Seismic Loads Influence Treatment on the Liquid Hydrocarbon Storage Tanks Made of Nanocomposite Materials

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Abstract: - The liquid hydrocarbon storage tanks are the objects of environmental danger. It is necessary to perform additional calculations and develop appropriate design solutions to minimize the risks of their accidents in the event of the earthquake or explosions. The degree of damage to the environmentally hazardous object during the earthquake depends not only on the seismic effects level, but also on the quality of seismic design and construction. The possibility of exposure to smaller but more frequent and prolonged seismic loads caused by technogenic and natural factors has not been sufficiently taken into account in tanks designing for the environmentally hazardous liquids storage. The composite materials using with nanoinclusions in tanks for storage liquid hydrocarbons, allows to increase the reliability of tanks under seismic loads and extend their service life under the influence of natural and technogenic influences of various origin. The results of the calculations have been shown that the use of composite materials with nanoinclusions in the steel spheres form is the best option for environmentally friendly operation of tanks under seismic loads.

Key-Words: - liquid hydrocarbon, storage tank, earthquake, nanocomposites, environmental safety, seismic loads

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1 Introduction

To design the liquid hydrocarbon storage tanks that are objects of environmental danger, according to current building standards, it is necessary to take into account the 1% probability of exceeding the estimated intensity of seismic impacts for 50 years. This factor also significantly increases the risks of trouble-free operation and, accordingly, the cost and complexity of construction of these engineering structures, as it is necessary to perform additional calculations and develop appropriate design solutions to minimize the risks of their accidents in the event of the earthquake or explosions. The degree of damage to the environmentally hazardous object during the earthquake depends not only on the seismic effects level, but also on the quality of seismic design and construction. According to recent seismological studies, it has been established that in Ukraine, including its platform part, there is the danger of local and strong subcortical earthquakes with the magnitude more than 5 points [1], [2], [3].

According to the existing standards [2], [3], the foundation ring is calculated for the main loads combination, and for construction sites with seismicity of 7 points and above is for the special loads combination. Thus, the possibility of exposure to smaller but more frequent and prolonged seismic loads caused by technogenic and natural factors has not been sufficiently taken into account in tanks designing for the environmentally hazardous liquids storage.

2 Problem Formulation

Containers and tanks for environmentally hazardous liquids storage are widely used in various engineering practice fields, such as aircraft construction, chemical and oil gas industry, energy engineering, transport. These tanks are operating under conditions of high technological loads and filling with oil, flammable or toxic substances. As a result of the sudden action of seismic loads, the liquid stored in the tanks begins to sense the intense splashes.

Sloshing is a phenomenon in the number of industrial facilities: in containers for storage of liquefied gas, oil, fuel tanks, in the reservoirs of cargo tanks. It is known that partially filled tanks are exposed to particularly intense splashes. This could lead to high pressure on the tank walls, destruction of the structure or loss of stability and can cause the release of environmentally hazardous contents into the environment and lead to serious consequences [4], [5], [6], [7], [8], [9].

The release of environmentally hazardous liquids, especially liquid hydrocarbons from storage tanks to the environment and their further spread to the territory of settlements could cause mass poisoning of people and animals, lead to environment pollution. Liquid spills could lead to explosions and fires that could spread to nearby reservoirs and surrounding areas. Economic losses from accidents with tanks destruction, leakage and fire of liquid hydrocarbons include not only direct losses, but also the cost of measures to restore the environment [10], [11].

To ensure the environmental safety of areas adjacent to tanks filled with liquid hydrocarbons, it is necessary to take into account the safe design of the tank, tank material, forecasting the effects of natural and technogenic factors on tanks. The set of natural factors that must be taken into account are seismic loads, groundwater level of the reservoir location and others. Technogenic factors should include sudden traffic accidents, industrial accidents, vibration, seismic and artificial impacts, and so on.

2.1 Literature analysis

In the most research papers of Shevtsov A. A. [11], Wilson S. [12] Islamovic F. [13], Godoy L.A. [14], Jaca R.C. [15] the significance estimation of tanks influences for liquid hydrocarbons storage on environment and monitoring of reservoirs tightness changes, the destruction rate of their structure under the technogenic and natural factors action have been investigated.

The issues concerned with liquid sloshing in tanks have been conducted in the works of Ibrahim R.A. [16], [17]. It should be noted the paper on sloshing liquid in cylindrical tanks under the seismic loads action [18], [19], [20].

