omega_{03}\}$ is the initial curvature vector; $(\varphi_1, \varphi_2, \varphi_3)$ are the angles of unit vector coincidence $\{e_i\}$ of the local coordinate system $\xi\eta\zeta$ connected with the section, with the unit vectors $\{i_j\}$ of the common; i.e. base system $O_1\bar{X}\,\bar{Y}\,\bar{Z}$ (Fig. 1). The axes $\xi\eta\zeta$ coincide with the main central axes of the spring section, the moments

M_ξ, M_η, M_ζ and rigidities EJ_ξ, EJ_η, GJ are written with respect to them.

The theory of large bar displacements [3] was used to take into account the geometric nonlinearity phenomenon in the landing gear structure deformations. In the framework of this theory the elastic center position in space of the bar arbitrary section (Fig. 1) is completely determined by three

$$\begin{cases} \varphi_1 - \int \left(\dfrac{1}{\cos\varphi_2} \left[(\kappa_\xi + \omega_{01}) \cos\varphi_3 - (\kappa_\eta + \omega_{02}) \sin\varphi_3 \right] \right) dS + C_1 = 0; \\ \varphi_2 - \int \left([\kappa_\xi + \omega_{01}] \sin\varphi_3 + [\kappa_\eta + \omega_{02}] \cos\varphi_3 \right) dS + C_2 = 0; \\ \varphi_3 - \int \left([\kappa_\varsigma + \omega_{03}] - \mathrm{tg}\,\varphi_2 \left\{ [\kappa_\xi + \omega_{01}] \cos\varphi_3 - [\kappa_\eta + \omega_{02}] \sin\varphi_3 \right\} \right) + C_3 = 0. \end{cases} \tag{1}$$

solid angles of the section rotation $(\varphi_1, \varphi_2, \varphi_3)$; to find these angles three integro-differential equations are written:

The connection between the angles of the section rotation and linear coordinates of the corresponding point on the elastic line in space is determined by the equations:

$$\begin{cases} y = \int \cos\varphi_2 \sin\varphi_1 dS + C_4; \\ x = \int \sin\varphi_2 dS + C_5; \\ z = \int \cos\varphi_1 \cos\varphi_2 dS + C_6. \end{cases} \tag{2}$$

The external load vector $\{M_x, M_y, M_z\}$ is written with the use of the bar equilibrium equations in the base coordinate system $O_1\overline{X}\,\overline{Y}\,\overline{Z}$. The bending moments are converted into the local section axes $\xi\eta\zeta$ with the aid of the known matrix of coordinates alignment L [3]:

$$\{M_\xi, M_\eta, M_\zeta\} = L\,\{M_x, M_y, M_z\} \tag{3}$$

Relations (1), (2) and (3) make it possible to determine the position in space of the bar elastic line. The integration constants C_1, C_2, C_3, C_4, C_5, C_6 are found by the bar attachment conditions. Six additional equations are made up for this purpose. In the matrix form relations (1) – (3) in the combination with the equations for integration constants are written in the following form:

$$F(X, P) = 0\,, \tag{4}$$

where X is the vector of the basic unknowns $(\varphi_1, \varphi_2, \varphi_3)$ and (C_i); P is the generalized loading parameter.

In this problem formulation the theory of large bar displacements makes it possible to calculate the statically determinate bar systems. As the skid landing gear is a statically indeterminate structure, the additional calculation methods are needed.

Matrix equation (4) can be written separately for each landing gear spring. In this case we obtain the extended system of equations:

$$\begin{cases} F_I(X_I, P) = 0; \\ F_{II}(X_{II}, P) = 0. \end{cases} \tag{5}$$

In system (5) the subscript "I" refers to the rear spring and the subscript "II" denotes the front spring. The skid provides the concurrent deformation of two springs. According to the preliminary analysis of real landing gear structures the proper displacements of skids under the action of design load are small as compared to the large displacements of springs and practically have no influence on shock absorption. In the design model, therefore, each skid is specified as an absolutely rigid bar providing the geometric and structural connection between the front and rear springs without regard for its proper deformations. The force method is used to calculate the statically indeterminate model formed.

