Methodology and Some Results of Studying Features of Helicopter Landing Impact Characteristics with Regard to Properties of Landing Site Surface

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The level of human safety aboard the helicopter is one of the key factors determining perfection of the helicopter design and its competitiveness. The domain of safety in general is fairly diversified in the composition of problems defining it.

This paper goes into the matters pertaining to one of the most acute problems: ensuring safety under critical conditions of the helicopter landing. We offer a procedure for evaluation and formation of the helicopter characteristics advisable, proceeding from the safety conditions, for landing under critical conditions with due account for the actual properties of the landing site surface. The initial phase in our work on the methodology was calculations presented in paper [1]. The methodology includes a set of requirements to the statement of the problem, generation of a theoretical model of the helicopter, wheeled and skid-type landing gear, a model of the landing site, as well as with respect to the computer process organization.

For analysis of the helicopter landing impact characteristics (loads, required reserve energy absorption capacity of the landing gear, dynamic behavior of the helicopter, etc.) with an allowance for the nature of the landing site soil, use is made of high-level analytical complexes.

The work opens a new wide area of analytical studies of how the properties of the landing site and landing technique influence the helicopter appearance, landing gear design, level of safety during forced landings, landing procedures, etc.

The paper contains some results of analytical studies intended to demonstrate the credibility and relevance of this work for the helicopter design practice.

The findings may change in principle the forced landing procedures.

1. Features of Helicopter LG Interaction with Landing Site Surface (LSS)

Under consideration is the helicopter movement in the vertical plane with the plane of symmetry of the helicopter being in agreement with the vertical plane. It is assumed that the helicopter is a perfectly rigid body. The system of external forces acting on the helicopter in flight at the time the landing gear touches down the LSS is reduced to the center of mass of the helicopter and is determined by the generalized vector

$$F = \begin{Bmatrix} Fx \\ Fy \\ Fz \end{Bmatrix}$$

One of the primal problems coming under review during analysis of the landing impact is the problem of absorption and dissipation of the helicopter's kinetic energy and stipulation of conditions under which this process runs at minimum and admissible loads applied to the helicopter. Solving of such problems predetermines the necessity of the analysis of the energy process running at the landing impact and this, in many ways, formalizes the requirements to the statement of problems provided for performing the analytical studies. Initial data of a problem, existence of energy sources and sinks taken into account during solving of the problem should be rigorously substantiated. The paper relies on a problem the statement of which is based on a generally accepted, both in this country and abroad, statement for problems of this kind.

The required kinetic energy of the helicopter that need to be absorbed and dissipated is determined by the initial conditions of the landing impact that includes conditions at the time the helicopter LG touches down the LSS. It is assumed that at the point of the landing impact the helicopter has got a vertical component (Vy) and a longitudinal component (Vx) of the linear travel, and the angular velocity (Wz) is zero. The main rotor thrust is directed strictly upward and under the landing impact retains its value, unless expressly specified, and direction. There are no other external forces or moments acting on the helicopter. Subsequently, the landing impact gives rise to secondary forces of the landing gear interaction with the LSS. At the point of the landing impact, the generalized vector F appears as follows

$$F = \begin{Bmatrix} 0 \\ T - G \\ 0 \end{Bmatrix},$$

where:
T is the propeller thrust force
G is the weight of the helicopter.
In what follows, vector F changes in view of the emergence of forces of the landing gear interaction with the LSS.

Thus, the presence of the (T – G) member in the generalized vector F provides, depending on the direction of movement of the center of mass of the helicopter, for consideration of only one active energy source when the center of mass of the helicopter moves downward (the helicopter's kinetic energy increases for the account of reduction of the helicopter's potential energy) and only one active energy sink when the center of mass of the helicopter moves upward (part of the helicopter's kinetic energy changes into the helicopter's potential energy).

With regard to the generalized load factor F, the equations of the helicopter motion can be expressed as a system:

$$\left.\begin{aligned} m\frac{d^2x}{dt^2} &= -X_{LG} \\ m\frac{d^2y}{dt^2} &= Fy + Y_{LG} \\ I\frac{d^2\theta}{dt^2} &= M_{YLG} - M_{XLG} \end{aligned}\right\} \qquad (1)$$

where

m – helicopter mass,

I – mass moment of inertia,

θ – center-of-mass rotation angle,

X_{LG} – longitudinal landing gear friction force,

Y_{LG} – vertical force of the landing gear interaction with the LSS,

M_{YLG}, M_{XLG} – moments produced by the X_{LG} and Y_{LG} forces.

Figure 1 shows two possible positions of the LG legs (numerated 1 and 2, the right-hand side of the Figure) after time ti depending on the direction of the helicopter rotation.