The necessity of control and impact assessment of nanomaterials on the environment for safety and efficient use of nanotechnologies has been substantiated in paper [7].

In the previous works of the authors [4],[5], [6] the seismic loads on the reservoirs of oil storages have been treated, the use of nanocomposite materials has been proposed to ensure the antistatic effect of nanocomposite materials [21], [22]. In other works [23], [24], [25] the mechanical characteristics of materials with different inclusions have been investigated. But the use of nanocomposites as the reservoir material to increase their strength characteristics has not been studied.

3 Problem Solution

The problem of free and forced oscillations of the elastic rotation shell, partially filled with an ideal incompressible fluid has been considered (Fig. 1.)

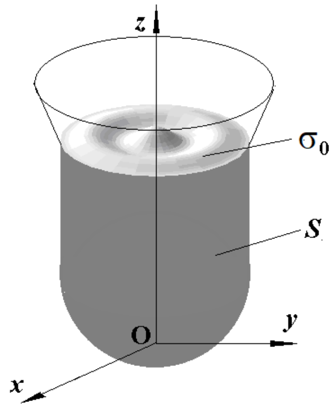


Fig. 1. Rotation shell, partially filled with liquid

Let S be the wetted surface of the shell, σ_0 is the free surface of the liquid.

Suppose that the fluid is ideal, incompressible, and its flow (induced by body motion) is vortex-free. Denoting the velocity components by V_x, V_y, V_z, the incompressibility condition of the continuous medium will be obtained from the following equality:

$$\mathrm{div}V = \frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z} = 0 \qquad (1)$$

Since the flow is vortex-free, there is the velocity potential φ that satisfies the harmonic equation due to (1).

The equations system of motion is symbolically written in the form

$$\mathrm{L(U)} + \mathrm{M}(\ddot{\mathrm{U}}) = \mathrm{P},$$

where L, M – operators of elastic and mass forces;

U=(u_1, u_2, u_3) – vector function of displacements;

P – the pressure of the liquid on the wetted shell surface.

The small harmonic oscillations of the elastic shell has been studied. There is represented the vector U in the form $U=ue^{i\Omega t}$, where Ω is the frequency and **u** is the natural oscillations form of the shell under consideration with the liquid.

To solve the free and forced oscillations problem of shell structures with compartments containing liquid, the method of given shapes has been developed. Its essence is as follows. The connected system of differential equations to elastic displacements of the structure and fluid pressure has been formed. Three sets of basic functions have been used to build the representation of system solutions. The first of them are the oscillations natural forms of the structure in the absence of aggregate used to build hydroelastic movements.

The second and third basic functions sets are used to represent the potential velocities and fluid pressure on the wetted structure surface. The velocity potential is described by the sum of two "partial" potentials. One of them describes the natural liquid oscillations in the rigid tank, taking into account the forces of gravity. The second set refers to the natural oscillations of the elastic shell with the fluid without taking into consideration gravitational forces. As basic functions for solving problems concerning free and forced oscillations of rotation shells, partially filled with liquid, the natural oscillation modes of the unfilled shell have been accepted.

The following presentation of the natural oscillation modes of the shell with the liquid has been used:

$$U(x,y,z,t)=\sum_{k=1}^{m} c_k(t)u_k(x,y,z), \qquad (2.1)$$

where $U(x,y,z,t)$– displacement vector;

$\boldsymbol{u}_k(x,y,z)=\big(u_k(x,y,z),v_k(x,y,z),w_k(x,y,z)\big)$ – vector-function, which are natural oscillation modes of the unfilled shell,

$c_k(t)$ – unknown coefficients that depend only on time.

To determine $\boldsymbol{u}_k(x,y,z)$ it has been assumed that $c_k(t)=e^{i\Omega t}$, $P=0$, $Q_i=0$ and it has been obtained the problem for determining the natural oscillations frequencies and forms of the unfilled shell.

The velocities potential will be determined. To do this, it will be found the "partial" velocity potentials that correspond to the natural oscillations forms of the unfilled shell.

According to (1.1) there have

$$w(x,y,z,t)=\sum_{k=1}^{m} w_k(x,y,z)c_k(t). \qquad (2.2)$$

Here the functions are normal components of the natural oscillations forms of the unfilled shell.