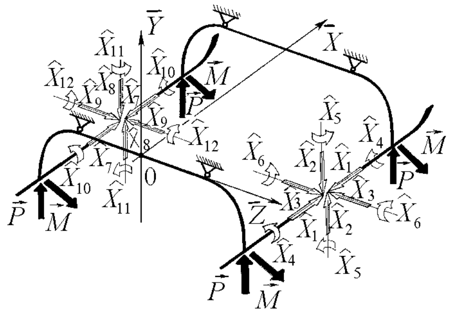


Fig. 2

The basic system of the force method is obtained by the introduction of additional cuts along the right and left skids and twelve unknown forces $\hat{X}_i$ (i = 1, …, 12) corresponding to these cuts (Fig. 2). To find the unknown forces we used conditions of zero equality of the displacements along the corresponding directions in the cuts section [6]: $\Delta_i = 0$. Then system (4) in the final form will be written as follows:

$$\begin{cases} F_I(X_I, X_{II},\ \hat{X}_1,\ \hat{X}_2, \ldots,\ \hat{X}_{12}, P) = 0; \\ F_{II}(X_I, X_{II},\ \hat{X}_1,\ \hat{X}, \ldots,\ \hat{X}_{12}, P) = 0; \\ \Delta_1(X_I, X_{II},\ \hat{X}_1,\ \hat{X}, \ldots,\ \hat{X}_{12}, P) = 0; \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ \Delta_{12}(X_I, X_{II},\ \hat{X}_1,\ \hat{X}, \ldots,\ \hat{X}_{12}, P) = 0. \end{cases} \tag{6}$$

The integral functions of nonlinear equation system (6) were digitized with the aid of the integrating matrix method [5] using the integrating matrices of the so-called "third type" which take into account the arbitrary position of the base coordinates origin along the bar and the finite number of integrand discontinuities along the integration interval. To solve system of equations (6) we used the Newton-Raphson method. By the technique developed we compiled a calculation algorithm for a computer and carried out a test analysis of static loading for the landing gear structure of a light multi-purpose helicopter. It should be noted that in the framework of this paper we consider solely the structures that retain their elastic properties to the point of destruction. It is these properties that the helicopter landing gear structure being analyzed possesses; the helicopter landing gear has springs made of glass-reinforced plastic-based composite. At present we have developed a technique which makes it possible to take into account plastic deformations accumulation in the landing gear spring material (metal springs) but it is not considered in this paper.

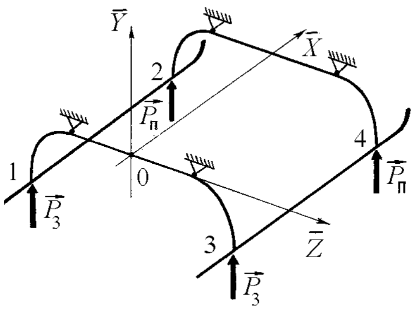


Fig. 3

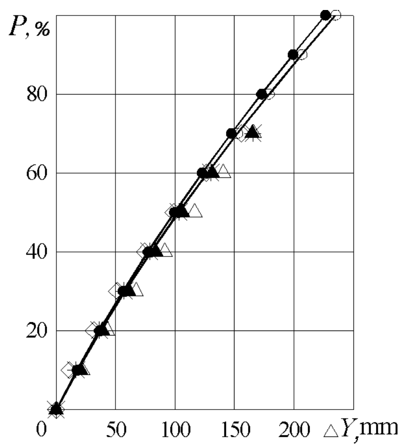


Fig. 4

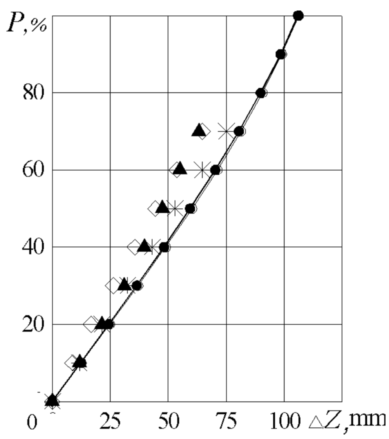


Fig. 5

As an example we present the calculation for the landing gear loading case at the vertical landing which corresponds to load standards in FAR-29 paragraph 29.501-(b). Figure 3 presents the scheme of landing gear loading and points for measuring displacements during tests (1, 2, 3, 4 are the points of load application and measurement of structure displacements). The displacements as a function of the external load value in the vertical ($O_1\overline{Y}$), lateral ($O_1\overline{Z}$) and longitudinal ($O_1\overline{X}$) directions respectively are shown in Figs. 4, 5 and 6. During tests the displacements were measured up to 70% of the external load. According to the experimental measurements, the dependence of point 1 displacements is conventionally denoted as ∴, the dependence of point 2 displacements – as ⊥, the dependence of point 3 displacements – as O, and the dependence of point 4 displacements is designated as . It should be noted that there exist longitudinal displacements of the force application points (Fig. 6) under the action of vertical load alone which are due to geometric nonlinearity of deformation and this fact was obtained as a result of calculations with quite reasonable accuracy.