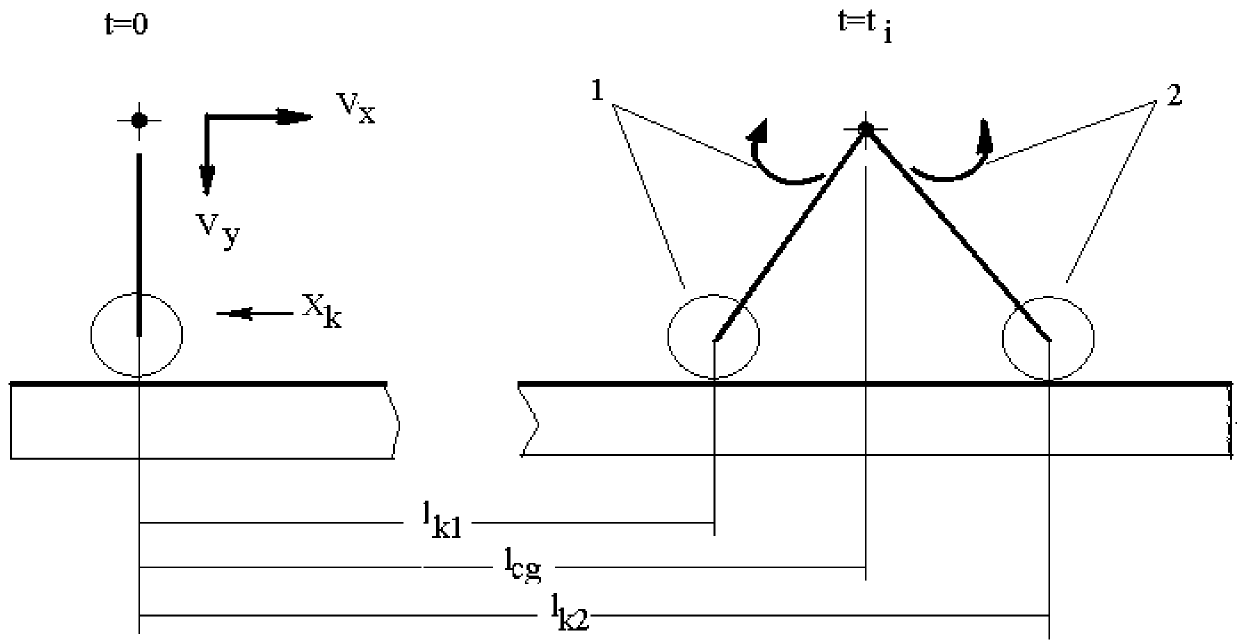

Figure 1 – Possible Positions of Helicopter LG Leg during Landing

The main thing that is noteworthy is that the centre of gravity of the helicopter and the point of the wheel contact with the LSS moved over different distances (lcg ≠lk1, lcg ≠lk2).

During nose-down pitching of the helicopter (position 1), the wheel moved longitudinally over a smaller distance relative to the helicopter CG displacement. It should seem, see Fig. 1, that during the helicopter movement in the longitudinal direction, force Xk dissipates part of energy of the longitudinal motion of the helicopter with the wheel moving to a distance of lk1 and does an active work during the helicopter rotation. But force Xk is unable to do any active work.

Let us refer to differential equation system (1) and consider the case where no other force, save for Xk, acts longitudinally.

The equation of longitudinal motion takes the form

$$m\frac{d^2x}{dt} = Xk$$

It suggests that the longitudinal motion of the helicopter has lost energy equal to the energy dissipated by force Xk on the helicopter's center-of-gravity path.

From the third equation of system (1) it follows that the helicopter's rotation energy increased, insomuch as the moment of force Xk is directed towards the helicopter rotation and force Xk supposedly does an active work.

If it is remembered that the dissipated from the system energy which is determined by the movement of force Xk along the path of the patch of the wheel contact with the LSS (lcg) and it is less than the energy lost in the longitudinal motion of the helicopter, then the energy changes become fairly clear. During nose-down pitching of the helicopter, force Xk in addition to the dissipation function also performs the redistributional function which consists in that part of the energy of longitudinal motion is converted into the helicopter's rotation energy and other components of the total energy.

During the helicopter rotation towards nose-up pitching (position 2) the patch of the wheel contact with the LSS will move longitudinally over a greater distance relative to the helicopter CG displacement. The moment of force Xk is directed in the opposite direction to the helicopter rotation. Taking into account the above reasoning with regard to position 1, it is obvious that the helicopter CG is retarded longitudinally fully for the account of dissipation of the energy of longitudinal motion by force Xk. However, during angular motion of the LG leg, force Xk dissipated complementary energy and that same energy which rotates the helicopter towards nose-up pitching.

Development of the landing impact in accordance with position 1 is extremely adverse: the helicopter tends to nose over. And vice versa, development of the landing impact process in accordance with position 2 is extremely positive-working, if the helicopter is rotated towards nose-up pitching by the energy of vertical motion of the helicopter. In this case, in angular motion of the helicopter towards nose-up pitching, force Xk plays a part of an efficient natural damper.

Figure 2 shows a system of forces acting on the helicopter at the landing impact in the statement of the problem per FAR 29, 27.

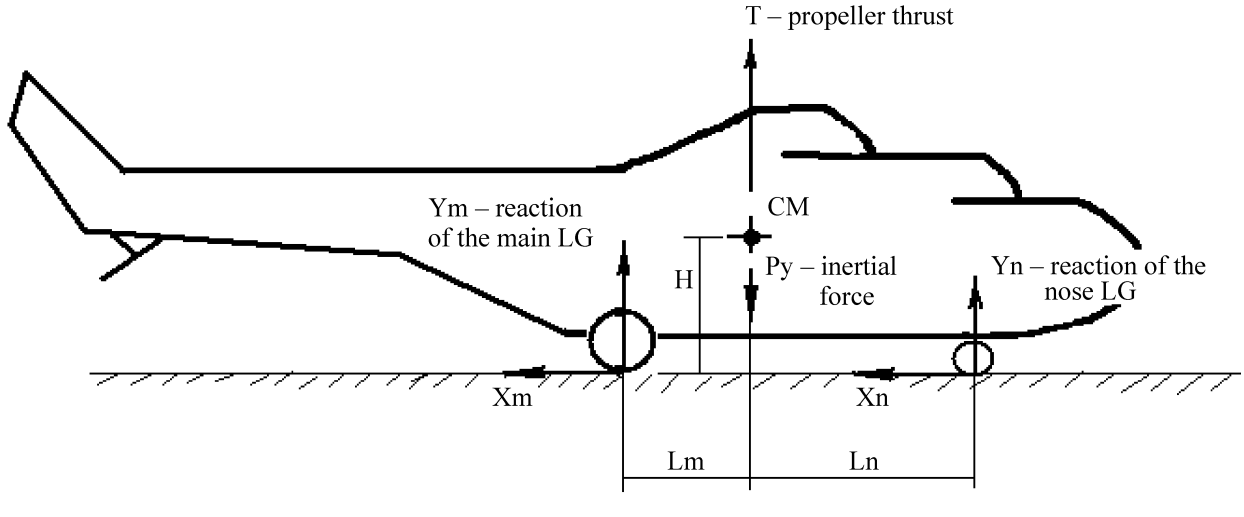

Figure 2 – System of Forces Acting on the Helicopter per FAR 29

Of all the forces acting on the helicopter only the vertical force of the nose LG reaction creates a nose-up moment, that is why the condition of the helicopter rotation towards nose-up pitching at the landing impact appears as follows:

Yn*Ln> Ym*Lm + (Xm +Xn)*H

In the course of designing, this inequality can be easily satisfied.

