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DETERMINING THE STABILITY OF A FIRE TRUCK TANKER AGAINST OVERTURNING WHILE DRIVING THROUGH CROSSED FOREST TERRAIN

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The object of this study is to consider dynamic processes in the tank of a fire truck with different levels of water filling. The task to be solved is to determine the data on the fluctuation of the center of mass of a dynamic system, which consists of the water tank of a fire truck tanker truck, when it moves through rough forest terrain at different speeds. The data make it possible to predict the danger of a fire truck tipping over. In the process of solving the task, an estimation model of a fire truck tanker truck was built together with a water tank, using the LS-Dyna dynamic systems simulation software package. In order to reproduce the dynamic impact on the fire truck tanker with the water capacity exerted by the relief of the rugged forest area, the time dependences of the angles of current position of the fire truck tanker – roll angle, yaw, and pitch – were established. The resulting dependences were used as boundary conditions to reproduce the dynamic influence of the terrain. The turning angles of the water tank of a fire truck were determined depending on the unevenness of the terrain, the geometry of which was calculated by a pseudo-random number generator. Using the explicit method for integrating the dynamics equations, implemented in the code of the LS-Dyna software package, the patterns of fluctuations of the center of mass of the water tank of the fire truck tanker depending on the level of filling and speed of movement were defined.

Using results from the mathematical modeling of dynamic processes in the fire truck tanker, a numerical algorithm was developed for this fire truck tanker to maintain its stability against overturning. Therefore, the results of this study have a direct practical application in the field of fire truck tanker design safety and could be used to improve and devise new technologies in this field

Keywords: fire truck, forest terrain, fluctuation of the center of mass, optimal route model

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1. Introduction

The general growth of the population and the density of its living, as well as the increase in anthropogenic pressure on the environment, lead to higher risks of large-scale disasters. The complexity of the man-made domain, its manifestation of danger and the impact of global climate changes also contribute to increasing the risks of natural and anthropogenic emergencies and disasters [1–3].

Statistical analysis of the current situation with fires reveals that the number and scale of forest fires has a tendency to increase, which is caused by modern challenges of a natural, ecological, and man-made nature [1]. The main means of transport that deliver fire extinguishing agents to fire stations and carry out fire extinguishing are fire vehicles, in particular fire trucks [2, 3]. During the operation of a fire truck that is not completely filled with water, there is an increased risk of its overturning due to fluctuations in its center of mass when it moves through rough forest terrain. This leads to the fact that when operating fire tanks, it is recommended for fire departments to avoid moving through forest terrain with an incompletely filled tank, which is equivalent to a ban. Such recommendations have to be violated every time since a strict ban on the operation of fire truck tankers is not economically and practically justified. Therefore, these basic recommendations should be revised taking into account the results of scientific research. In view of the above, the conclusion is that the study of patterns in fluctuations of the center of mass of fire truck tankers, caused by the dynamic impact of unevenness during their movement through forest terrain, is an urgent scientific and technical task.

At the same time, in emergencies, it is possible to determine in advance safe routes for the delivery of a fire extinguishing agent to the source of fire only under certain meteorological conditions with additional assumptions about the volumes of emissions of hazardous substances [4, 5]. And in the case of the occurrence and spread of a forest fire, it is impossible to do this at all since the configuration of the site and, in connection with this, the configuration and connectivity of the transport network (movement along part of the roads may become impossible) are not known in advance. In such cases, an alternative to the evacuation plan could be an operational fire extinguishing plan, taking into account all logistical features and the safe movement of fire vehicles, including fire truck tankers. Such a plan nay be devised only when developing the appropriate software. Its basis should be the forecast of forest fire evolution and mathematical models for finding optimal routes, taking into account the requirements for the resistance of fire truck tankers to overturning. Guaranteeing the safety of the movement of fire truck tankers and reducing the time of transporting the fire extinguishing agent to the sites of forest fires could significantly improve the efficiency of assessing their localization. Therefore, the construction of mathematical models of safe and optimal logistics for special fire equipment, in particular fire truck tankers, is an urgent scientific and technical task.

2. Literature review and problem statement

In work [1], based on the level of danger associated with the scale of spread, socio-economic losses, and ecological consequences, landscape fires are categorized as the most dangerous. In order to create the prerequisites for successfully fighting these fires, intensive scientific research is underway in almost all areas of this industry. The likely reason is the objective difficulties associated with extinguishing landscape fires. However, there is a need to increase the mobility of means for transporting fire-extinguishing agents to fire stations while maintaining safe working conditions of fire departments. Among the main means for extinguishing landscape and forest fires are special fire truck tankers, for which the prevention of their overturning is an essential aspect of increasing efficiency. The danger of overturning is especially evident when the fire truck tankers are not completely filled. As a result, dangerous waves could form in them, which could cause large fluctuations of the center of mass and, as a result, overturn the fire truck tanker. The provision of scientifically based recommendations on the parameters of the movement of fire truck tankers through rugged forest terrain would create prerequisites for increasing their safe operation and would improve the efficiency of their use. Works [2, 5] consider dynamic processes occurring in fire truck tanks. In these works, various approaches to forecasting the dynamics of these systems are formulated. However, the dynamic processes during splashes of water in the tanks due to the influence of the chassis design on these processes were neglected. In [3], an approach to represent the mass of water in the tank in the form of a pendulum dynamic system is proposed. This approach makes it possible to determine the fluctuations of the center of mass of the dynamic system, but the disadvantage of this approach is the limitation when taking into account the influence of the internal system of breakwaters and partitions. Work [6] reports the study of dynamic processes in tanks using a general theoretical approach based on the use of the system of Navier-Stokes equations. This approach fairly accurately reproduces the dynamic processes of the formation and propagation of waves in tanks with partitions; however, difficulties arise in determining the fluctuations of the center of mass of this dynamic system. The smoothed particles hydrodynamics (SPH) method [2, 7] is promising for modeling dynamic processes during the movement of a fire truck. According to it, the water in the tank could be simulated with the help of particles; this method allows modeling the mutual viscous interaction between the particles and the enclosure of the tank. Under such conditions, it is convenient to study the fluctuations of the center of mass of the formed dynamic system. Given the complexity of mathematical models, their implementation is possible only when using special software. In work [8], the LS-DYNA universal software package, developed by Livermore Software Technology Corporation (LSTC) for the study of dynamic systems, was very effectively used to solve scientific and technical problems of fire safety. In the code of the LS-DYNA computing software package, an approach for modeling fluid dynamics based on the SPH method in combination with the explicit method is implemented. The differential equations of dynamics are integrated with their approximation by the finite element method, which is a prerequisite for its use for mathematical modeling of dynamic processes in a fire truck during its movement through rugged forest terrain.

When extinguishing forest fires, special vehicles are most often used, in particular fire truck tankers [2–5]. Automation of the procedure for finding the optimal parameters of the fire extinguishing agent transportation process leads to a significant increase in its effectiveness due to operational efficiency. At the same time, the possibility of using computing equipment, in particular personal computers, requires the availability of appropriate software and input data adapted to their requirements.

Carrying out the transportation of fire-extinguishing substances under off-road conditions, fire truck tankers move in different landscape and topographical conditions. Their speed of movement is influenced by the local values of natural factors – the type of soil (underlying surface) and the topography of the area. In this connection, there is a need to adequately assign these factors at each point of the forest fire zone. In addition, safety must be taken into account for ensuring the fire truck tankers do not overturn.

