FINITE ELEMENT SIMULATION OF A HELICOPTER CRASH IMPACT

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Abstract

This paper describes first stage results of research of a helicopter fuselage dynamic reaction during emergency landing. Evaluation of a helicopter crashworthiness requirements and present time FAR-29 requirements for overloads during emergency landing and fuselage construction elements crashworthiness during extreme loads taking was analyzed. The simulation of emergency landing was conducted with finite element method modeling using explicit time integration by central difference method. Stringers, spars of frames and keelbeams were modeled using Belytschko beam element. Skin, walls of keelbeams, frames and diaphragms were modeled using Belytschko-Lin-Tsay shell element. The solution was received with allowance for of physical and geometrical nonlinearity, i.e. large strains and plasticity of a material were taken into consideration. For treating large displacements and to separate the deformation displacements from the rigid body displacements was used co-rotational technique in the element formulation. This approach allows to evaluate loading different load-bearing fuselage elements during impact energy absorbing, to conduct overloads analysis in attachment points of pilots and passengers seats and variation of the sizes of room pilots and passenger cabins, to give the recommendations for improving construction crashworthiness.

Introduction

At all phases of aviation evolution, the aircraft landing was and rests the most dangerous stage of the flight. According to statistics, more than 50 percents of air accidents happen during landing. The analysis of reasons of helicopters crashes shows, that the considerable part of crashes (by different estimations up to 50 % and more [1]) is connected with piloting errors on small and extreme small (no more than 30 m) altitudes. Thus, even a small increase of a maximum permissible vertical speed of impact of the helicopter with ground on conditions of a survival rate, can substantially reduce human losses and lower a rate of heavy wounds for the passengers and crew.

Still the development stage it is necessary to include in a design of an aircraft the special measures, permitting to route an absorption of energy and destroying on the least dangerous path, and guaranteeing survival in case of emergency landing. Till now many researches, aimed at safety assurance, are carried out by means of complicated and expensive (frequently unique) full-scale experiments. Though such experiments are very relevant, their results have restricted value, as the design of the aircraft is already developed and it is difficulty to change something in it.

In this connection a problem of a numerical simulation of the helicopter emergency landing procedure becomes very actual. Such simulation would allow for early development stages to evaluate the included design solutions from a point of view of assurance of safe emergency landing and to give the guidelines on improvement of crashworthiness of a construction.

Development of requirements for helicopter crashworthiness

The definition of requirements to crash resistance of the helicopter should, first of all, to be based on data of a tolerance of a human organism under effect of impact loads on it [2]. It is necessary to note, that on estimation of a tolerance of a human organism in these conditions, it is necessary to take into consideration not only the value of overloads, but also the rate of their increase and duration of the effect.

The other necessary component for definition of requirements to crash resistance is the statistical information on parameters, defining the degree of heaviness of air incidents, such as a position of a fuselage at impact, its trajectory speed and, at last, a stopping distance or time expressed through overloads or through change of overload in unit of time. Obtaining of these data in itself is a not prime technological problem, requiring large financial costs.

Apparently, the researches carried out in the USA in 60-70 should be considered as the first fundamental researches of this kind. In this period the different aeronautical research teams have carried out the extensive program, aimed at thorough investigation of a problem of assurance of the safe emergency landing of aircraft. The analysis of more than 3500 air incidents, as well as destructive tests of 45 full-scale aircrafts, and more than 400 tower drops and 600 tests with acceleration on guides were carried out. On the basis of this data one can see what happens to a structure of aircraft and its parts at crash. The detailed review of these researches is presented in work. [3].

On the basis of these researches the criticality of crash was defined in the terms of a survivability of the occupant. The survivable accident was defined as such, at which one the diagram of changes of overloads on time does not exceed values, defined by possibilities of a human organism, and there is a sufficient living space for the occupants on board [4].

For survivable accidents the family of curves reflecting percent of crashes as a function of speed of impact was plotted (Fig. 1 [4]). The curves in fig.1 present distribution of change of vertical and horizontal speed for helicopters and light aircrafts with fixed wing at survivable accidents, including accidents with considerable damages of a structure or injuring of the occupants on board.