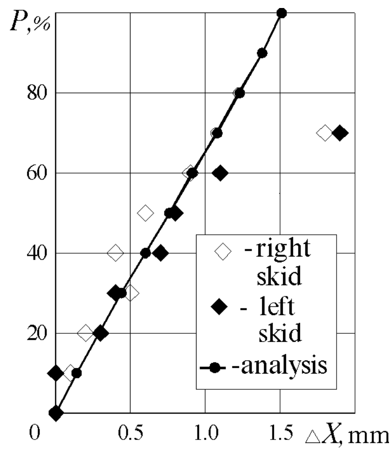


Fig. 6

The application of the integrating matrix method to the landing gear structure analysis makes it possible to simulate properly the spring-to-fuselage attachment conditions. The spring attachment fittings of the landing gear under consideration are represented schematically in Fig. 7. The point of the bracket *K* rotation fixed in position on the fuselage is removed with respect to the spring elastic axis by an eccentricity value r_0; during spring deformation the bracket slides along the spring axis rotating about this point. Strictly speaking, such a structure is a geometrically changeable one, but consideration of the difference of actual friction forces in the left-hand and right-hand clamps makes it possible to simulate properly the deformed state of the spring for each specific case of loading. For this purpose we introduce additional unknowns determining the geometry of the structure being deformed: increment of the distance between the left-hand and right-hand brackets ΔS (along the arc coordinate) and rotation angles of the brackets θ_1, θ_2 (Fig. 7). The equations for their determination complement system of equations (6) and at each step of the integration solution of this system the integrating matrices must be converted since during loading the length of one of the integration sections changes along the spring elastic line.

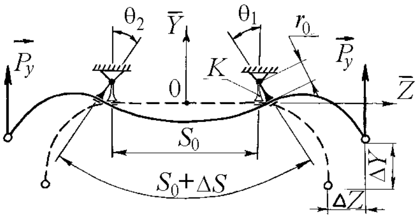


Fig. 7

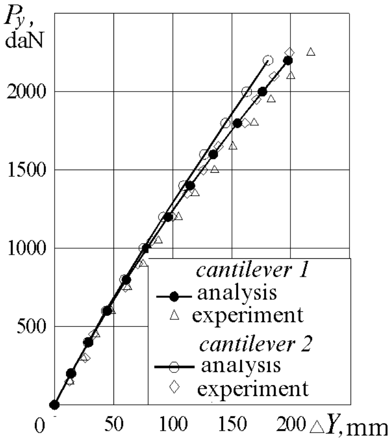


Fig. 8

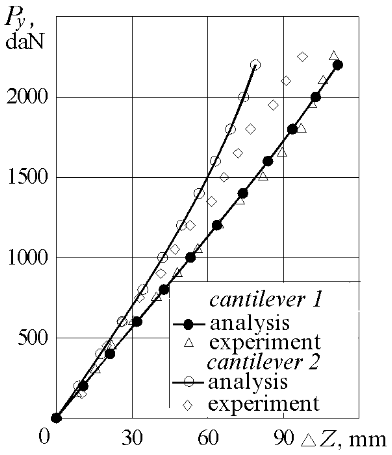


Fig. 9

Such a model was used to reconstruct the experiment for determining a diagram of rear spring static compression of the landing gear under study. The scheme of spring loading and attachment on the test stand corresponds to Fig. 7. The displacements of the force application points in the vertical ($O_1\overline{Y}$) and horizontal ($O_1\overline{Z}$) directions respectively are shown in Figs. 8 and 9. The difference in displacements of the left-hand and right-hand spring cantilevers is explained by the difference in forces of the initial motion of the left-hand and right-hand brackets; as a result one of them slides along the spring, and the other merely rotates about the stationary attachment point but does not slip. The consideration of this phenomenon made it possible to simulate properly the conditions of the landing-gear structure attachment and to study a problem of the influence of these conditions on the stress-strain state of the structure on the whole. In addition, this model made it possible to solve a problem of identification of the elastic and rigid characteristics of the landing-gear composite springs using the test results on static compression since the model takes into proper account the spring attachment conditions on the test stand.

The three-dimensional landing gear model developed allows the static stress-strain state of the structure to be calculated for any design case of helicopter landing agreed in FAR-29, FAR-27 requirements. Besides, this model is used in the quasistatic approach to the solution of the helicopter landing dynamics problem.