Geographic information systems (GIS) are a software tool that makes it possible to adequately reflect the real natural and man-made situation in the emergency zone. The topographic base of GIS is electronic maps based on digital terrain models (DTMs) [4, 5].

Vector DTMs describe the boundaries of square landscape objects in the form of closed polygons specified by the coordinates of broken peaks. In addition to field objects specified in GIS in the form of polygons, there are a number of objects specified as linear. Later, these objects were assigned some small width, and they were also defined as planar.

In work [9], a vector-functional model (VFM) of the geodata assignment is proposed, which combines the possibilities of a highly accurate vector description of polygon boundaries with a simultaneous functional assignment of physical parameters within their boundaries.

The vector format of geodata is used as input parameters of the model, approximating each original line (polygon boundary) with a broken line, information about which is stored in the form of an ordered array of coordinates of its *N* vertices.

In order to quickly calculate the optimal routes of vehicles, it is necessary to have at your disposal models of the influence of landscape factors, tactical and technical characteristics, and parameters on the speed of movement of these vehicles.

The terrain affects the speed of vehicles both on roads and under off-road conditions [2–5].

Works [2–5] show data for the speed of vehicles, depending on their technical characteristics and the steepness of the slope.

Having information about the power of the engines, it is possible to obtain the value of the speed of the vehicle depending on the steepness of the slope.

An option to overcome related difficulties is to conduct research on the movement of the vehicle under off-road conditions, which leads to the need to take into account the safety of traffic according to the criterion of their stability on the slope. Works [2–5] propose a model of the azimuthal speed of the vehicle, taking into account its stability on the slope. The disadvantage of this model is the numerical solution procedure for finding limiting azimuthal angles that limit the stable orientation of this vehicle. This procedure significantly slows down the process of immediately finding a logistics route, and therefore it is necessary to find an analytical solution to this problem.

However, the safe movement of the vehicle on the surface of the terrain and, accordingly, the possibility of its movement in the azimuth direction depends on its technical characteristics and the steepness of the terrain in the direction and perpendicular to it. This is the approach used in works [4, 5, 9], in which this limitation is overcome by finding permissible directions of movement of the vehicle on the surface of non-uniform terrain. The forward movement of the vehicle in the direction of its orientation is equivalent in this direction.

All this gives reason to assert that it is expedient to carry out a study aimed at determining the safe and optimal logistics models for special fire equipment, in particular, fire trucks when they move through rough terrain during forest fire extinguishing.

3. The aim and objectives of the study

The purpose of our study is to identify patterns of fluctuations in the center of mass of fire truck tankers caused by the dynamic impact of unevenness during their movement through forested terrain. This will make it possible to build a mathematical model of optimal logistics for fire truck tankers during forest fire extinguishing, ensuring their resistance to overturning.

To achieve the goal, the following tasks were set:

– to build an estimation model of one of the most common fire trucks with a water capacity using the capabilities of the LS-DYNA software package;

– to construct a mathematical model of rugged forest terrain for its reproduction of influence when applying boundary conditions to the dynamic water tank system of a fire truck tanker during its movement through rugged forest terrain;

– to conduct a numerical experiment on the study of dynamic processes in a container with water during the movement of a fire truck through a rugged forest area and to investigate fluctuations under the predefined conditions;

– to define the optimal safe logistics routes and provide recommendations for the relationship between the level of water filling of the tank of a fire truck and its speed of movement through rough terrain during forest fire extinguishing.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study was the dynamic processes occurring in the water tank of a fire truck during its movement through rugged forest terrain, and their influence on the fluctuation of the center of mass of the structural system of the fire truck tanker. In order to take into account the influence of the surface relief on the dynamic processes that take place in the tank of a fire truck during its movement through forest terrain, one of the most common options of equipment was considered. The AC-4,5-60 (TGM 12.240)-364 fire truck can be used to extinguish landscape fires with water and air-mechanical foam. The appearance of the fire truck tanker together with a water tank is shown in Fig. 1. The internal structure of the tanker tank is also depicted.

The main expected result, which should be obtained during the study of the movement of liquid in the tank, is the pattern of changes in the position of the center of mass of the mechanical system. They include the tank itself and the water in the tank. To this end, an appropriate task must be set, in which the influence of the topography of forest terrain, on which the vehicle moves, on the dynamic processes in the water tank must be taken into account. An appropriate mathematical model was built that reproduces the movement of liquid in the tank with the possibility of predicting the position of the center of mass of the mechanical system, which consists of water and the tank. Determine the appropriate method for the numerical implementation of integration of the dynamics equations of the proposed mathematical model and perform the appropriate calculations based on this method. At the same time, a mathematical description of the topography of the forest cross-country terrain should be specified. Mathematical description of the interaction of the liquid in its inner layers. To describe the interaction of the liquid with the solid walls of the tank, it is necessary to take into account the relevant properties of substances and materials, such as the viscosity of the liquid, the hardness of the surface of the solid material, and the inertial characteristics of the substances.

With such features of the statement of the dynamic problem for similar mechanical systems, the mathematical model describing the dynamic processes under such conditions takes on a very complex form. In order for the solution method to be comprehensible, a simplification was adopted regarding the dynamic processes that occur in a water tank during the movement of a fire truck in rough forest terrain:

1. The mechanical system was considered, consisting of a car chassis, on which the body of a container with water is installed, and the inertial characteristics of the latter are assumed to be insignificantly small. This allows us to estimate only the fluctuations of the center of mass of a given system due to the movement of water, and then these fluctuations could be taken into account when analyzing the problem of fluctuations of the center of mass of a mechanical system.

2. The enclosure structure of the tank is represented as a completely solid body, and its elastic characteristics are tak-

en into account only when describing the contact interaction between the liquid and the enclosure.

3. The water in the tank is represented by a finite number of particles characterized only by mass and having vanishingly small geometric dimensions. To describe the movement of particles and their contact interaction, the SPH (Smooth Particles Hydrodynamics) hydrodynamic model is used [2, 7]. Interaction between the particles takes place according to Monaghan's hydrodynamic model [2, 7] of the formed system, the viscosity of which is similar to that of water. This, in turn, makes it possible to calculate the position of the center of mass of the formed system.

4. The movement of the system is considered under normal atmospheric conditions, gravity, and temperature, and the heat exchange between the water and the walls of the tank is not considered.

5. When analyzing the contact interaction of particles and the enclosing surface, a corresponding mathematical contact model based on the method of penalty functions is used [2, 8].

6. To describe the dynamics of particles, their contact interaction between themselves and the walls of the tank, the method for integrating the generalized equations of dynamics using the implicit method is used [2, 7, 8].

7. When considering the dynamics of the system, the processes of damping and energy dissipation in the car's depreciation system are not considered.

8. To form the movement of the tank under the influence of the surface relief, the randomness of the appearance of unevenness of the relief is taken into account when using pseudo-random number generators.

9. To simulate the movement of the tank, its turns relative to horizontal axes are used, which reproduce roll and yaw, as well as vertical movement. Rotation around the vertical axis (pitch) is not taken into account.

The structural system of the AC-4,5-60 (TGM 12.240)-364 fire truck tank together with the water tank is shown in Fig. 2. This structural diagram demonstrates that a container with water and additional loads are installed on the chassis of the car, reproducing the structural elements of this fire truck tanker.

An important feature is the presence of holes and windows in the partitions for the normal movement of liquid when pumping in or pumping out water while maintaining the ability to block the formation of large waves in the tank when it moves over terrain. However, a large number of circular contours of holes increases the number of elements, reduces the performance of calculations, and worsens the conditions of contact interaction. Therefore, a simplified reproduction of the geometric configuration of partitions was used for mathematical modeling. The simplified geometric configuration of the tank with partitions is shown in Fig. 3.