2. General Provisions and Theoretical Model

Regulatory documents prescribe that during development of the helicopter, landing data should be normalized to a level dry surface and demonstrated for landing on a prepared site. Obviously, these conditions define a minimum level of requirements to the helicopter structure with regard to ensuring safety during critical landings. Critical are forced landings that, in general, are performed on unprepared sites. The site condition, including the nature of soil, brings significant influence to bear on safety. And that, to what extent the nature of soil is accounted for in the helicopter design, is embodied in its strength characteristics and landing procedures, in many ways determines the level of safety.

Paper [1] was the first to discuss some of the above issues as applied to the helicopter with a skid-type landing gear. In particular, said paper marked the following points.

"The landing process is materially affected by dynamic behavior of the helicopter. The question of dynamic behavior becomes of prime importance when friction forces arise during the landing gear interaction with the landing site surface (LSS). If with a wheeled LG the effect of friction forces can be practically completely eliminated by landing without wheel braking, then with a skid LG it is not possible."

The analysis of the skid interaction with the landing site surface testified to the fact that *"It turns out that the forces of the skid friction on the LSS can have either negative or positive effect on the landing process. With particular parameters of its configuration and adequate rigidity and shock-absorbing characteristics of the landing gear, the helicopter may feature such dynamic properties that make the positive influence of the friction forces considerable, and friction-tight landings are not only unperilous, but also preferable."*

This paper also discusses the question of the effect of the helicopter's dynamic behavior on the stability of its motion at the landing impact.

"The helicopter motion is stable, if its dynamic properties are such that regardless of the initial value of the pitching angle within the range of –5° – +5° the helicopter at the end of the landing impact upon rebound features a nose-up pitch.

The helicopter motion is unstable, if at the initial values of the pitching angle within the range of –5° – +5° the helicopter at the end of the landing impact features a nose-down pitch."

Paper [1] describes the landing impact studies with the aid of special software developed at Mil Moscow Helicopter Plant on a particular configuration of the helicopter equipped with a skid landing gear. An unexpected for common views result was established: *"At the landing impact, the helicopter with the initial nose-up pitch moves through the angle of pitch to nose-down pitching, i.e. has a steady tendency to nose-over."*

The same paper specifies the basic principles of the helicopter configuration proceeding from the landing impact characteristics with a view to mitigating or completely eliminating the nose-over tendency.

Algorithms and their appropriate software tools used in paper [1] were based on a number of hypotheses limiting consideration of some nonlinear problem parameters, which made it possible to conduct investigations that would ensure consistent results in a fairly narrow sphere.

The authors of this paper had managed to develop a methodology with the use of high-level programming tools and thus to exclude the necessity entering hypotheses, which substantially expanded the area of possible research. It became feasible to conduct investigations of the landing impact characteristics for helicopters with a wheeled LG, account for the properties of the landing site. Such software tools enable calculations with due consideration of all behavioristic characteristics of the helicopter structure, shape and material of the landing site, including plasticity of the material, account of its eventual failure, etc. That is to say that to solve the problem with extensive account of potential deep geometrical and physical nonlinearity. The program flow is based on the use of the finite element method.

Figure 3 shows (see also [2]) shows the fullest theoretical model of the helicopter which can be used for studying characteristics of the landing impact of the helicopter with a wheeled LG.

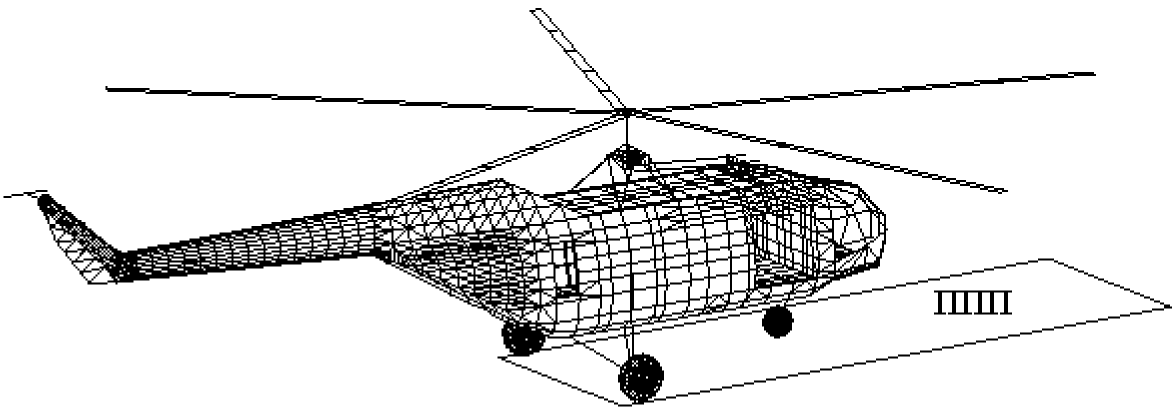

Figure 3 – Theoretical Model of Helicopter

The model includes finite element representations of the fuselage, landing gear with damping properties of shock absorbing, major components with the system of their attachment to the fuselage, including also the main rotor. The structural mass of the helicopter in the theoretical model was distributed so that the model mass and mass-inertia characteristics were identical to the object under consideration. The surface and properties of the landing site were modeled either by a solid body or finite elements. The helicopter motion is regarded with an allowance for all degrees of freedom.

As shown in paper [2], the presented theoretical model enables investigation of the most diversified problems of the helicopter strength.

As applied to the problem of studying the landing impact, the following should be emphasized, which are classed as the major ones:

– designation of the required reserve energy absorption capacity of the landing gear,
– study of the landing gear and helicopter loading,
– evaluation of the helicopter dynamic behavior,
– influence of the landing impact dynamics on the fuselage loading with an allowance for its flexibility,
– study of the process of structural damage of the helicopter under critical loading conditions,
– development of recommendations to the pilot for execution of forced landing with account of the landing site condition.