For the function φ it has been obtained the following boundary value problem:

$$\Delta\varphi=0;\ \frac{\partial\varphi}{\partial n}=\begin{cases}\dfrac{\partial w}{\partial t}; & M\in S\\ \dfrac{\partial\zeta}{\partial t}; & M\in\sigma_0\end{cases}$$

$$\frac{\partial\varphi}{\partial t}+a_s(t)x+g\zeta=0;\quad M\in\sigma_0.$$

where $w(x,y,z,t)=\sum_{k=1}^{m} w_k(x,y,z)c_k(t)$.

It has been proposed to present the velocity potential φ as the sum of two potentials $\varphi=\varphi_1+\varphi_2$.

To determine φ_1 it has been formulated the following boundary value problem:

$$\nabla^2\varphi_1=0,\qquad \frac{\partial\varphi_1}{\partial n}=\frac{\partial w}{\partial t},\ M\in S,$$

$$\frac{\partial\varphi_1}{\partial t}=0,\ M\in S. \qquad (2.3)$$

Note that from relation (1.2) and the second of equations (1.3) it could be obtained the series

$$\varphi_1(x,y,z,t)=\sum_{k=1}^{m}\varphi_{1k}(x,y,z)\dot{c}_k(t). \qquad (2.4)$$

To determine the functions φ_{1k} it has been gained m of the following boundary value problems:

$$\nabla^2\varphi_{1k}=0,\qquad \frac{\partial\varphi_{1k}}{\partial n}=w_k,\ M\in S,$$

$$\varphi_{1k}=0,\ M\in\sigma_0. \qquad (2.5)$$

It could be note that problems (1.5) correspond to zero acceleration of free fall. Also important that (1.5) are mixed problems for the Laplace equation, the solution condition for such problems is not checked.

To determine the potential φ_2, it has been started with the auxiliary problem of fluid oscillations in the rigid shell, taking into account the forces of gravity. Such problem has been formulated in the form:

$$\nabla^2\Psi = 0, \quad \frac{\partial \Psi}{\partial n} = 0, \ M \in S_1,$$

$$\frac{\partial \Psi}{\partial n} = \dot{\zeta}, \ M \in S_0,$$

$$\dot{\Psi} + g\zeta = 0, \ M \in S_0 \quad (2.6)$$

The last equation in (1.6) is the dynamic condition (equality of atmospheric pressure) on the free surface. Differentiation of this equation by the variable *t* taking into account the third relation in (1.6) gives:

$$\ddot{\Psi} + g\frac{\partial \Psi}{\partial n} = 0, \ M \in \sigma_0. \quad (2.7)$$

The problem (1.7) - (1.8) as the eigenvalues problem and representation of its solution in the next form will be considered as

$$\Psi(x,y,z,t) = e^{i\kappa t}\psi(x,y,z).$$

For the function ψ it is the following problem about harmonic oscillations of the liquid in the rigid tank:

$$\nabla^2\psi = 0, \quad \frac{\partial \psi}{\partial n} = 0, \ M \in S,$$

$$\frac{\partial \psi}{\partial n} = \frac{\kappa^2}{g}\psi, \ M \in \sigma_0. \quad (2.8)$$

Solving this problem gives the number of κ_k eigenvalues and their corresponding eigenfunctions, which has been denoted by φ_{2k}. Next, after solving this auxiliary problem, there will be looking for the potential φ_2 in the form:

$$\varphi_2(x,y,z,t) = \sum_{k=1}^{n}\dot{d}_k(t)\varphi_{2k}(x,y,z). \quad (2.9)$$

So, there are $\varphi = \varphi_1 + \varphi_2$,

where

$$\varphi_1(x,y,z,t) = \sum_{k=1}^{m}\dot{c}_k(t)\varphi_{1k}(x,y,z)$$

$$\varphi_2(x,y,z,t) = \sum_{k=1}^{n}\dot{d}_k(t)\varphi_{2k}(x,y,z).$$

First of all, it has been noted that the total potential constructed in this way satisfies the Laplace equation, i.e.

$$\Delta\varphi = \Delta\varphi_1 + \Delta\varphi_2 = 0.$$

Next, on the wetted surface of the shell, the condition of non-leakage is met, namely

$$\frac{\partial \varphi}{\partial n} = \frac{\partial \varphi_1}{\partial n} + \frac{\partial \varphi_2}{\partial n} = \frac{\partial w}{\partial t}, \ M \in S.$$