2. Helicopter Landing Dynamics Analysis

According to FAR-29 instructions, in the analysis of the helicopter landing dynamics the fuselage is specified as a rigid body with the mass concentrated at the point of the center of gravity which possesses the given inertia characteristics. The landing surface in the analysis is specified as an analytical plane fixed to the earth coordinate system $O_2X_0Y_0Z_0$ which may be horizon-oriented by means of angles of lateral and longitudinal inclinations. The common origin of the normal $OX_gY_gZ_g$ and fixed $OXYZ$ coordinate systems is at the helicopter fuselage center of gravity (Fig. 10). The base axes $O_1\overline{X}\,\overline{Y}\,\overline{Z}$ of the landing gear design model are specified with respect to the fixed coordinate system. Since the skids are simulated as rigid bars then the forces of the earth reaction R_i (i=1,..,4) are reduced to the front and rear ends of each skid. In this case the skid friction on the landing surface is given by means of the corresponding friction coefficients. During the landing analysis the forces R_i must be determined at each moment of time, that is, they should be added to the number of basic unknowns.

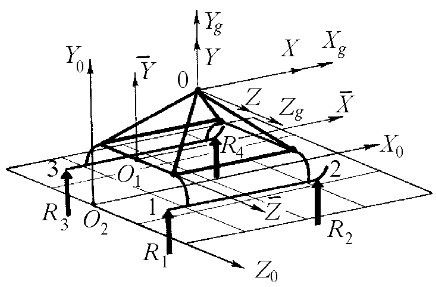


Fig. 10

We have thus considered the helicopter landing as a body motion in space under the action of its own weight, the main rotor thrust and earth reaction forces. The helicopter attitude at any moment of time is completely determined by three linear coordinates x, y, z and three solid angles: of bank γ, yaw ψ and pitch ϑ.

The quantities of the earth reactions specified in earth axes are converted into the body-fixed axes by means of the directional cosines matrix:

The inverse conversion of the deformed structure geometry determined in the base coordinate system into the normal axes is carried out with the aid of the inverse matrix $L_\varphi^{-1} = L_\varphi^T$ obtained by transposition of matrix (7).

The helicopter motion from the moment when the skids touch the landing surface is described by the known equations of dynamics:

$$\begin{aligned}
\ddot{x} &= \frac{\sum P_x}{M_0} - \dot{\psi}\cdot\dot{z} + \dot{\vartheta}\cdot\dot{y};\\
\ddot{\gamma} &= \frac{\sum M_x}{J_x} - \frac{J_z - J_y}{J_x}\cdot\dot{\psi}\cdot\dot{\vartheta};\\
\ddot{y} &= \frac{\sum P_y}{M_0} - \dot{\vartheta}\cdot\dot{x} + \dot{\gamma}\cdot\dot{z};\\
\ddot{\psi} &= \frac{\sum M_y}{J_y} - \frac{J_x - J_z}{J_y}\cdot\dot{\vartheta}\cdot\dot{\gamma};\\
\ddot{z} &= \frac{\sum P_z}{M_0} - \dot{\gamma}\cdot\dot{y} + \dot{\psi}\cdot\dot{x};\\
\ddot{\vartheta} &= \frac{\sum M_z}{J_z} - \frac{J_e - J_x}{J_z}\cdot\dot{\gamma}\cdot\dot{\psi}.
\end{aligned} \tag{8}$$

Here $\overline{P} = \{\Sigma P_x; \Sigma P_y; \Sigma P_z\}$ and $\overline{M} = \{\Sigma M_x, \Sigma M_y, \Sigma M_z\}$ are the principal vector and the principal moment of external forces; $\overline{J} = \{J_x, J_y, J_z\}$ is the helicopter fuselage inertia tensor. The numerical integration in time of system of differential equations (8) with the use of (7) and (6) makes it possible to determine the helicopter attitude and landing gear loads at each moment of time. Since the numerical solution in the landing gear deformed state analysis is based on the Newton iteration method then the most time-consuming part of calculations is to make up a partial derivative matrix [6]. In the general case the vector of basic unknowns has a rather large dimension: $X = \{X_I, X_{II}, \hat{X}_1, \ldots, \hat{X}_{12}, \Delta S, \theta_1, \theta_2, R_1, \ldots, R_4\}$. This fact called for optimization of the problem solution algorithm. The time necessary to calculate one landing case amounts from 15 to 40 minutes depending on the complexity of landing conditions realization in each specific case.