It should be noted that application of the theoretical model shown in Figure 3 in the full-scale variant is a time-consuming computation process; therefore, whenever practicable and depending on the study objectives, it is preferred that the number of the theoretical model dimensions be reduced.

2. Some Investigation Results of Landing Impact Process for Helicopter Equipped with Skid Landing Gear

2.1. Theoretical Model Features

For analytical studies of characteristic features of the landing impact of the helicopter equipped with a skid LG, a model of a real-life commercial helicopter was constructed, Fig. 4.

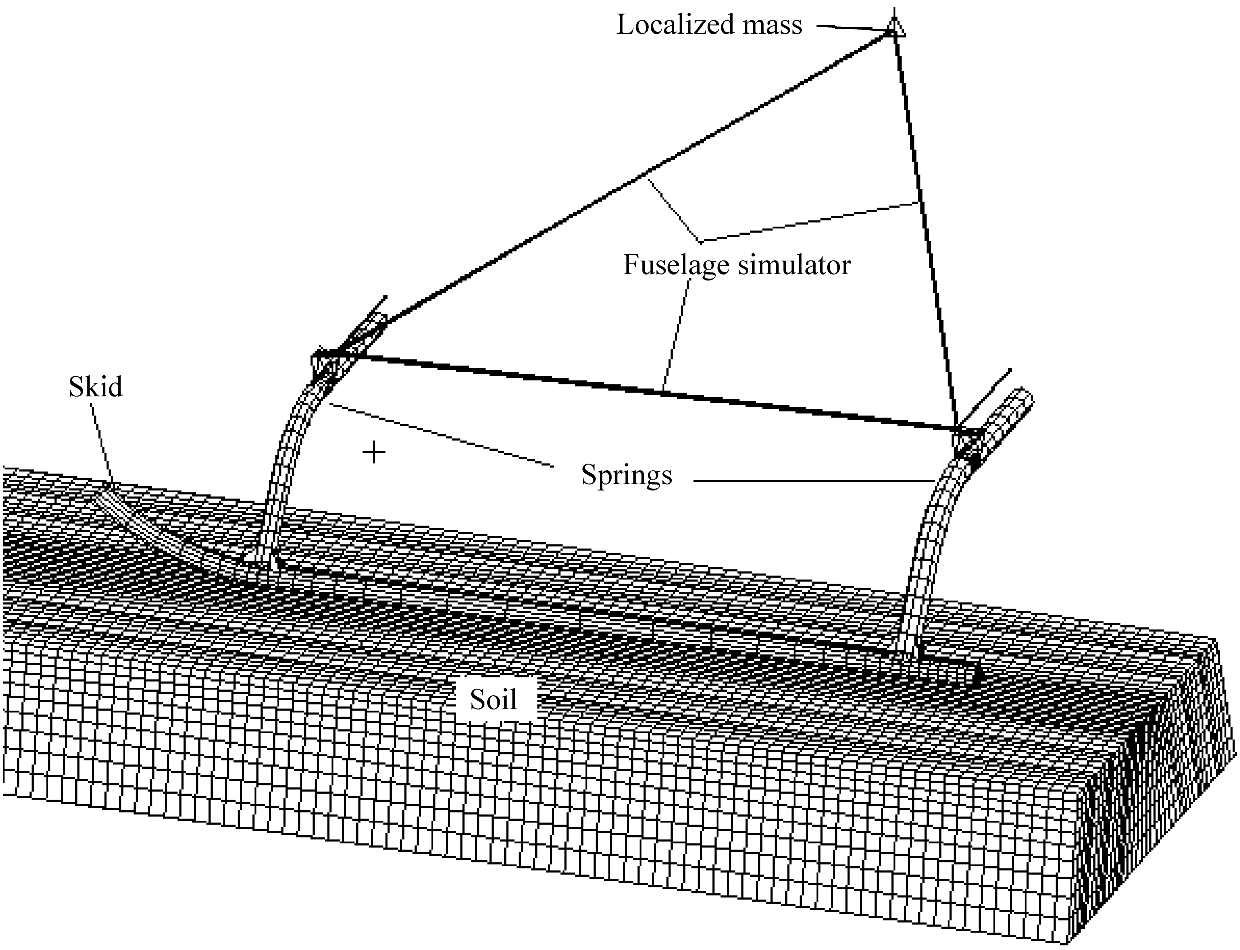

Figure 4 – Theoretical Model of Helicopter Equipped with Skid LG in Studying Off-Field Landing

It is assumed that the helicopter structure is rigid and symmetric with respect to the vertical plane. The helicopter mass is concentrated in the point that is located at the centre of gravity of the helicopter and features mass/torque/inertia characteristics conforming to the helicopter's.

For all components of the finite element representation of the helicopter, we applied prime elements with linear approximation of the field of displacement within the elements. On the assumption of the symmetry of the helicopter structure, computation was made for half of the theoretical model.

The springs were modeled by two 2D elements with an elasto-plastic material allowing breakage based on the criterion of maximum allowable relative elongations. It should be noted that dimensions of the finite elements were selected as a result of a series of computations dealing with the influence of the number of elements both in the circumferential and longitudinal directions on the quality of stress and displacement solution.

The model of the rear spring was validated in the in elastic domain by way of comparisons with the outcome of the experiment carried out in the TsAGI. It was found that divergence of the results at an actual drop of a full-sized spring and its computational modeling is negligible.

The front spring was modeled by analogy with the rear one. It is fair to say that the spring models are essentially reasonably good finite element analogs of the physical prototype.

The helicopter under discussion has got a tubular skid. Two variants of its modeling were considered. The first variant employs one-dimensional elements: beam elements with equivalent rigidity. The second variant – with the aid of two-dimensional elements – is shown in Figure 4.

The landing site was considered in two variants. The first variant – the site is rigid. The second variant modeling was carried out using a model of a rigid surface, which added no equations to the system. The second variant material model is elasto-plastic with breakage. For this case modeling we used solid elements. Figure 4 shows a landing site modeled particularly with application of the second variant.