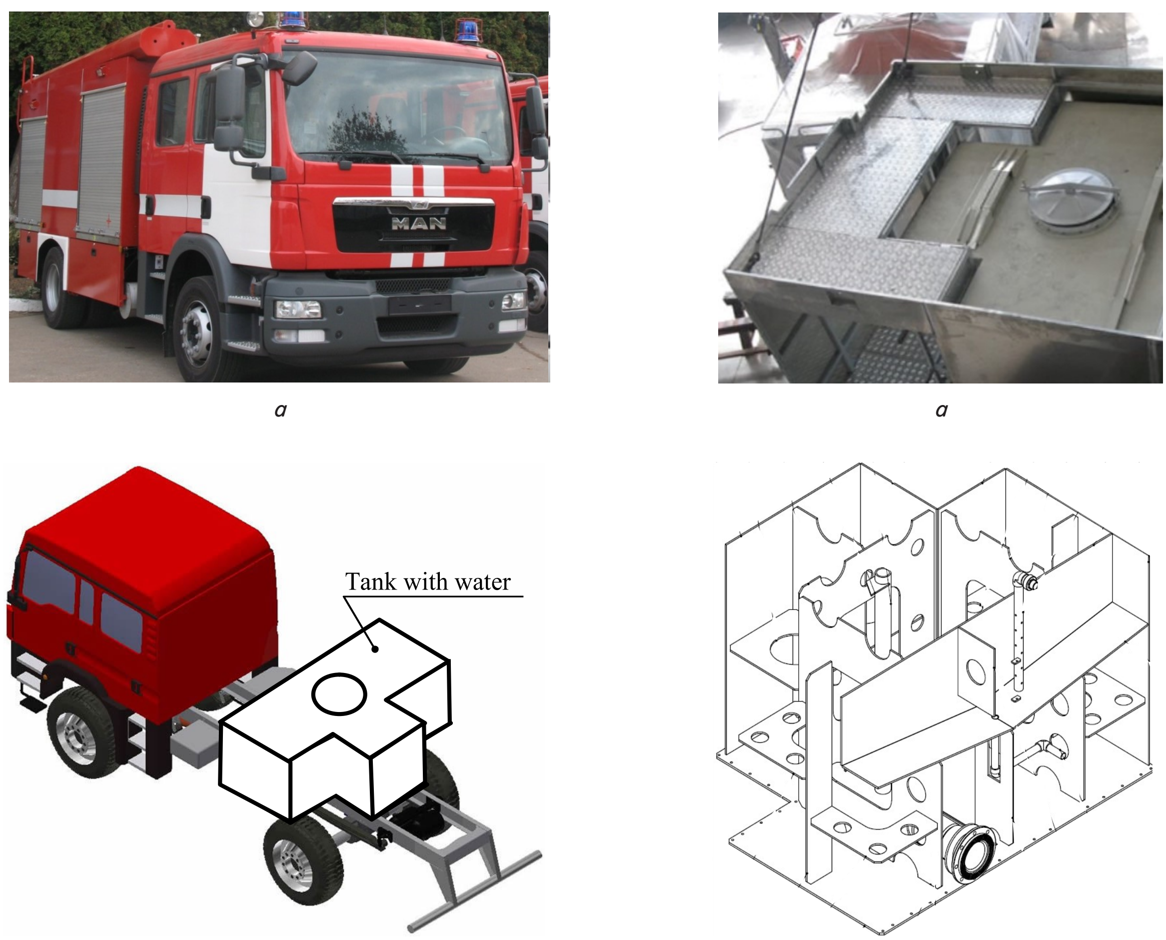

Fig. 1. Location of a water tank in the fire truck AC-4,5-60 (TGM 12.240)-364: *a* – general view of the fire truck; *b* – water tank of a fire truck tanker; *c* – the location of the container with water in the fire truck tanker; *d* – a diagram of a container with water in a fire truck tanker in cross section

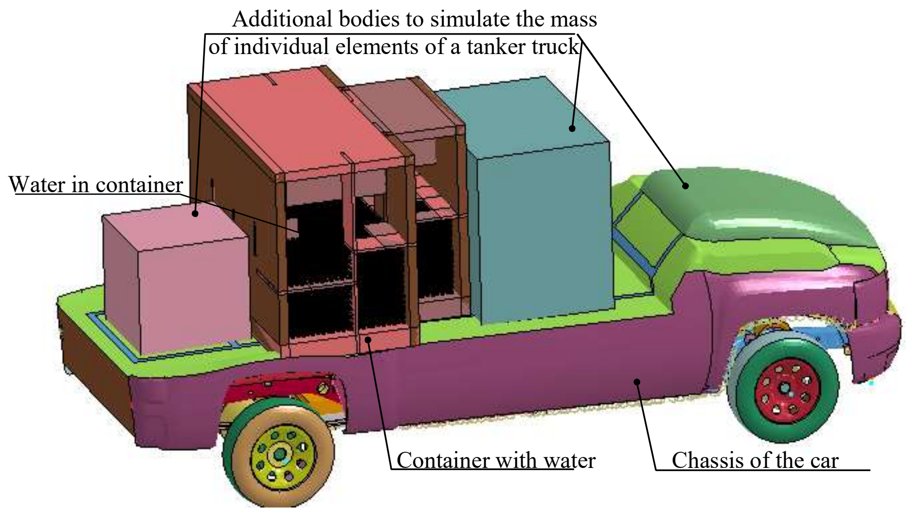

Fig. 2. Structural system of the fire truck tank AC-4,5-60 (TGM 12.240)-364 together with a water tank

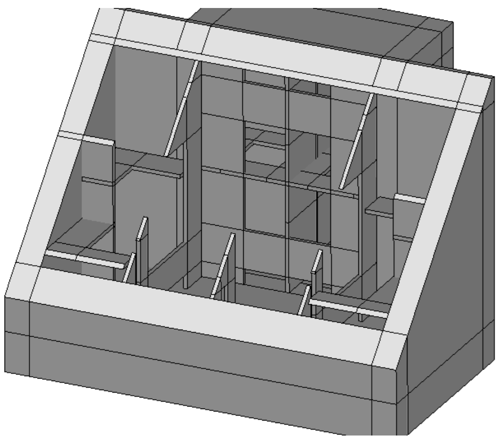

Fig. 3. Scheme of a simplified geometric configuration of a fire truck tanker's water tank with partitions

5. Results of simulating the dynamic processes in the tank of a fire truck moving through forest terrain

5. 1. Construction of an estimation model of a fire truck

Using the obtained geometric model of the structural system of the fire truck tanker, a finite element diagram was constructed, shown in Fig. 4. During the construction of the finite-element scheme of the fire truck, volumetric finite elements of the Lagrangian type, shell two-dimensional elements of the type of Belichka-Tsai shells, beam elements of the Hysal-Liu type, as well as SPH particles that reproduce the liquid were used. The number of volumetric finite elements was 5,952, the number of shell finite elements was 177,089, the number of beam finite elements was 1,515, and the number of SPH particles was 24,800; a total of 209,356 finite elements.

Two types of materials are used to model the elements of the mechanical system representing the water tank: particle material and tank enclosure material. Basic information about the types of these materials is given in Table 1 [2, 8].