As examples of the helicopter landing simulation with the aid of the technique developed we present the analysis results for the cases of horizontal landing and one skid landing (with the initial angle of bank $\gamma_0 = 1.5^\circ$) in Figs. 11 and 12. The comparison of the analysis results with those of landing simulation by the technique realizing the "classical" approach is shown in Fig. 11. The quantities of R_i reactions as a function of time are given in Figs. 11, *a* and 12, *a*; the vertical displacements Δh_i of the spring-skid connection points against time are presented in Figs. 11, *b* and 12, *b* (the numbers of the points *i* correspond to Fig. 10); the solid angles of bank γ, yaw ψ and pitch ϑ as a function of time are shown in Figs. 11, *c* and 12, *c*.

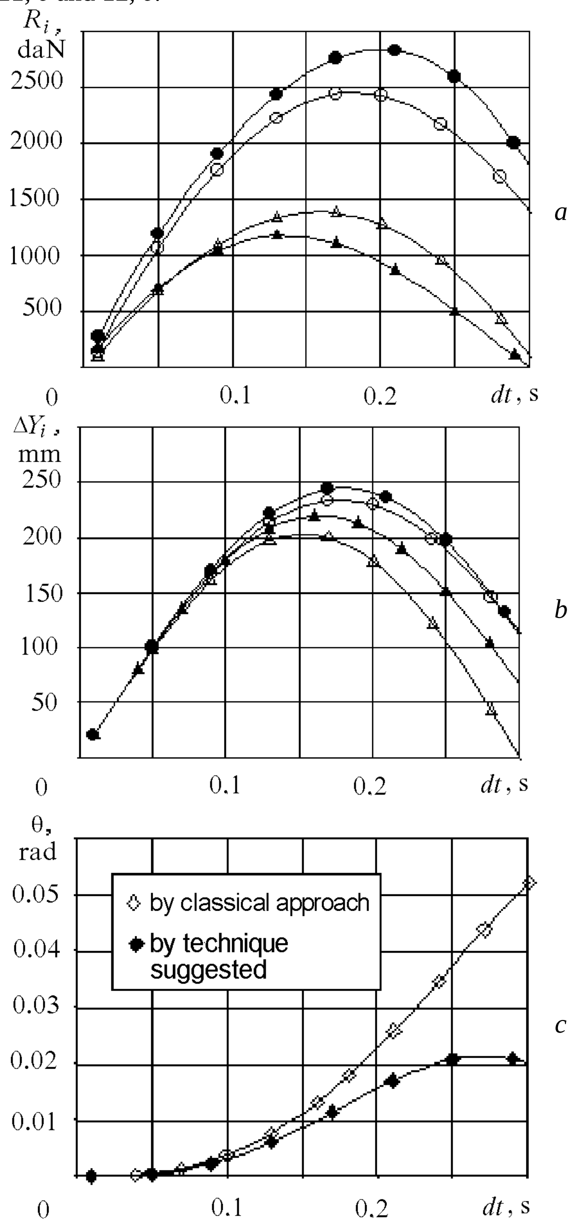


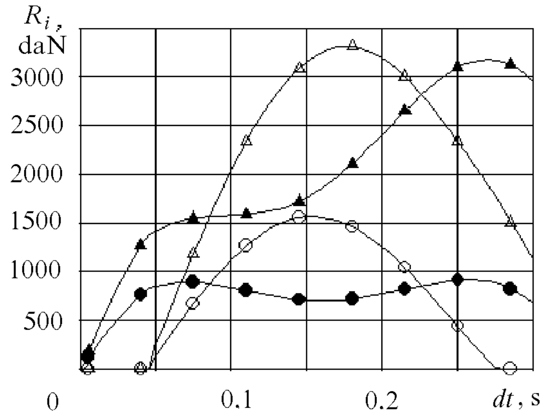
Fig. 11. —△— – front spring, —○— – rear spring: by classical approach; —▲— – front spring, —●— – rear spring: by technique suggested

In Fig. 11, *a* we see the effect of load redistribution to the front and rear landing gear springs due to