The boundary conditions must be met on the free surface:

$$\frac{\partial \varphi}{\partial n} = \dot{\zeta}, \ M \in \sigma_0$$

$$\dot{\varphi} + g\zeta + a_s(t)x = 0, \ M \in \sigma_0.$$

From equations (1.8) and (1.9) it will be obtained that the motion of the liquid free surface determined by the ratio

$$\zeta = \sum_{k=1}^{n} d_k(t)\frac{\partial \varphi_{2k}(x,y,z)}{\partial n} + \sum_{k=1}^{m} c_k(t)\frac{\partial \varphi_{1k}(x,y,z)}{\partial n}$$

The advantage of the proposed approach has been noted in determination of the free surface shape that does not need to differentiate seismic acceleration $a_s(t)$ over time, which is quite a challenge.

Consider a dynamic boundary condition on a free surface. From the last relation in (1.4) we have. Therefore, the condition leads to differential equations

Dynamic boundary condition on the free surface has been considered. From the last relation in (1.4) it has been gained $\dot{\varphi}_1 = 0$. Therefore, the condition $\dot{\varphi} + g\zeta + a_s(t)x = 0$ leads to differential equations

$$\sum_{k=1}^{n}\ddot{d}_k(t)\varphi_{2k}(x,y,z) + g\sum_{j=1}^{m}c_j(t)\frac{\partial \varphi_{1j}(x,y,z)}{\partial n} + g\sum_{k=1}^{n}d_k(t)\frac{\partial \varphi_{2k}(x,y,z)}{\partial n} + a_s(t)x = 0.$$

(2.10)

There are no forms that correspond to the first potential due to equality

$$\varphi_{1k} = 0, \ M \in \sigma_0.$$

In addition, there are expression for pressure

$$-\frac{p}{\rho_l} = \sum_{k=1}^{n}\ddot{c}_k(t)\varphi_{1k}(x,y,z) + \sum_{k=1}^{n}\ddot{d}_k(t)\varphi_{2k}(x,y,z) + gz + a_s(t)x$$

. (2.11)

Using the ratio φ_{2k} for functions

$$\frac{\partial \varphi_{2k}}{\partial n} = \frac{\kappa_k^2}{g}\varphi_{2k}, \ M \in \sigma_0,$$

there are equation (1.10) takes the form

$$\sum_{k=1}^{n}\left[\ddot{d}_k(t)+\kappa_k^2 d_k(t)\right]\varphi_{2k}(x,y,z)+g\sum_{k=1}^{m}c_k(t)\,\frac{\partial\varphi_{1k}(x,y,z)}{\partial n}+a_s(t)x=0$$

.

After performing the scalar product of this relation on the functions φ_{2l} there the following equations have been obtained (due to the orthogonality of the oscillations natural forms of the fluid in the rigid tank, at least for the shells of rotation, [9]):

$$\ddot{d}_l(t)+\kappa_l^2 d_l(t)+\frac{g}{(\varphi_{2l},\varphi_{2l})}\sum_{k=1}^{m}c_k(t)\left(\frac{\partial\varphi_{1k}}{\partial n},\varphi_{2l}\right)+a_s(t)(x,\varphi_l)=0,\quad l=1,2..,n$$

.

Defining the functions φ_{1k} and φ_{2k}, there the expression for the pressure calculated by formula (1.11) have been found. The scalar product of the obtained equations on the proper form $\mathbf{u}_j$ has been also performed. The scalar product here is in the sense:

$$\left(\boldsymbol{u}_k,\boldsymbol{u}_j\right)=\iint_S\left(u_k u_j+v_k v_j+w_k w_j\right)dS\,.$$

The differential operators from (1.15) corresponding to the stiffness and mass matrices as follows have been denoted:

$$\boldsymbol{L}=\begin{pmatrix}L_{11} & L_{12} & L_{13}\\ L_{21} & L_{22} & L_{33}\\ L_{31} & L_{32} & L_{33}\end{pmatrix};\quad \boldsymbol{M}=\rho h\frac{\partial^2}{\partial t^2}\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix}\cdot$$

The condition of eigenforms orthogonality of the unfilled shell on the matrix of masses have been applied [48]

$$\boldsymbol{L}\boldsymbol{u}_k=\omega_k^2\boldsymbol{M}\boldsymbol{u}_k,(\boldsymbol{M}\boldsymbol{u}_k,\boldsymbol{u}_j)=\delta_{kj}\,.\qquad(2.12)$$

where ω_k – the natural frequency of the corresponding unfilled shell k – that own form.