The theory of contact interaction between nodes and surfaces, described in detail in [2, 8], is used for the interaction between particles and the enclosure of a fire truck tank. The method of penalty functions is used to identify the contact between the point and the surface, and the predetermined elastic characteristics of the materials are used for the force interaction conditions.

The parameters of the material properties that were used to build the computer model were taken according to the data given in [2]. Table 2 gives values of the accepted parameters of the material properties.

Using the given data, a corresponding computer model of the water tank of the AC-4.5-60 (TGM 12.240)-364 fire truck was built.

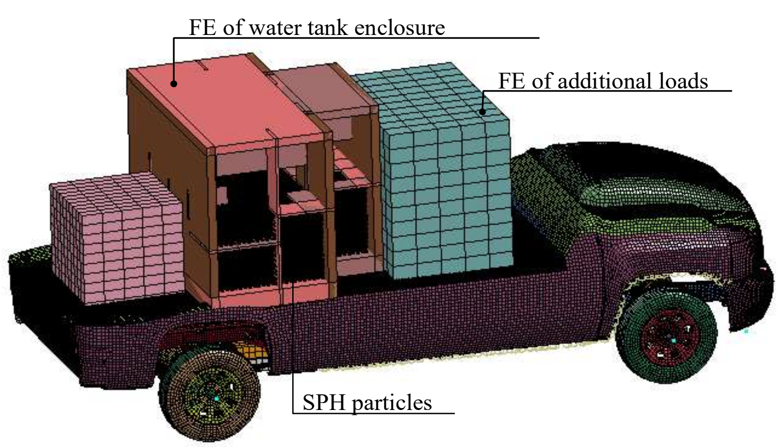

Fig. 4. Finite element scheme of the fire truck tank AC-4,5-60 (TGM 12.240)-364 together with a water tank

Table 1

Basic information about the material types of the mechanical system of the water tank

Particle modeling material	Material for modeling a tank enclosure
This material model serves to describe the properties of an idealized material, in which there is no need to calculate the internal stresses included in the stress deviator. In this case, one can neglect the strength of the material. Viscous stresses are determined by the formula: $\sigma_{ij}=\mu\dot{\varepsilon}'_{ij}$, where $\dot{\varepsilon}'_{ij}$ – the rate of accretion of deviator deformations. Also, the use of this material is due to the possibility of establishing a contact interaction between particles and a solid	This material model is used when there is no need to consider a stress-strain layer in its inner layers. At the same time, it remains possible to set the inertial characteristics of bodies. Also, for this material, the task of its elastic characteristics remains relevant, which is a necessary aspect for the task of elastic interaction when bodies come into contact with this model of material with other bodies. This material is used to specify predetermined conditions of motion of the entire system, since the degrees of freedom of bodies made of this material and their laws of motion are optionally specified

Table 2

Values of parameters regarding the properties of construction materials of the water tank model of the fire truck AC-4.5-60 (TGM 12.240)-364

Material	Density, *r*, kg/m^3	Modulus of elasticity, *E*, MPa	Poisson's ratio, *n*	Viscosity (artificial), μ
Polypropylene (tank enclosure)	0.001	900	0.25	–
Null material (particle material)	1,000	–	–	0.001

5. 2. Construction of a mathematical model of the surface relief

To simulate the movement of a fire truck through a forested terrain, it is necessary to build a mathematical model of surface relief. According to the schemes in Fig. 5, the turning angles of the fire truck could be determined by the vertical movements of the rear and front axles of the vehicle. The roll angle, yaw angle, and vertical displacement due to the mutual movement of the wheels is determined from the following formulas:

$$\alpha=\mathrm{arctg}((Z_r-Z_l)/l_w);$$

$$\beta=\mathrm{arctg}((Z_f-Z_b)/L_w);$$

$$Z=(Z_r+Z_l)/2+(Z_f+Z_b)/2. \qquad (1)$$

When determining the turning angles of the local terrain, a separate sequence of surface irregularities is specified for the right and left wheels of the rear axle. The local topography, taking into account recommendations from [2], is given as a sequence of a typical section of the track, the view of which is shown in Fig. 6.

When using the scheme in Fig. 3, a function was written that determines the shape of the unevenness of the reference track for the study of fluctuations in the position of the center of mass of the mechanical system of a water tank in the form:

$$Z(x)=\begin{cases}(-1)^{R_4^*}\dfrac{R_3^*}{R_2^*}x, \ 0\le x<R_2^*,\\ (-1)^{R_4^*}\left(R_3^*-\dfrac{R_3^*}{R_2^*}x\right), \ R_2^*\le x<2R_2^*,\\ 0, \ 2R_2^*\le x<R_1^*+2R_2^*.\end{cases} \qquad (2)$$

Here, quantities R_1^*, R_2^*, R_3^*, R_4^* are values obtained using a pseudorandom number generator, belonging to the ranges listed given in Table 3.

To reproduce the possible options, three cases of tanker truck movement at speeds of 6 km/h, 4 km/h, and 2 km/h are considered. In this way, 3 sets of motion laws for the fire truck tank were obtained. In Fig. 7, as an example, the laws of movement of a tanker for a speed of 6 km/h are presented.

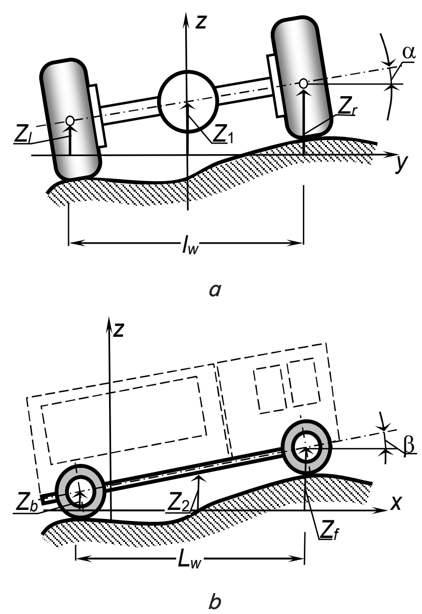

Fig. 5. Calculation schemes for determining the angles of movement of the AC-4,5-60 (TGM 12.240)-364 fire truck tanker: *a* – roll; *b* – yawning

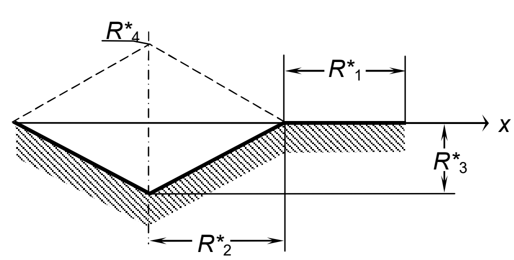

Fig. 6. The scheme for determining the area with local unevenness of the reference track for the study of fluctuations in the position of the center of mass of the mechanical system of a water tank

Thus, the unevenness of the relief of the rugged forest area was reproduced for the simulation of dynamic processes in the capacity of a fire truck tanker.