The skid and site interacted for the account of contact forces arising between the skid and site and friction forces. The friction force is a three-dimensional vector directed against the vector of relative motion of the interacting sections of the skid and site. In the conducted studies, the friction coefficient varied from 0 to 0.8.

Initial Conditions.

Hereinafter we will discuss emergency and forced landings. That is why for studying we applied applicable initial conditions. That includes. The helicopter model has some initial velocity $V_0=\{V_x, V_y\}$; Most of the computations were carried out with $V_x= -5$ m/s, $V_y= -2.4$ m/s.

A concentrated force is applied to the center of mass simulating a standard rotor lift (save as otherwise provided).

2.2. Influence of Number of Elements along Skid Arc with 2D Elements

The primal question that interested the authors at that stage was the influence of the accuracy of reproduction of the skid angular geometry on contact forces and, accordingly, on the results of the model computation in general. The results were compared by the maximum acceleration in the center of mass with varying number of elements on half of the perimeter in circumferential direction N. As a result of computations it was found that the maximum acceleration in the center of mass is weakly dependent on the number of elements. And the processor problem time as a function of N was adopted as a criterion for selection of the most rational value of parameter N.

It was demonstrated that the most rational value N is 6–7, Fig. 5.

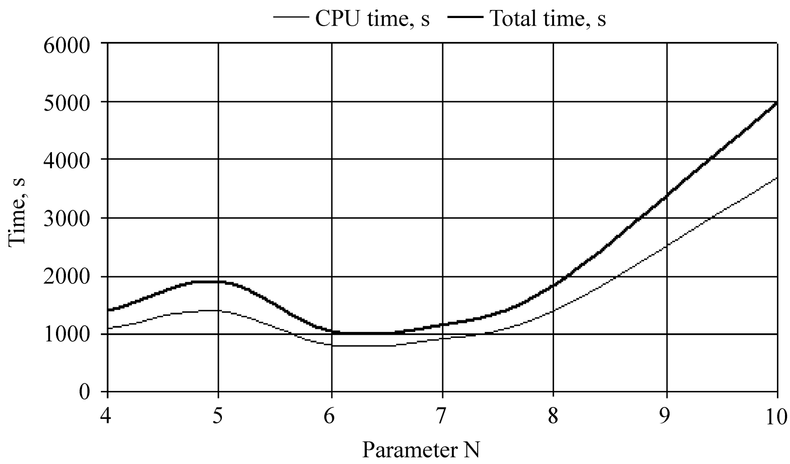

Figure 5 – Problem Time VS Number of Elements along Skid Arc

2.3. Features of Skid Modeling Methods Using One– and Two-Dimensional Elements

From general ideas, it would seem that modeling using one– and two-dimensional finite elements should not lead to a perceptible difference in the results of computation of the helicopter's landing impact. However, the modeling exercise testified to the fact that it is far from true. Figure 6 shows vertical displacements of the center of mass Uy for these two modeling methods at the length of the skid section from its end to the rear spring L = 0.25m.

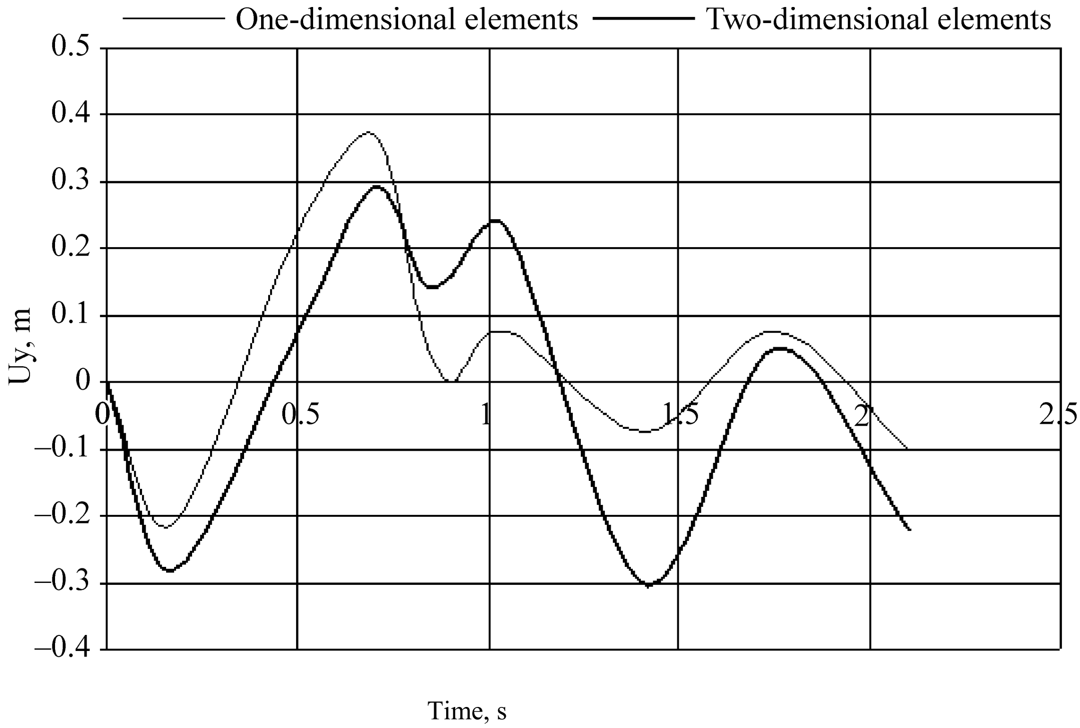

Figure 6 – Comparison of Results for One– and Two-Dimensional Skid Models

It can be seen that the first landing impact is reproduced in both variants approximately identically, but further behavior differs and very drastically.

A sequence of studies conducted to clarify the reasons for such substantive divergence showed that it is exceedingly difficult to select an equivalent stiffness of beam elements when using one-dimensional elements. This is attributable to the fact that at a relatively small value of L/R (R is the skid radius), which is used in the helicopter under discussion, shifts contribute significantly to the deformation energy. Aside from that, during modeling with the use of one-dimensional elements, length L also includes the zone of transition from the spring to the skid, which should also be accounted for when designating rigidity. But during modeling with the use of two-dimensional elements load transfer over the skid cross-section and coming into operation of the skid cross-section are determined automatically.