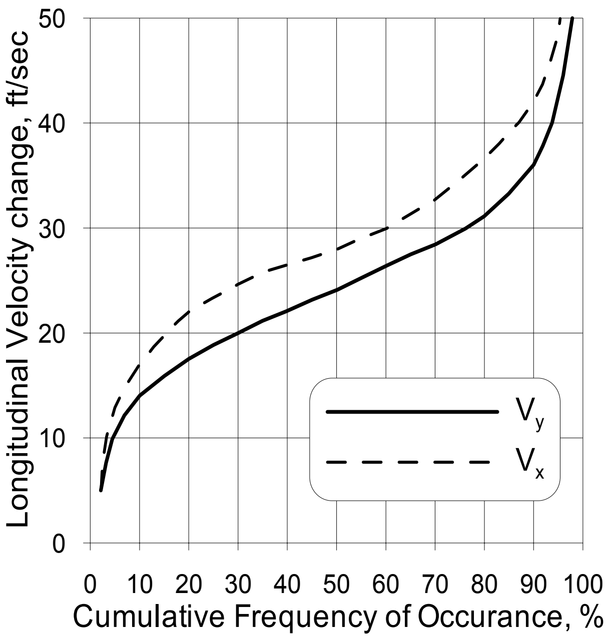

Fig. 1 Change of speed for survivable accidents of rotary-wing and light aircrafts with a fixed wing.

It is seen in Fig. 1, that at 95% of survivable accidents the change of a vertical speed constitutes less than 42 feet/sec, and change of longitudinal speed – less than 50 feet/sec. The change of speed in lateral direction for light aircraft with a fixed wing and for cargo and fighting helicopters usually does not exceed 30 feet/sec. As the emergency landing of the aircraft, having speed only in one direction, is very seldom, the actual trajectory is a combination of three vectors.

The basic researches carried out in the context of the above-mentioned program, have resulted in acceptance in USA in 70 years of a series of military standards concerning different aspects of assurance of safe emergency landing. It would be desirable to note the MIL-STD-1290 [5] standard among these regulating documents, in which seven calculated cases of impact load application were defined and should be taken into account at development of aircrafts. Basic value of the MIL-STD-1290 standard is its precise requirements to minimum criteria of resistance to impact loads for application on initial stages of development by aircraft designers.

The concept of emergency landing with reference to FAR-29 regulations

The summary of the present section is based on the analysis carried out in work [6].

The FAR-29 regulations on assurance of safe emergency landing are divided on requirements to a static strength of the helicopter (§29.561) and requirements on ensuring the injury-safe landing under given dynamic conditions of emergency landing (§29.562).

The requirements to a static strength concern the fastening of seats and objects able to traumatize the occupants on board (§29.561 (b)), security of attachment of cargoes, arranged above or behind of a cockpit and occupants (§29.561 (c)), structural strength of a fuselage in the area of arranging of fuel tanks below the floor level of a passenger cabin (§29.561 (d)).

The meeting the requirements of §29.561 of Aviation Regulations to a static strength of a construction essentially rises chances of survival of the occupants, but nevertheless it is necessary to note, that their isolated application does not secure safety at emergency landing.

The standards on dynamic conditions of emergency landing are used to supplement the first group of requirements up to an orderly system of safety assurance at emergency. This part of requirements standardizes an admissible level of loads on the occupant's organism: a load on a vertebral column, head, and restraint system belt.

The requirements §§29.561 and 29.562 are developed on the quite definite concept of emergency landing. The analysis of requirements allows to affirm, that the controlled landing is included in the basis of the concept, i.e. the landing at a normally operating helicopter control system, while the pilot performs correct operations on helicopter control is considered as emergency. At such statement critical emergency landing is the landing on a condition of autorotation of a rotor on an unprepared site at the completely failed power plant.