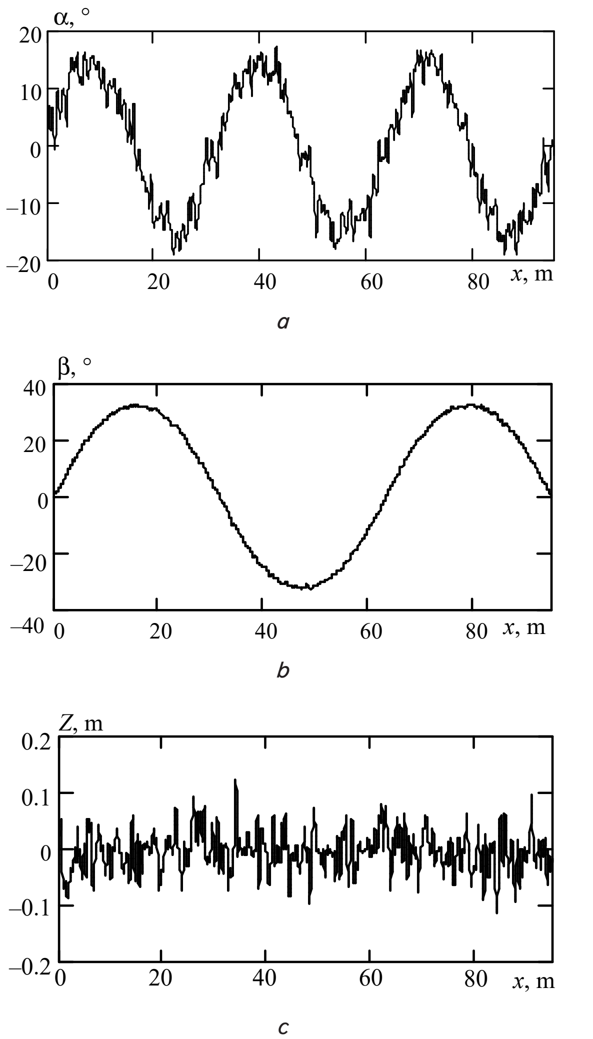

Fig. 7. The laws of movement of the tank when the fire truck is moving along the reference track of the forest rough terrain at a speed of 6 km/h: *a* – roll angle; *b* – yaw angle; *c* – vertical movement

Table 3

Ranges of values for reproduction of irregularities of the local topography of the track for the study of fluctuations in the position of the center of mass of the mechanical system of a water tank

Parameter R_1^*, m	Parameter R_2^*, m	Parameter R_3^*, m	Parameter R_4^*, m
0.2–0.5	0.2–0.5	0.05–0.2	1 or 2

5. 3. Results of a numerical experiment on the study of dynamic processes in a container with water during the movement of a fire truck through rugged forest terrain

After the calculations, the results are obtained in the form of images of the geometric configuration of the water in the tank. Each moment of the movement of the fire truck AC-4,5-60 (TGM 12.240)-364 corresponds to the value of the selected time step of recording information in the output file of the results of the LS-DYNA software package. To visualize the data obtained during the calculations, the time points when the car takes the position with the largest yaw angle when moving at a speed of 6 km/h were selected, as shown in Fig. 8.

The position of the water tank with a filling level of 25 % of the AC-4.5-60 (TGM 12.240)-364 fire truck at different time points when it is moving at a speed of 6 km/h along a reference track on forest terrain is shown in Fig. 9.

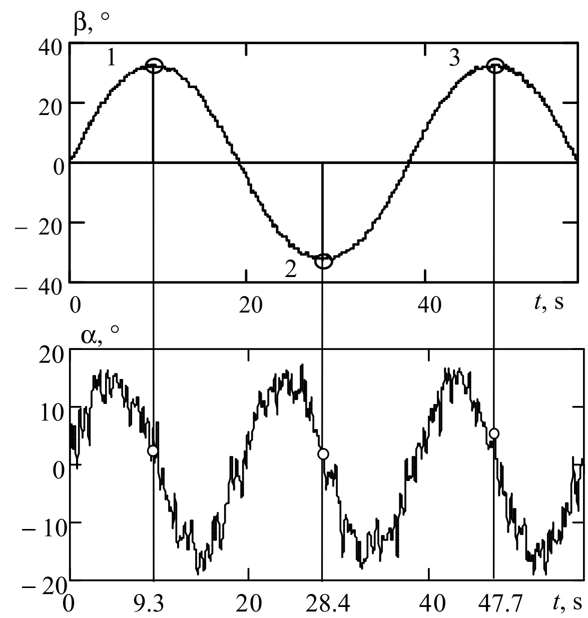

Fig. 8. Time points for visualization of the image of the position of the water tank of the fire truck AC-4,5-60 (TGM 12.240)-364

Analyzing the image of the geometric configuration of the water in the tank at the time of movement of the AC-4,5-60 (TGM 12.240)-364 fire truck and the general results of the calculations, it was noticed that the implemented system of breakwaters and partitions effectively prevents the formation of large waves. They could significantly affect the displacement of the car's center of mass.

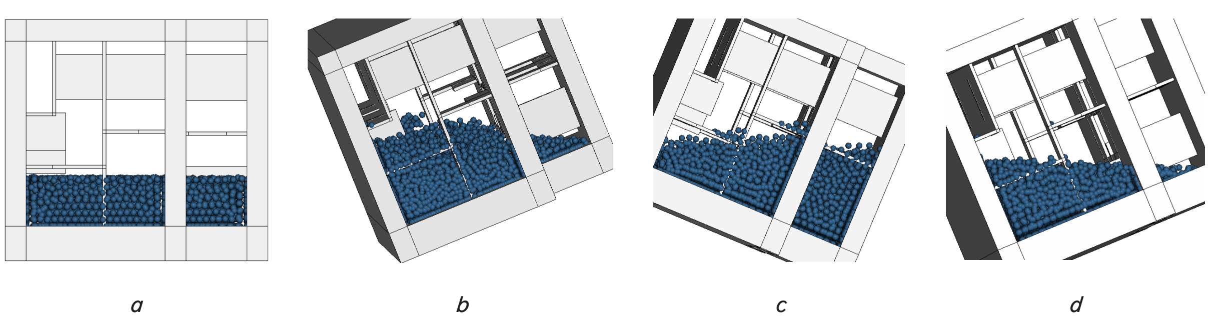

Fig. 9. Position of the tank with 25 % water filling level of the AC-4,5-60 (TGM 12.240)-364 fire truck at different time points when it is moving at a speed of 6 km/h along a reference track on forest terrain: *a* – 0 s; *b* – 9.3 s; *c* – 28.4 s; *d* – 47.7 s

For a more detailed study of the influence of the level of filling the tank and the speed of its movement on the fluctuations of the car's center of mass on the reference track of the forest terrain, the curves of the changes in the coordinates of the center of mass of the water in the tank were constructed. The curves express the dependences of the coordinates of the center of mass of the tank depending on the amount of linear movement of the fire truck tanker along the reference track on a forested terrain for the possibility of comparing these graphs for different speeds of the vehicle.

Fig. 8 shows dependence plots of the local coordinates of the center of mass of the tank. They depend on the magnitude of the linear movement of the fire truck tanker along the reference track on forest terrain. They are made for different filling levels of fire truck tanks AC-4.5–60 (TGM 12.240)-364.

The plots shown in Fig. 10 demonstrate that the largest fluctuations of the center of the mechanical system, which is a tank with water, occur when the tank is filled with water by 25 %. The same result is repeated for cases of fire truck tanker movement with other speeds. It should also be noted that the local relief has a much smaller influence on the fluctuations of the center of mass of the mechanical system. It is a tank with water rather than a large-scale relief. Since the plots of local coordinates in the horizontal plane in Fig. 10 retain a periodic character, it is possible to analyze the data on the movement of the fire truck along the reference track only for its first half. Taking into account such considerations, analysis of the influence of the speed of movement of a fire truck on the fluctuations of the center of mass of the mechanical system, represented by its water tank, was carried out. Fig. 11 shows dependence plots of the local coordinates of the center of mass of the tank depending on the speed of the fire truck tanker. Moving along the reference track on forest terrain to fill the tank of the fire truck AC-4,5-60 (TGM 12.240)-364 with 25 % water.