After performing the scalar product of the first three equations in (1.15) on $\mathbf{u}_j$, taking into account the relations (1.33) it has been obtained

$$\ddot{c}_j(t)+\omega_j^2 c_j(t)+\rho_l\sum_{k=1}^{m}\ddot{c}_k\left(\varphi_{1k},w_j\right)+$$
$$+\rho_l\left[\sum_{i=1}^{n}\ddot{d}_i\left(\varphi_{2i},w_j\right)+g\left(z,w_j\right)+a_s(t)\left(x,w_j\right)\right]=\left(Q,\boldsymbol{u}_j\right),\ j=1,m$$

Finally, the system of ordinary second-order differential equations with respect to unknown coefficients has been gained $c_k(t),\quad k=1,...,m$, $d_k(t),\quad k=1,...,n$:

$$\ddot{c}_j(t)+\omega_j^2 c_j(t)+\rho_l\sum_{k=1}^{m}\ddot{c}_k\left(\varphi_{1k},w_j\right)+$$
$$+\rho_l\left[\sum_{i=1}^{n}\ddot{d}_i\left(\varphi_{2i},w_j\right)+g\left(z,w_j\right)+a_s(t)\left(x,w_j\right)\right]=\left(Q,\boldsymbol{u}_j\right),\ j=1,m$$

(2.13)

$$\ddot{d}_l(t)+\kappa_l^2 d_l(t)+\frac{g}{(\varphi_{2l},\varphi_{2l})}\sum_{k=1}^{m}\dot{c}_k(t)\left(\frac{\partial\varphi_{1k}}{\partial n},\varphi_{2l}\right)+a_s(t)(x,\varphi_l)=0,\quad l=1,2..,n$$

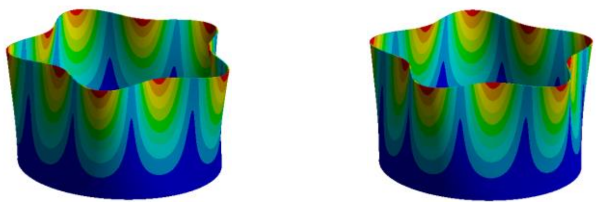
Since it has been assumed that at the initial time (for example, before the earthquake or explosion) the system "shell-liquid" was at rest, zero initial conditions have been accepted

$$c_k(0)=\dot{c}_k(0)=0,\quad k=1,...,m;$$
$$d_k(0)=\dot{d}_k(0)=0,\quad k=1,...,n.\qquad(2.14)$$

Thus, the scheme of solving the related dynamic problem for the rotation shell, partially filled with fluid, contains several stages, each of that has its own value. These stages are as follows:

1. Frequencies and forms determination of free oscillations of the unfilled shell by the finite element method.
2. Frequencies and forms determination of fluid oscillations in the rigid shell under the action of gravity using the limiting elements method.
3. Frequencies and forms determination of oscillations of the elastic shell without taking into account the action of gravity using the limiting elements.method.
4. Solving the system of second-order differential equations using the 4th and 5th order Runge-Kutta method.

Provided calculations have been allowed to build the necessary systems of basic functions for the forced oscillations study, as well as the study of the surface tension influence and nonlinear effects on oscillations of shells with fluid. First, the empty shell has been considered. The Fig. 2 shows the oscillations forms of such shell under the specified conditions of attachment.



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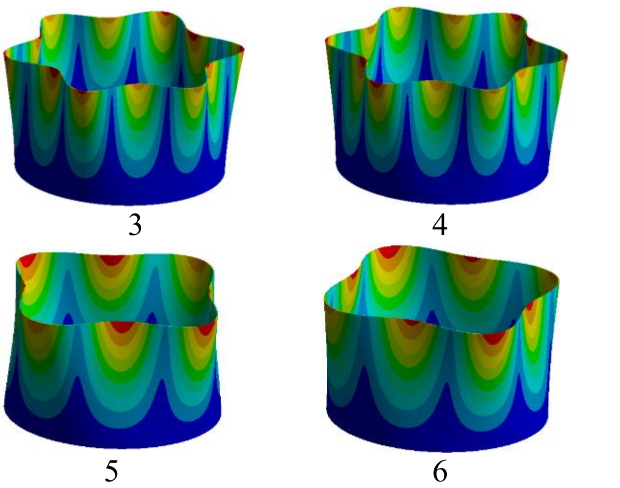


Fig.2. Oscillations modes of the unfilled shell

The eigenfrequencies of the unfilled shell have been given for different materials in Table 1.