The following results in such conclusion:

- Given in §§29.561 (c) and (d) value of positive vertical overload (+4) is rather insignificant and comparable to overloads at in-flight maneuver (§29.337). On the other part, the calculations for helicopters with a skid landing gear show that such overload is reached on landing with a maximum speed about 3 m/s using only energy absorption capabilities of landing gear;
- Requirements of §29.562 are concentrated exclusively on an absorption of energy of impact by seat structure, and do not state nothing about fuselage crash resistance;
- There are no conditions of dynamic load application in side direction.

Two loading conditions are indicated in seats dynamic tests requirements. The analysis of conditions stated in standards, and concerning the position of a seat relative to impact speed vector and its magnitude shows the following:

- To meet the conditions of § 29.562 (b) (1) there is an emergency landing on the bounded site, at which to perform a landing close to vertical, the horizontal component of float speed is fully dissipated by main rotor, while the vertical component rated 9,15·sin 60°=7,92 m/s with respect to occupants, restrained in seats, is dissipated by seat structure.
- To meet the conditions of § 29.562 (b) (2) there is an emergency landing on a condition of autorotation when to a moment of a beginning of landing impact the vertical component of float speed is fully dissipated by main rotor, while dissipation of the horizontal component rated 12.81 m/s with respect to occupants, restrained in seats, occurs in conditions close to frontal impact by the platform of a floor.

The present concept incorporates in the scope of safety the requirements to emergency landing with the requirements of § 29-75 “Landing”, according to which the design of the helicopter should allow to perform the safe landing on the prepared horizontal site on a condition of autorotation of main rotor.

Thus, in the context of the described concept the totality of requirements to safety at helicopter landings in a critical conditions takes on completeness and fullness: in the presence of landing site the construction of the helicopter ensures a possibility of execution of safe landing having undamaged state of the helicopter, in case of absence of landing site for execution of safe landing, the construction of the helicopter allows to prevent injury of the occupants, having partial destruction of the helicopter during landing impact.

However, there is a problem, as not always there is a possibility to perform a controlled landing on condition of autorotation. At first, as it was already described in introduction, the considerable portion of air incidents happens at small and extremely small altitudes, when a clearance may be insufficient for transition to autorotation mode. Secondly, one cannot exclude form consideration the accidents, connected with destruction of a main rotor, or failure of a control system, that also obviously excludes the controlled landing.

Apparently, the development and supplement of FAR-29 regulations on assurance of safe emergency landing is necessary. The works in this direction are carried out. The amendments which essentially raise the level of requirements to prevent injury of the occupants on board of the helicopter in conditions of emergency landing are regularly appeared. It is necessary to note, that the edition in force of FAR-29 and FAR-27 regulations by its level of requirements to a static strength of the helicopter at emergency landing does not meet any more to actual standards of FAR.

Numerical simulation of landing impact

The prediction of behavior of structure under conditions of action of large loads of impact character and able to cause the destruction of separate parts, is connected with necessity of decision of the whole set of problems. It is the account of large displacements, physical and geometrical nonlinearity, definition of zone of contact and mathematical modeling of power interaction in it, account of time dependence (or dependence on speed of deformation), mechanical performances of material, definition of criteria of destruction, account of changes in the model connected with destruction of configuration components.
At the present time two basic approaches to a numerical integration of systems of differential equations describing the behavior of a deformed rigid body are used in practice of solution of such problems: a finite-element method and discrete-element approach.

A finite-element method, widely applicable at calculations on a static strength, assumes a greater level of detail of mathematical model describing an actual construction. However, the direct transfer of developed methods and programs in the domain of dynamic force calculations till recently was very restrained by sharp increase of costs of a computing time and memory of digital computers, that required active search for ways of reduction of dimension of problems.

One of the ways of efficient simplification of a mathematical model is the so-called discrete-element approach. At that the construction is represented by a rather small set of localized masses and rigid bodies (beams), jointed by inertialess linear and non-linear springs, which simulate rigid and strength properties of macroparts of a structure. The parameters of such macroelements should be defined by special experiments or by usage of the finite-element analysis.

After appearance of supercomputers, and especially now with the development of the device of parallel distributed computing on cluster systems, the limitations on dimension of problems in case of usage of finite-element method, have sharply reduced.