Plots in Fig. 11 show that the fluctuation of the center of gravity relative to the longitudinal horizontal and vertical axis of the fire truck is insignificantly affected by its speed along the reference track. The greatest influence of the speed of movement could be seen in relation to the transverse axis of the fire truck tanker.

In order to track the position of the center of mass of the tank with different levels of its filling with water during the movement of the fire truck, the trajectory of its movement was constructed at a vehicle speed of 6 km/h. Fig. 12 shows a curve that reproduces this trajectory.

The movement trajectories of the position of the center of mass of the tank at the speed of fire truck movement of 6 km/h along the reference track of the forest rough terrain are built taking into account the initial position of the center of mass. Fig. 12 demonstrates that the geometric center of the area of the center of mass positions is shifted by a certain amount relative to the initial position of the center of mass of the water tank. Fig. 13 shows the configurations of the areas of the positions of the center of mass of the tank with different values of the level of its filling with water.

In order to establish the largest values of displacement of the center of mass of the tank when the fire truck tanker is moving, curves of dependence of this value on the most significant parameter – the level of filling of the tank – were constructed. Fig. 14 shows dependence of the largest transverse displacement of the center of mass of the tank during the movement of the fire truck tanker on the level of its filling.

Fig. 14 demonstrates that the dependence of the maximum transverse displacement of the location of the center of mass of the tank during the movement of the fire truck tanker on the level of its filling has a character that is close to linear. The most significant parameter that affects the displacement of the location of the center of mass of the tank when the fire truck is moving is the level of filling the tank, but to a certain extent this parameter is also affected by the speed of the fire truck.

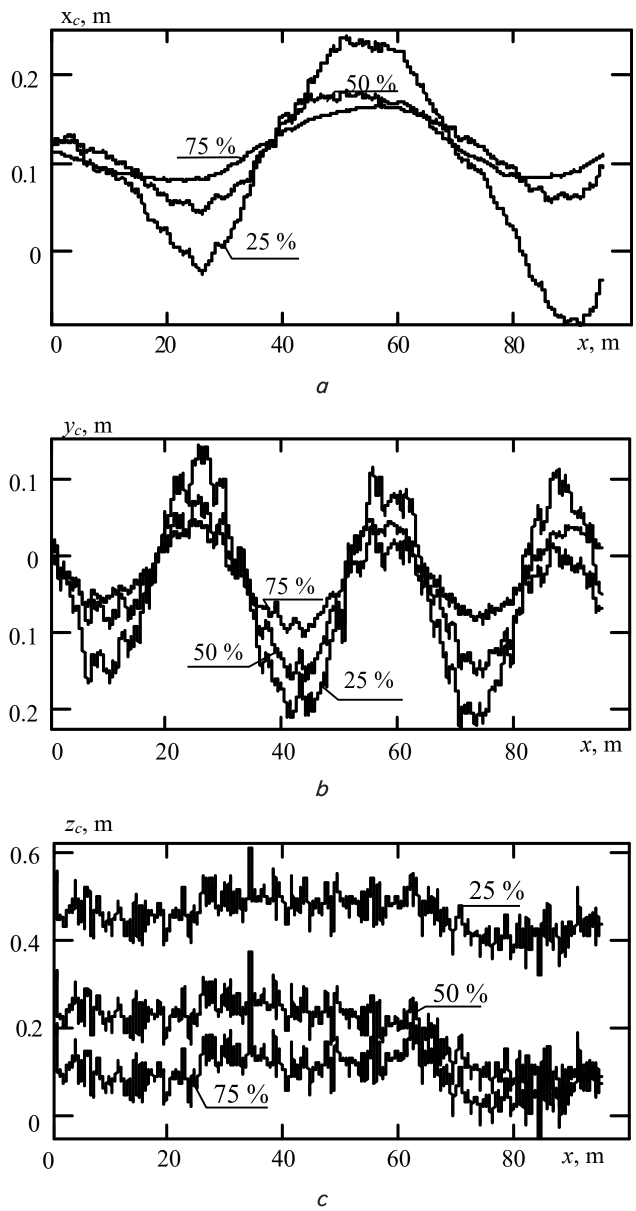

Fig. 10. Local coordinates of the center of mass of the tank with different levels of its filling when the fire truck tanker moves along the reference track of the forest terrain at a speed of 6 km/h: *a* – X_c coordinate; *b* – Y_c coordinate; *c* – vertical movement Z_c

In order to build a mathematical model that describes the dependence of the largest displacement of the center of mass of the water tank on the most significant parameters that determine the conditions of fire truck tanker movement, a full factorial numerical experiment was conducted. Such parameters include the filling level of the fire truck's tank and the speed of its movement through forest terrain. Analysis of the data presented in Fig. 14 reveals that such a dependence could be described by a simple two-factor linear regression of the following type [8, 9]:

$$y=a_0+a_1x_1+a_2x_2+a_3x_1x_2, \quad (3)$$

where x_1, x_2 are factors determined by the parameters that express the conditions of movement of a fire truck through forest terrain.

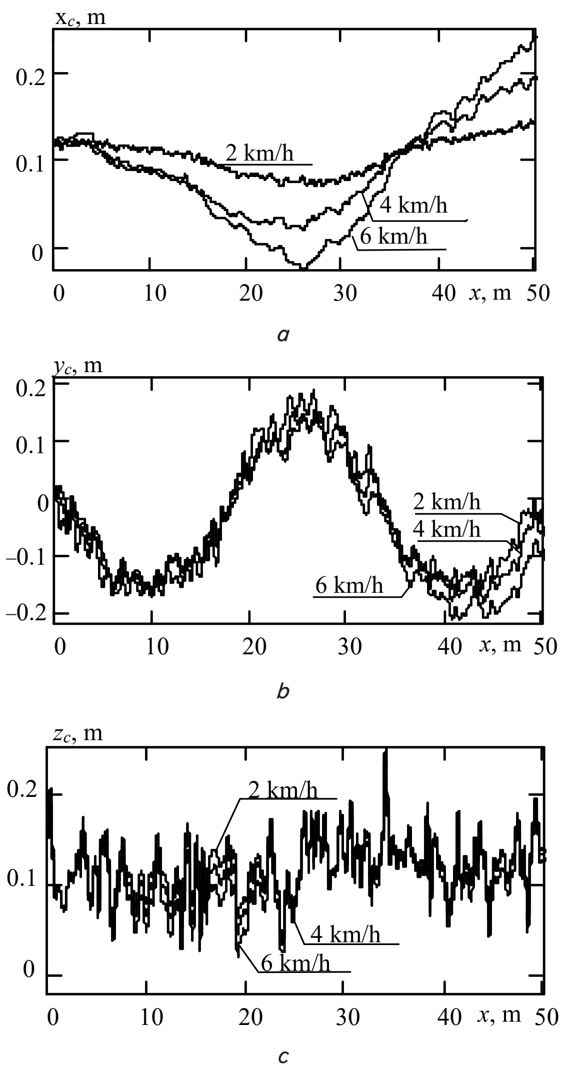

Fig. 11. Local coordinates of the center of mass of the tank with a level of its filling of 25 % when the fire truck tanker moves along the reference track of the forest rough terrain at different speeds: *a* — X_c coordinate; *b* — Y_c coordinate; *c* — vertical movement Z_c

Since the factors of this regression are independent in nature, its coefficients could be obtained using the simplest orthogonal plan of the first order according to [10, 11].