The general finding of this part of work is that application of one-dimensional elements for the skid modeling is possible in principle; however, one should meticulously select the equivalent bending and shear stiffness of the elements.

2.4. Influence of Initial Landing Pitch Angle on Landing Characteristics

Paper [1] notes that the initial pitch-up under the above landing speed conditions creates preconditions for nose-over. This paper studies stability of the helicopter motion at the landing impact with varying horizontal component of the landing speed (the vertical component is constant) and the coefficient of the skid friction on the landing site.

Figure 7 shows nose-over regions during landing on a rigid surface.

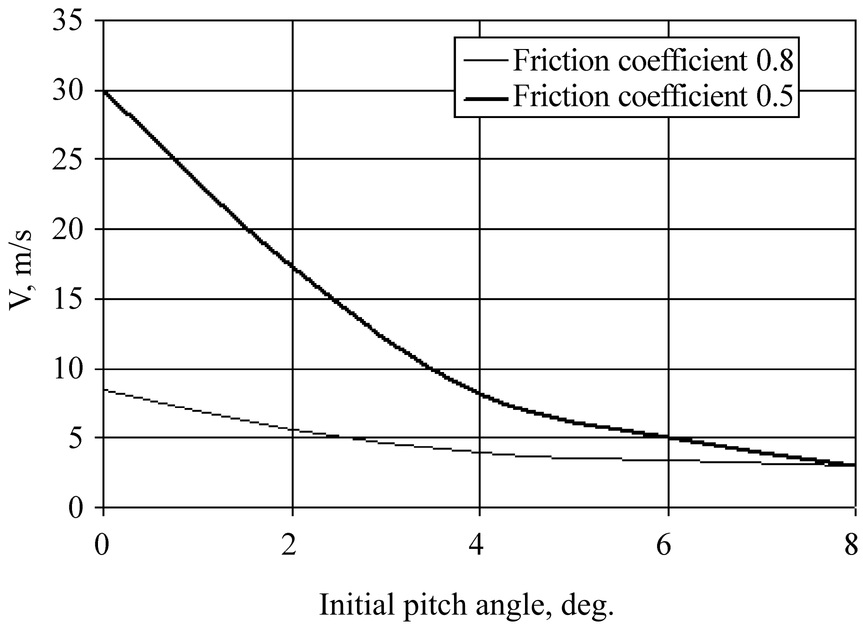

Figure 7 – Longitudinal Landing Speed Limit Vx VS Initial Pitch Angle

From Figure 7 it follows that at wide initial pitch angles (>6 deg.) the permissible horizontal velocity is weakly dependent on the friction coefficient. As the angle of pitch decreases, high initial horizontal velocities become permissible. And overall behavior of curves in Figure 7 makes it possible to assert that i**nitial nose-down pitching is even more favorable**.

Thus, statements made in paper [1] about the effect of the initial pitch angle on the helicopter's tendency to nose-over are fully confirmed by these studies, **and afford strong ground for reviewing the existing emergency and forced landing procedures that provide for landing with an obligatory nose-up pitch (5–8 degrees).**

Another important circumstance is that even at a high friction the possibility exists to land without problems associated with nose-over, if the landing is carried out with minimum nose-up pitching, or even with initial nose-down pitching.

2.5. Influence of Rotor Lift

The analytical studies confirm the duality of action of the rotor lift. During the landing phase from touchdown to the point of full compression of the shock struts, the lift plays a positive role absorbing part of the kinetic energy of the helicopter's vertical motion. However, after commencement of the rebound, the lift contributes complementary energy to the system and thus aggravates conditions for subsequent landing impacts. Figure 8 presents the mode of vertical displacements of the center of mass of the model for two cases: with a constant lift and with a lift which is removed at the instant of maximum compression of the springs.

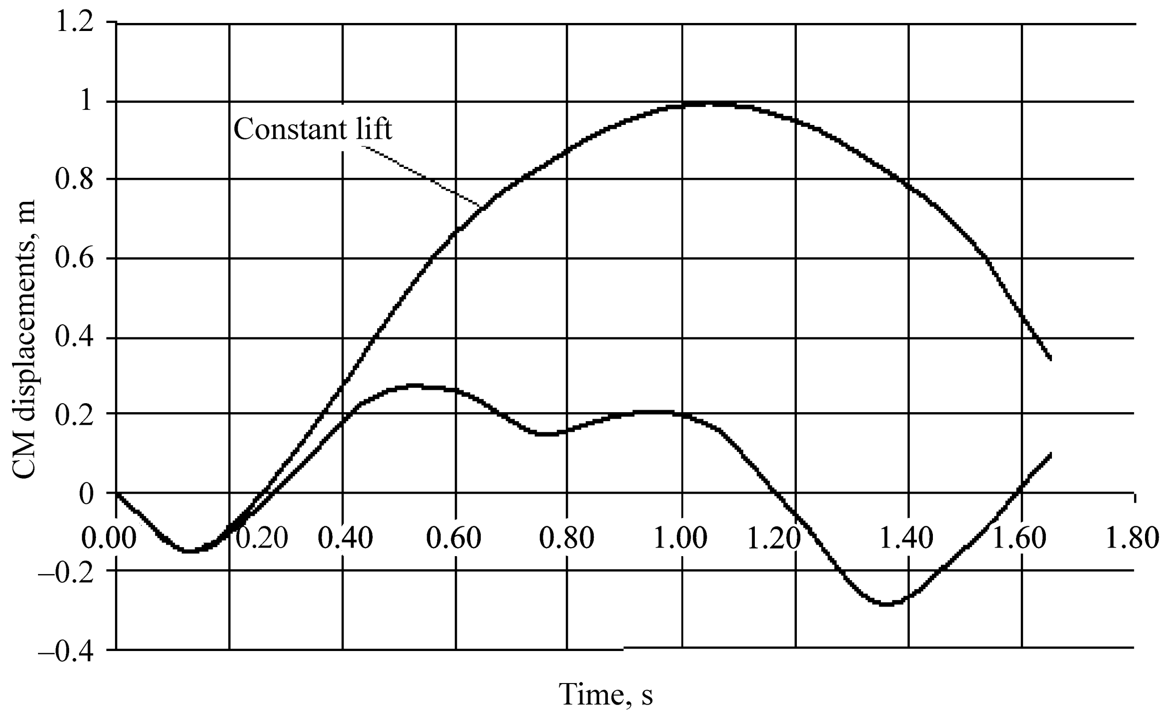

Figure 8 – Vertical Displacements of Helicopter Center of Mass in Two Variants of Rotor Lift. Initial Pitch Angle Is Equal to 5 Degrees

The upper curve describes a constant lift, and the lower one a lift removed at the instant of full compression of the springs.