The important feature exerting considerable influence on flexibility and completeness of the program is the method used for simulation of contacts and contact forces. The non-linear springs and contact members may serve as the roughest means of simulation of interaction of moving body with a barrier. Considerable limitation of applicability of this approach is the necessity to include beforehand in the simulator the possible zones of contact and direction of action of contact forces. Only a very restricted slip along a spot of contact is admitted at that. However, possible impacts and recoils cannot be always predicted beforehand, and their searching and simulation are one of the basic features of these problems.

One of the major difficulties is the necessity of simulation and destruction. It is connected with formulation of destruction criteria (that is especially complicated for composite materials) and with the method of elimination of components from the simulator after compliance with given condition of destruction.

Let's stay a little bit in more detail on realization FEM for such solution of problems both mathematical methods and physical theories which have been trusted to in its basis.

In a general view an equilibrium equation of a system of finite elements were in a state of move is possible to record so:

$$\boldsymbol{M}\ddot{\boldsymbol{U}}(t)+\boldsymbol{C}\dot{\boldsymbol{U}}(t)+\boldsymbol{K}\boldsymbol{U}(t)=\boldsymbol{R}(t) \quad (1)$$

Where M, C and K accordingly matrixes of masses, damping and stiffness; $\boldsymbol{R}$ - vector of an exterior nodal offloading; $\boldsymbol{U}$, $\dot{\boldsymbol{U}}$ and $\ddot{\boldsymbol{U}}$ - vectors of nodal movements, speeds and speed-up of an ensemble of finite elements. The equations (1) are obtained from consideration of equal balance in an instant *t*, when according to a d'Alembert's principle the body is in equal balance under operating of external forces, internal forces, forces of damping and force of inertias.

Mathematically (1) represents a system of differential second-kind equations with float factors (in case of the account of physical and geometrical nonlinearity). For practical accounts of high-speed processes with a large extent of nonlinearity direct time integrating by a method of central differentials is utilized more often. Algorithmically it will be realized by usage of a numerical single step routine. Thus the equal balance is esteemed in discrete points of a time interval that allows effectively utilizing all computational vehicle of static analysis.

One of major advantages of a method of central differentials is that in case of usage of scalar matrixes of masses and damping, the matrixes do not owe is resulted in a triangular aspect, i.e. there is a necessity of forming of matrixes for all ensemble of members and the solution can be obtained at a level of members. Thus, the exception of a routine of a factorization of large matrixes essentially economizes computational resources.

Main deficiency of a method of central differentials is its conditional stability. An integration step Δt should be less extreme value, Δt_{cr}, computed proceeding from slugged and stiffness of properties of all ensemble of elements. For deriving an authentic solution the implementation of a condition is necessary so:

$$\Delta t \le \Delta t_{cr} = \frac{T_n}{\pi},$$

Where T_n - least free period of an ensemble of finite elements; n - order of a system. Thus, it is necessary to escape appearance in the pattern of members with very small mass or very large stiffness. In substantial problems at duration of impact impulse 30-40 milliseconds the integration step on time compounds about 1 microsecond.

At percussion deforming of a construction the relative movements of members become, as a rule, of same order, as characteristic size of the construction. In such conditions of a strain depend on movements non-linearly and, besides become so large, that the behavior of a material is not confined to elastic deformations. For the mathematical specification statement of such problem the so-called incremental theories will be utilized, in which one the geometrical proportions enter the name by the way links between increments of movements and increments of strains, and physical proportions - by the way links between increments of strains and increments of stresses.

There are some theories depicting plastic behavior of metals, but, as demonstrate experiments, results of accounts under the theory of plastic flow are best agreed with experimental data. In it the linear coupling between increments of stresses $d\sigma_{ij}$ and strains $d\varepsilon_{ij}$ is postulate.

For the account of slip and contact there are some algorithms. For example, method of kinematic anchoring, penalty method, distributed parameters method. The greatest propagation was received with a penalty method because of a relative simplicity of its realization and small influencing on magnitude of an indispensable integration step on time.