According to the matrix of the accepted plan, the values of the largest transverse displacement of the center of mass of the water tank during the movement of the fire truck should be determined. At the same time, these values are determined by varying the accepted most significant factors of the model.

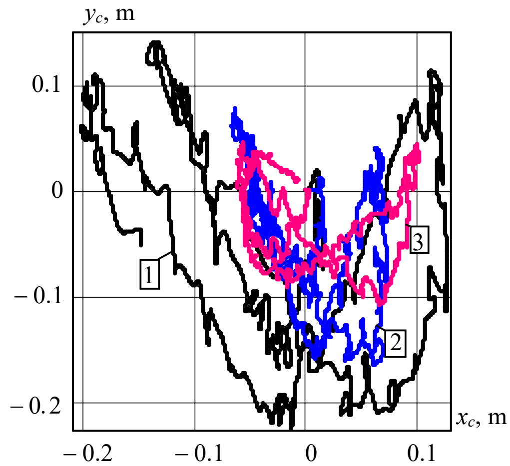

Fig. 12. Trajectories of the position of the center of mass of the tank at the speed of the fire truck tanker of 6 km/h along the reference track of the forest rough terrain with different levels of filling with water: 1 — 25 %; 2 — 50 %; 3 — 75 %

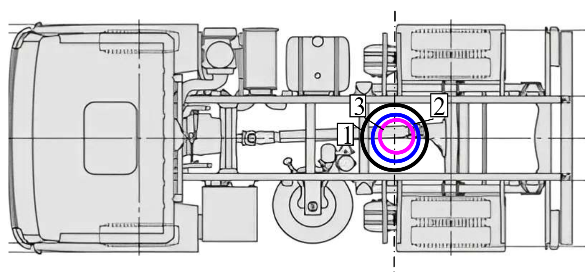

Fig. 13. Configurations of the areas of the positions of the center of mass of the tank when the fire truck tanker is moving at 6 km/h along the reference track of the forest rough terrain with different values of the level of filling the tank with water: 1 — 25 %; 2 — 50 %; 3 — 75 %

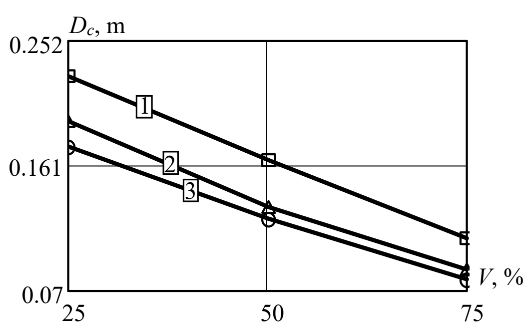

Fig. 14. Dependences of the largest transverse displacement of the center of mass of the tank during the movement of the fire truck on the level of its filling at a speed of: 1 — 6 km/h; 2 — 4 km/h; 3 — 2 km/h

By varying the accepted most significant parameters according to Table 5, based on the results of calculations shown in Fig. 12, the corresponding values of the maximum displacement of the center of mass of the water tank during the movement of the fire truck were derived. The resulting values are given in Table 6.

Using the data of Table 6, the regression coefficients (3) are determined in coded form according to the following formulas [10, 11]:

$$a_0 = \frac{1}{N}\sum_{i=1}^{N} y_i; \quad a_1 = \frac{1}{N}\sum_{i=1}^{N} x_1 y_i;$$

$$a_2 = \frac{1}{N}\sum_{i=1}^{N} x_2 y_i; \; a_3 = \frac{1}{N}\sum_{i=1}^{N} x_1 x_2 y_i, \quad (4)$$

where N=4 is the number of separate experiments according to the adopted plan;

x_i – parameter value according to the plan matrix;

y_i – the value of the maximum displacement of the center of mass according to Table 6.

The obtained values of the coefficients are given in Table 7.

Using the constructed mathematical model of the displacement of the center of mass of the water tank during the movement of a fire truck tanker in the form of a regression dependence, a corresponding nomogram was constructed. Determining the value of the maximum displacement of the center of mass of the selected most significant parameters of the movement of the fire truck tanker during its movement through forest terrain. The constructed nomogram is shown in Fig. 15.

Table 5

Factor variation intervals according to the numerical experiment plan

Filling level, V, %			Vehicle speed, v, km/h		
Least value, V_{-1}	Average, V_0	Greatest value, V_1,	Least value, q_{-1}	Average, q_0	Greatest value, q_1
25	50	75	2	4	6

The resulting mathematical model makes it possible to predict the maximum displacement of the center of mass of the water tank depending on the speed of the fire truck tanker when it moves through forest terrain and the level of its filling

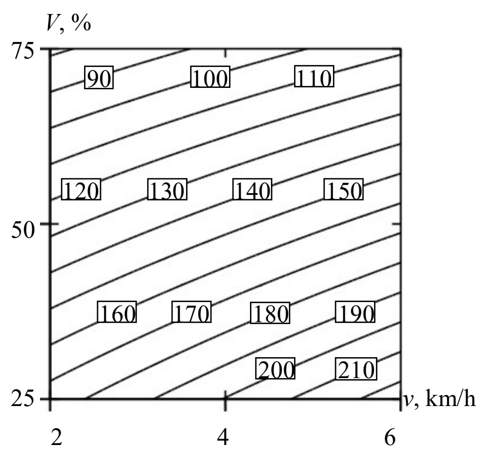

Fig. 15. Nomogram for determining the value of the maximum displacement (mm) of the center of mass of a water tank depending on the speed of the fire truck tanker during its movement through forest terrain and the level of its filling

Table 6

Values of the maximum displacement of the center of mass of the water tank during the movement of the fire truck, obtained as a result of conducting a numerical experiment according to the plan

Experimental situation	1	2	3	4
Maximum displacement of the center of mass of the water tank, y, mm	108	78	226	175

Table 7

Regression coefficients for the maximum displacement of the center of mass of the water tank when the fire truck is moving

Regression coefficients	a_0	a_1	a_2	a_3
In coded form	146.75	20.25	–53.75	–5.25
Real coefficients	192.75	1.23	–21.625	– 0.105

5. 4. To determine the optimal safe logistical routes of a fire truck tanker when moving through rough terrain during forest fire extinguishing

The above information about the maximum displacement of the tank's center of mass could be used to calculate the mass displacement of the entire car as a whole. Taking into account the information about the dimensions of the car, it is possible to calculate those directions of movement that would lead to the loss of stability of the tanker truck on an inclined surface of the terrain, depending on the angle of its inclination. Accordingly, it is possible to obtain forbidden directions of movement, as it is done in works [5, 12] but already taking into account the dynamic position of the center of mass and, unlike the deterministic model of the topographic base in the mentioned works, taking into account the random component of the relief surface. This, in turn, makes it possible to build a field of indicators of the speed of the fire truck tanker, that is, to find the speed of the vehicle at each point of the topographic base in any direction. The use of the Huygens principle when obtaining areas of transport reach [5, 12] makes it possible to build optimal (in the sense of arrival time) routes of tanker traffic under off-road conditions, taking into account real topographical conditions.

Using the devised methodology, optimal routes were built through rough forest terrain for the AC-4,5-60 (TGM 12.240)-364 fire truck, from the point of view of its safety and time to overcome it. Fig. 16 shows examples of the construction of such routes.