Figure 9 shows functions of longitudinal displacements of the center of mass (along the OX axis) for the same two cases.

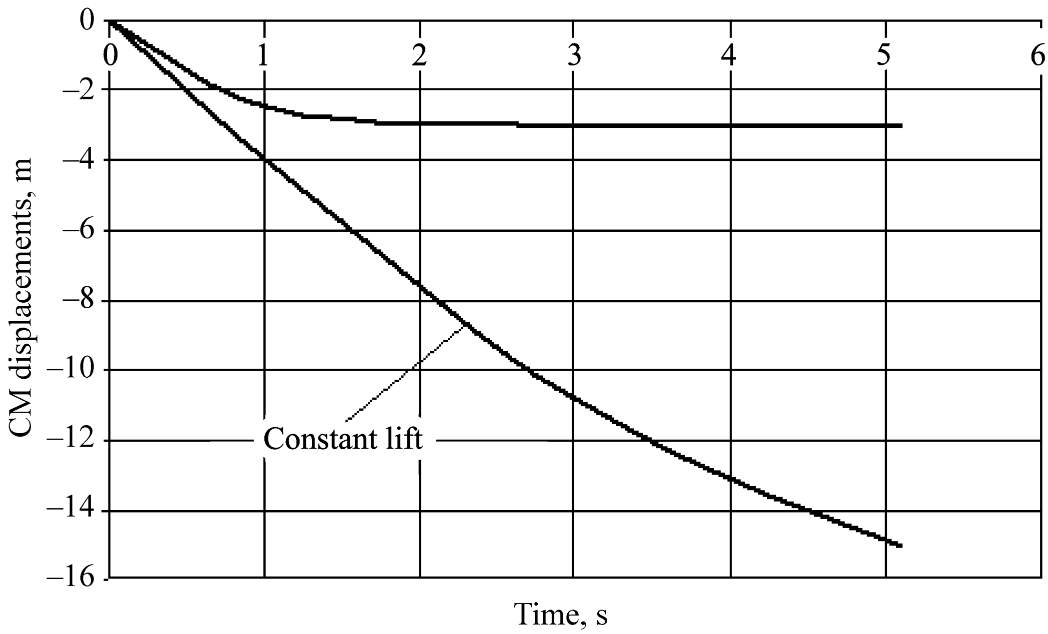

Figure 9 – Longitudinal Displacements of Helicopter Center of Mass in Two Variants of Rotor Lift. Initial Pitch Angle Is Equal to 5 Degrees

The lower curve in Fig. 9 corresponds to a constant lift. On elapse of 5 seconds after the commencement of the process, the model continues to move longitudinally at almost a constant speed. The analysis showed that the nose-over process develops.

The upper curve was received when the lift was removed at the instant of full compression of the springs. In no more than 2-3 seconds after the commencement of landing, the longitudinal velocity is virtually zero.

This, somewhat unexpected, result can be simply explained from physical standpoint. At a constant lift during the rebound of the center of mass of the helicopter the propeller thrust contributes complementary energy to the system, and this results in the helicopter's nose-over.

There is no doubt that a change in the propeller thrust during emergency or forced landing is an essential factor that can greatly affect the safety of the crew and passengers.

2.6. Off-field Landing/Landing on Unprepared Site

Peculiarities of the skid landing gear topology prompted suggestion that landing on an unprepared site, even of the ploughed field type, is practicable. For analytical validation of this assertion, we conducted computations with the use of soil as the landing site material.

The computations relied on an elasto-plastic model of soil, with eventual failure. According to [3], plastic deformations are brought about in soil upon attainment of the limit state:

$$\sigma_i \geq C + P*tg(\varphi),$$

where:

σ_i – normal stress intensity,

C – cohesion of soil,

P – hydrostatic pressure,

φ – internal friction angle.

The analytical studies dealing with the landing on soil were preceded by refinement of a number of methodological issues. Based on the resolution of said issues, the authors performed computations demonstrating a possibility in principle of landing on an unprepared site of the ploughed field type. Figure 10 shows the computed "helicopter – plough land" system.

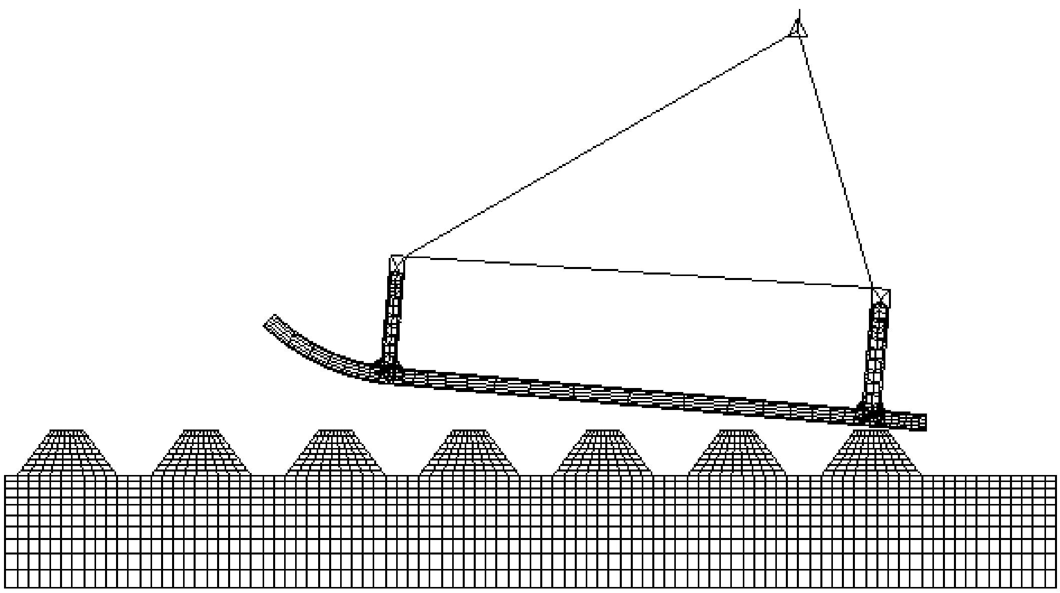

Figure 10 – Theoretical Model for Studying Ploughland Landing

Figure 11 presents a snapshot of the helicopter "ploughland" landing process.