The computing time necessary for full simulation can vary from several tens of minutes for elementary discrete-element models up to 100 hours for large finite-element models.

As discussed above, the design solutions providing the structure crash resistance should be defined on the initial stages of development. Certainly, the simulation of procedure of emergency landing for finished design of aircraft on the digital computer is also useful for estimation of its crash resistance. However, such narrow application of modern computing devices and methods is to be recognized as inefficient. There is a need for unification of the development methodology, in which the objective function, determining the structure crash resistance will be used together with the other objective functions, defining the quality of optimized object (the helicopter as a whole, or its separate units and systems). At that the formation of objective function is performed taking into account such output parameters as overloads change diagram in the area of seats of pilots and passengers (the values, defined by human organism capabilities, should not be exceeded), permanent deformations of living spaces (saving of sufficient living space is necessary), deformation of the bottom in case of mounting of fuel tanks below the floor level (it is necessary to prevent the fuel pouring out), etc. The controlled parameters are the number and topology of power and energy-absorption elements, their section, performances of applied materials.

The implementation of such methodology would allow to improve the structure crashworthiness successively and purposefully, together with the other requirements to the helicopter.

The numerical simulation of the helicopter emergency landing is a direction, which is intensively developed in all leading helicopter-engineering corporations all over the world.

Approach used for simulation of emergency landing

The numerical simulation of the helicopter emergency landing is a new area of researches in the practice of design bureau of Kazan Helicopter Plant. Therefore, at the first stage it was decided not to go beyond the consideration of a simple problem, which would allow to study the creation of the design simulator, to evaluate the time required for calculations and to give the preliminary estimation of obtained results.

Primarily it was decided to abandon the discrete-element approach in favor of the finite-element method because of:

- technical complexity and high cost of macro-elements performances obtaining in the course of experiments using discrete-element approach;
- long time to obtain the same performances using detailed finite-element analysis;
- availability of general-purpose finite-element complexes proved in solution of problems of this kind (examples of their usage are given in works [7], [8], [9], [10], [11], [12]);
- possibility of quick converting of available finite-element simulator, intended for static strength and modal characteristics analysis (Fig. 1), in the simulator for calculation of energy absorption at landing impact.

The fuselage lower panel together with skid-equipped landing gear of one of the helicopters, designed by Kazan Helicopter Plant, was the subject of analysis. The fuselages of the helicopters manufactured by Kazan Helicopter Plant generally have a thin-wall reinforced riveted structure, made of duralumin alloys. In spite of implementation of many new engineering solutions in newly developed helicopters (such as composite hingeless main rotor hub, skid landing gear, electroremote control system), the fuselage structure and power elements remain “classic” and made of conventional materials. This structure is time- and technology-proved, and probably, it will be used long enough despite of gradual implementation of composite materials.

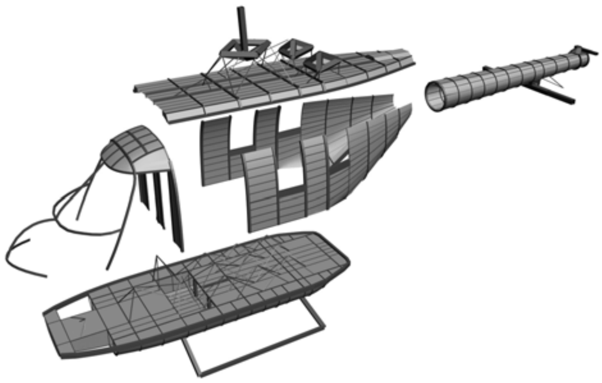

Fig. 2 Complete finite-element model of the helicopter for calculation of static strength and modal characteristics.

The lower panel constructively consists of the following components:

- 4 longitudinal power beams with chords, made of extruded sections, and webs, reinforced by posts. The beams are bending members and react a concentrated load in the points of seats and cargo attachment, as well as from landing gear attachment units;
- 13 frames of structure similar to that of longitudinal beams, form together with the longitudinal beams a common rigid framework;
- 14 stringers used for skin reinforcement and reacting an axial loads;
- thin metallic skin, which form an outer aerodynamic fuselage outline and a floor of cockpit and passenger cabin. React a shear loads.