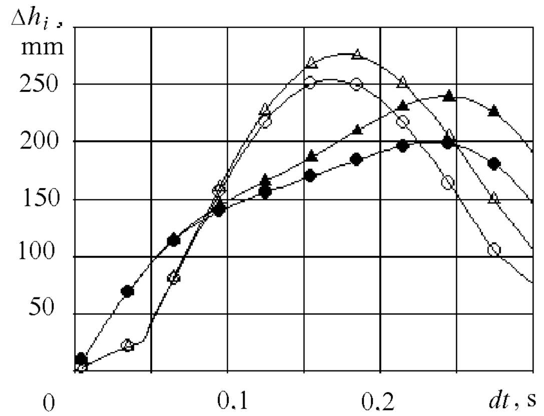
$$L_\varphi = \begin{vmatrix} \cos\vartheta\cos\psi & \sin\vartheta\cos\gamma + \cos\vartheta\sin\psi\sin\gamma & \sin\vartheta\sin\gamma - \cos\vartheta\sin\psi\sin\gamma \\ -\sin\vartheta\cos\psi & \cos\vartheta\cos\gamma - \sin\gamma\sin\psi\sin\vartheta & \cos\vartheta\sin\gamma + \sin\vartheta\sin\psi\cos\gamma \\ \sin\psi & -\sin\gamma\cos\psi & \cos\gamma\cos\psi \end{vmatrix} \tag{7}$$

the skid influence. In addition to this landing gear elements load redistribution the inclusion of the skid makes it possible to adjust the helicopter attitude at any moment of time by the pitch angle (Fig. 11, *c*). One skid landing case cannot be calculated by the technique realizing the "classical" approach.

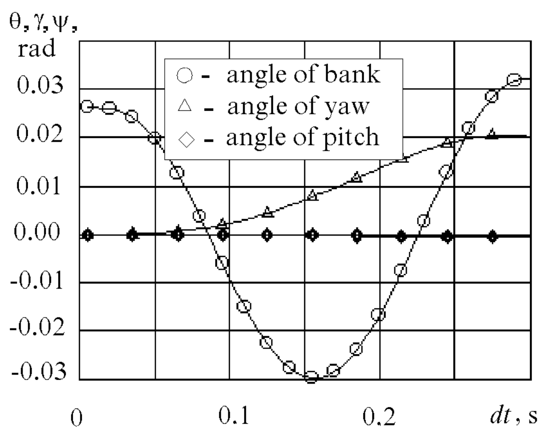
The simulation results for the case of one skid landing with a lateral restriction are given in Fig. 13. In this case one of the points of the spring-skid connection encounters a stationary lateral obstacle which constrains sliding of this point along the landing surface. Here the landing gear structure experiences a shock which is transmitted to the fuselage structural elements. Figure 13 presents variation in time of the vertical reaction quantities in the fittings of spring-to-fuselage attachment (the conventional symbols of points 1, 2, 3, 4 correspond to those in Figs. 12, *a* and 12, *b*).



a



b



c

Fig. 12. △ – point 3, ○ – point 4
▲ – point 1, ● – point 2

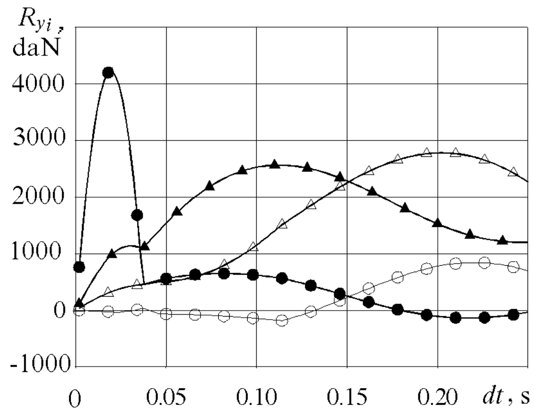


Fig. 13

The analysis of this landing case is not included in FAR-29 requirements but it is a necessary present-day calculation condition in the skid landing gear design.

3. Concluding Remarks

The technique developed was used in designing the skid landing gear of a light multi-purpose helicopter and allowed good results to be achieved both at the stage of design and at the stage of checking strength analysis.

The application of the technique developed is not restricted by the helicopter landing dynamics analysis. The technique makes it possible to study landing safety to exclude: a) possibility for helicopter structure elements to touch ground when the landing gear springs are compressed both during landing on the horizontal place and in the presence of longitudinal and lateral inclinations; b) possibility for a helicopter to turn over during landing with the initial angle of bank to the lateral inclination.

The technique makes it possible to develop crew recommendations for the most advantageous landing. The further development of the technique enables us to study a problem of helicopter transverse balancing on the inclined place. This problem is solved for the scheme of a wheel landing gear but it cannot be studied for the skid landing gear if the complete model of such a landing gear like the considered one is not used.

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