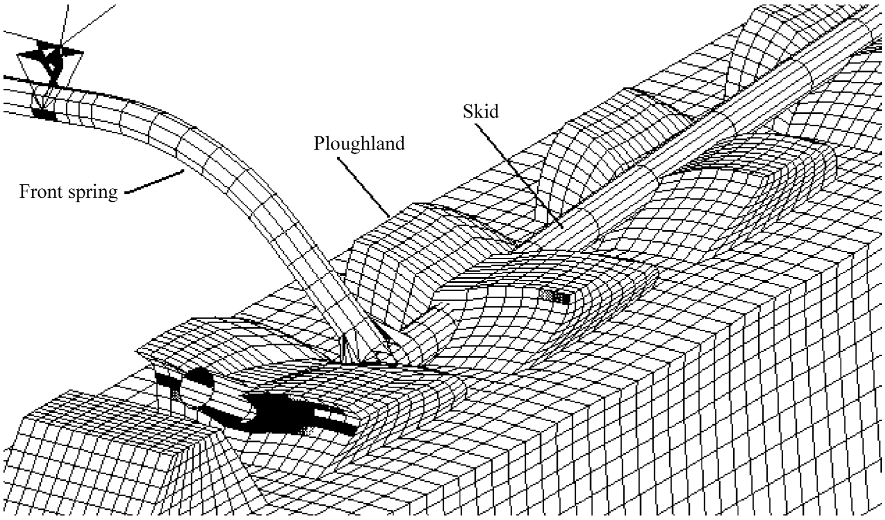

Figure 11 – Soil Deformation Behavior

For this model, a set of computations was conducted with varying initial pitch angle. An interesting physical result is absence of nose-over even at a high initial nose-up pitch angle (8 degrees). Apparently, this is a consequence of a great energy capacity of a pliant soil.

In the course of our work, we tried out procedures for and approaches to solving problems of this sort that enable carrying out, with a sufficient degree of credibility, of investigations the result of which may be an appearance of a skid landing gear capable of landing on soil featuring particular strength properties.

3. Analytical Study of Wheeled Landing Gear

For analytical studies with the use of a wheeled landing gear, we developed a model based on data about one of the modifications of the Mi-8 helicopter, Fig. 3.

The model features stiffness and mass-inertia characteristics in coincidence with the characteristics of the physical analog.

One of the stages of working along here was the necessity of figuring out issues related to the wheel spin-up and the propeller rotation.

Without going into technicalities, one may note that the applied software tools enabled complete resolution of the issues. Figure 12 shows the change of speed of two points on the main landing gear wheel. The points are located at the ends of the vertical wheel diameter. The initial longitudinal velocity of the helicopter is Vx = 5 m/s.

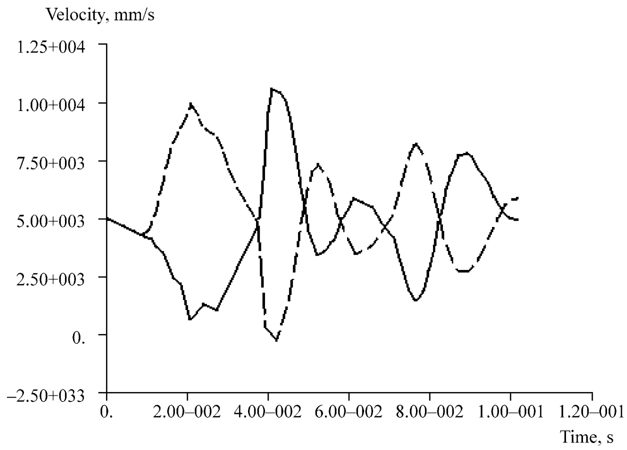

Figure 12. Spin-up of Main Landing Gear Wheels

As a result of this part of work, an analytical study of a wheeled helicopter landing on a rigid surface was conducted based on the full model of the helicopter. Similarly to the findings with respect to the skid landing gear, landing of the wheeled helicopter with the wheels **locked** (an analog of skid friction) may be safer.

Conclusions

1. A procedure for computation of the landing impact with a skid-type and wheeled landing gear for the case of emergency or forced landing was finished off. The procedure includes the basic principles of development of a finite element representation, the choice of element types, certain peculiarities of specifying initial and borderline conditions, etc. – complete information enabling investigation of the landing impact during emergency and forced landing.

2. The landing impact of a skid-equipped helicopter during landing on a rigid surface was subject to an analytical study. Statements made in paper [1] as to the advisability of carrying out emergency and forced landings with minimum nose-up pitching, or even with initial nose-down pitching had been proved out.

Reduction of the initial pitch angle has a positive effect on the landing impact characteristics and contributes to curbing the nose-over tendency.

Repeated landing impacts will feature substantially lower amplitude with the lift removed at the instant of maximum compression of the springs.

3. Methodological issues were tried out and landings on soil were computed. The computations testify to a possibility in principle of a skid-equipped helicopter landing on a ploughed field.

4. The use of friction forces in a wheeled helicopter, which equivalent to landing with the wheels locked, is capable of improving safety during emergency and rough landing.

5. The results of the work in general change in principle the approach to the emergency or forced landing procedures, and their use in designing may also significantly influence the helicopter layout solutions.

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