The skid landing gear consists of main and nose springs, connected by skids. The spring and the skids are manufactured of tubes made of high-strength steel alloy.

The finite-element complex, realizing the scheme of forth explicit integration on time by central difference method, was used in calculations. The Belytschko beam finite elements were used for simulation of stringers, beam chords and frames. The Belytschko-Lin-Tsay envelope elements were used for simulation of skin, beam webs, frames and diaphragms. The physical and geometrical nonlinearity, i.e. the large deformation and material plasticity, are taken into account in solution. The general view of finite element model of the lower panel is shown in Fig. 3.

Since only the lower panel and landing gear were simulated, and the remaining part of the fuselage, power train and engines were not taken into account in any way, the approach taken from work [7] was used for simulation of landing impact. The simulator (model) was attached in units, in which the lower panel is connected with the fuselage upper portion. The impact is made by a massive rigid impactor with a mass equal to that of helicopter minus the mass of lower panel. At that the direction and speed of impact are easily corrected by setting the appropriate characteristics of impactor.

The results presented in the paper are for a case of vertical impact with speed of 7,32 m/s (24 feet/s). Such value is provided by a median of distribution of vertical speeds of impact (fig. 1).

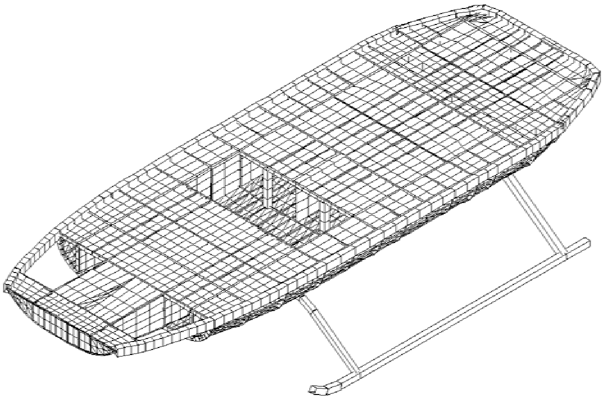

Fig. 3 General view of finite-element model of lower panel.

Unfortunately, the absence of any experimental data has not allowed properly verify the model and obtained results. Therefore deductions can be made in the basic quality nature.

First of all, it was interesting to evaluate time indispensable for account such enough for the composite pattern. The communal time of account has compounded 2 hours 18 minutes on a workstation with the processor AMD Athlon 2700 + from 512 MB of the RAM. Thus was not effected of any special optimization of the pattern. It allows to hope, that the time of account for the pattern of all fuselage bodily will not exceed one day. Besides there are ещ ё spares of magnification of output, bound both with optimization of the model, and with magnification of power of computational facilities. By an effective solution here would be applying a computational cluster [13].

The magnitude of absorbed energy has compounded 69,1 kilojoules. Considerable a part was came on springs the chassis, primarily on front. The construction of the lower desk distorted a little, basically in front, in a zone of contact with "ground". The maximal strains have not exceeded 3 cm.

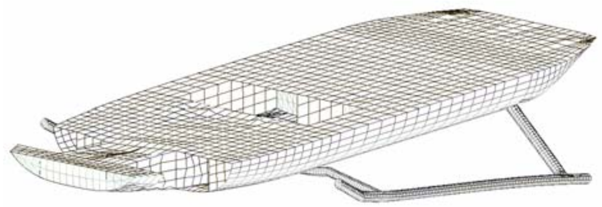

Fig. 4. Deformations at the moment t=0,1 sec.

The Fig. 4 is rotined strained state in an instant t = 0,1 s. Such offset of strains to a nose of a fuselage is explained, is interquartile, two reasons: at first, the front spring has smaller stiffness, than basic, secondly, considerable assumptions accepted at allocation of a weight of the helicopter, cloning a dissected away part, have reduced in an ante position of center of gravity of the pattern.