The first diagram shows the consideration of dangerous zones (for example, steep slopes), which affects the laid route to ensure stable movement of the fire truck. The algorithm avoids areas with a high level of risk, such as steep climbs or slopes, which minimizes the possibility of accidents or overturning of the tanker.

The second diagram illustrates an optimized route that takes into account not only safety but also the minimum time to cover the segment. Reducing the curvature of the route and avoiding unnecessary obstacles indicates optimization in the context of time, which is critically important in firefighting.

The devised methodology has proven effective in building optimal routes for the fire truck, providing a balance between safety and recovery time.

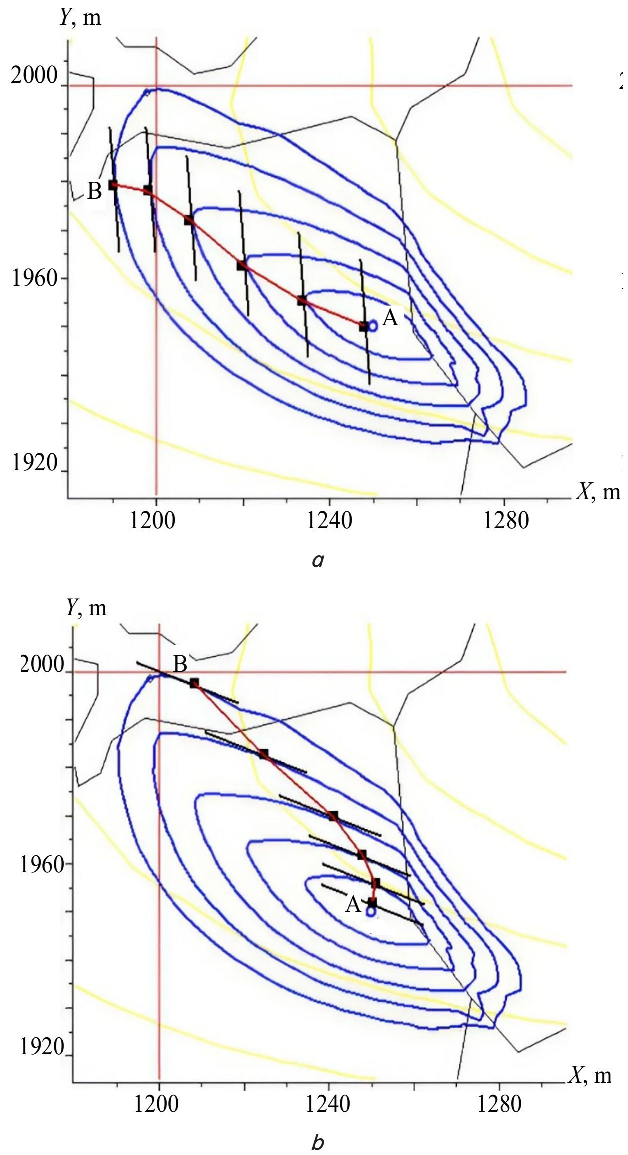

Fig. 16. Examples of building optimal routes through rugged forest terrain for the fire truck AC-4,5-60 (TGM 12.240)-364, from the point of view of its safety and the time it takes to overcome it: *a* — example 1; *b* — example 2

6. Discussion of results describing the oscillating process of water in the tank of a fire truck

In order to obtain detailed data on the fluctuation of the center of mass of the structural system of the fire truck tank during its movement through a rugged forest area, a calculation method was devised with mathematical models of its components and materials that could have an effect on oscillatory processes, including the dynamics of the movement of liquid in the container of the fire truck tanker when it is partially filled. Fig. 2–4 and Tables 1, 2 show calculation schemes and basic data on the mathematical models used. As boundary conditions, the calculation scheme took into account the influence of the surface relief in the form of the laws of its rotation angles in accordance with formulas (1), (2), and Fig. 5–7. These laws are derived using a generator of pseudorandom numbers. Calculations were carried out using complex calculation schemes and mathematical models. As could be seen, these fluctuations do not have critical values at speeds less than 6 km/h, as shown in Fig. 13, 14. This result could be explained by the presence of partitions in the tank of the fire truck, as shown in Fig. 6. The results of our study indicate the effectiveness of modeling the fluctuating processes of water in the tank of a fire truck when moving through rugged forest terrain and have an important application in the field of safety in the design of fire truck tankers.

In order to generalize our calculation results, the regularities of fluctuations of the center of mass were investigated. The regularities of the maximum displacement of the center of mass of the fire truck tanker depending on the speed of movement and the level of filling of the container with water are obtained in the form of a regression dependence. This makes it possible to predict the danger of movement at different combinations of speed and level of capacity filling when solving engineering problems of the safety of fire truck movement when extinguishing forest and landscape fires. The nomogram constructed using the obtained regression is shown in Fig. 15, it could be the basis for an express method for assessing the danger of tanker traffic in these connections and could be used as a tool for compiling recommendations regarding the traffic parameters of these vehicles. However, this pattern is limited to a speed of 6 km/h. At the same time, it should be noted that this restriction is imposed by safety considerations since faster movement is difficult to control when moving through rugged forest terrain. For greater confidence in the validity of our results, we compared them with the data from other studies [3]. The results are explained by the increased accuracy of reproduction of dynamic processes in the structural system of the fire truck tanker when using advanced mathematical models of its component materials.

The obtained data on the fluctuation of the center of mass of the fire truck tanker allow us to develop software, the mathematical base of which is the construction of the field of indicators of the speed of the fire truck tanker to obtain areas of transport reach. This will make it possible to solve the complex logistical problems of transporting fire-extinguishing substances to the sites of forest fires by fire truck tankers. The comparison showed that the results correspond to the general trend and are consistent with known data.

The devised calculation methods, based on the use of our results, have certain limitations since they do not yet take into account all the designs of tanker trucks and their water tanks, which have different configurations of partitions. The identified shortcomings could be eliminated by conducting further research for other types of fire truck tankers. When summarizing the results, it is possible to cover and devise the most general methods based on the proposed methodology.

7. Conclusions

1. The design of the water tank of the AC-4,5-60 (TGM 12.240)-364 fire truck has been analyzed. Based on this, an estimation model of one of the most common fire truck tanks with water capacity was built using the capabilities of the LS-DYNA software package. The features of this model are the reproduction of all the structural elements of the fire truck, including the water tank, which was modeled using the SPH method.

2. A mathematical model of the relief of rugged forest terrain was constructed for reproduction on the basis of a gener-

ator of pseudo-random numbers of its influence when applying boundary conditions to the dynamic system of a water tank of a fire truck tanker during its movement through rugged forest terrain. The obtained function determines the shape of the unevenness of the reference track for the study of fluctuations in the position of the center of mass of the mechanical system of the water tank. In particular, in order to reproduce possible options, three cases of the movement of a fire truck tanker with speeds of 6 km/h, 4 km/h, and 2 km/h were considered, which made it possible to obtain 3 sets of laws of movement for a fire truck tank.

3. The regularity of change in the maximum displacement of the center of mass of the water tank depending on the speed (v, km/h) of the AC-4.5-60 (TGM 12.240)-364 fire truck during its movement through forest terrain and the level of filling of the tank (V, %) was derived in the form of a regression dependence y=192.75+1.23×V-21.625×v-0.105×V×v.

4. Optimum safe logistic routes have been defined, and recommendations have been given for the relationship between the level of water filling of the tank of a fire truck and its speed of movement over rough terrain during forest fire extinguishing. This made it possible, in particular, to build safe and shortest routes for the AC-4,5-60 (TGM 12.240)-364 fire truck.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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