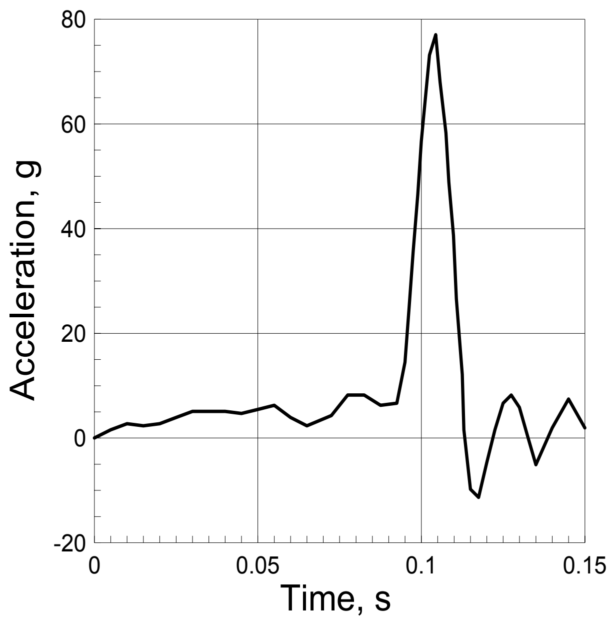

Fig. 5. Overloads on a pilot seat floor location.

One of main specifications indispensable for estimation for safety of the pilots and the crew members is the chart of variation of overstrains in zones of attachment of their seats. In a fig. A Fig. 5 and Fig. 6 such charts for the considered pattern are reduced. Certainly, to apply these charts to an estimation crashworthiness of the particular helicopter is invalid, allowing, however considerable assumptions were made at account. It is enough to indicate that these magnitudes are predatory for the reason, that the energy absorption of other parts of the helicopter, except for the chassis and lower desk is leave outed.

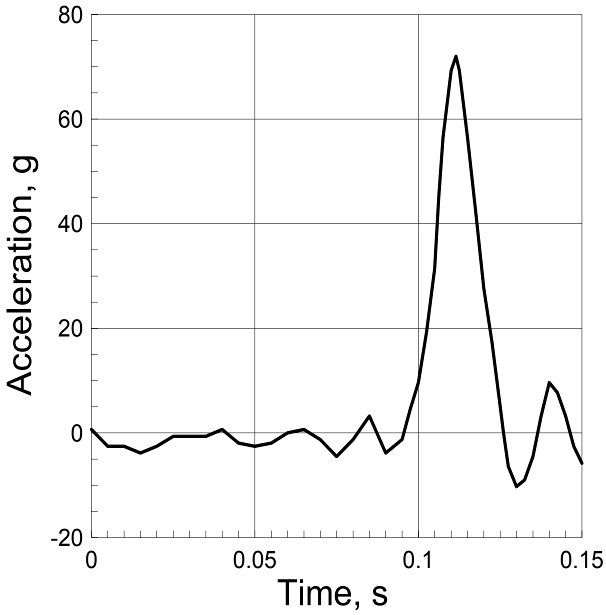

Fig. 6. Overloads on a cargo compartment floor location.

Concluding Remarks

By results of the held studies it is possible to make the following conclusions:

(1) at present there are legible enough requirements for minimum stability to impulsive loads for applying on early stages of designing.

(2) the requests FAR-29 will realize these requests not to the full, since the concept of emergency fit, on which one they grounded means fit controlled. In practice the undertaking of controlled autorotation landing can be prevented with set of the factors.

(3) existing programmatic and the hardware allow with adequate accuracy and for reasonable time to model rather composite problems of percussion affecting on a construction of the helicopter.

(4) at creation of the certainly - element pattern of the helicopter for simulation of process of emergency fit the pattern for account of a static strength and modal performances can be utilized. And can be created automatic translator of input data, in this or that measure computerizing such conversion. The major difficulty here is encompassbyed conversions of data about girder members, since the slugged performances of cross-sections used at static account do not approach for a solution of a dynamic problem.

(5) for an estimation of survivable space conservation both analysis of hardness of side and upper fuselage panels at their dynamic loading braking by a main reducer and engines the simulation of entire fuselage is necessary.

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