Table 1. Eigenfrequencies of the unfilled shell, Hz

Material/ Frequency number	Aluminum	Composite, steel bullets	Composite, steel fibers	Composite, carbon fiber	Composite, steel spheres
1	90,573	85,429	85,789	85,071	84,674
2	90,575	85,43	85,791	85,073	84,676
3	100,36	94,567	94,974	93,599	93,644
4	100,37	94,578	94,985	93,61	93,654
5	103,52	97,751	98,153	97,874	96,986
6	103,52	97,753	98,154	97,876	96,988

Note that the oscillation shapes are the same for shells made of different materials, while the frequencies differ by about 5-7%. This allows tuning from unwanted resonant frequencies, including by selecting the appropriate material. These calculations refer to the construction of the basic functions first system according to [18], [19].

Next, it has been formed the second system construction of basic functions, for which the liquid sloshing in the rigid tank has been considered. The acoustic approximation has been applied. The Fig. 3 shows the finite element grid for acoustic calculation.

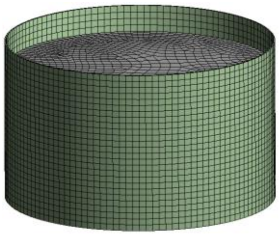


Fig. 3. Finite element grid for acoustic calculation

The 31928 finite elements have been selected, further increase in their number did not lead to the significant change in the results. The method of boundary elements has been also used to compare the calculations [18], [19]. The 100 boundary elements along the cylindrical wall, 100 elements along the bottom radius and 120 elements along the free surface radius have been selected. Fig. 4 shows the modes of the liquid surface sloshing.

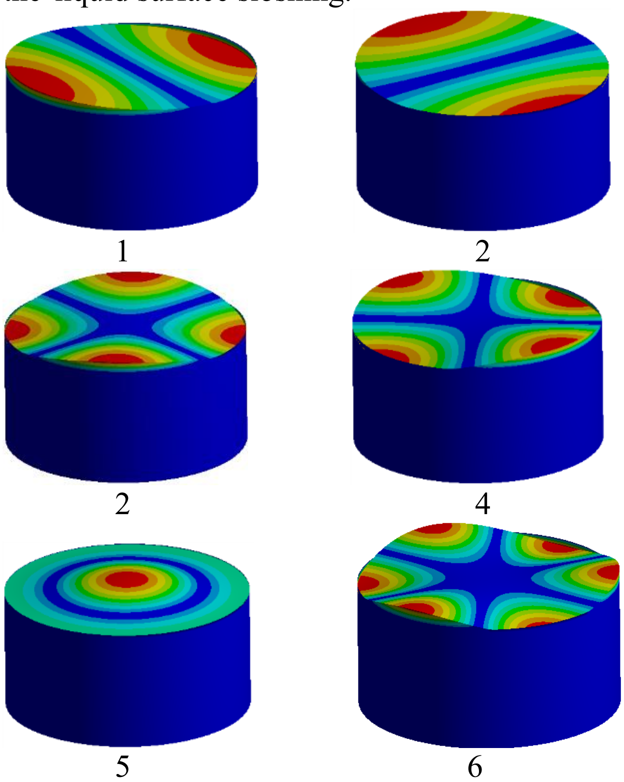


Fig. 4. The free surface sloshing modes

Table 2 shows the values of the frequencies of free surface oscillations.

Table 2. Sloshing frequency of the liquid free surface, Hz

Frequency	1	2	2	4	5	6

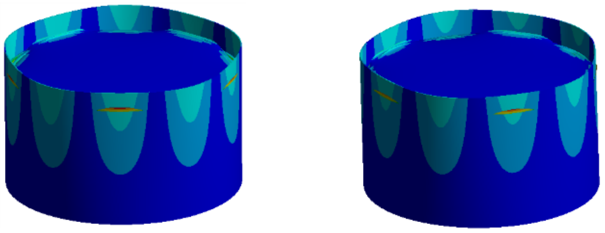
numbe r						
FEM	0.65 965	0.65 965	0.86 931	0.86 931	0.97 542	1.02 16
BEM	0.65 967	0.65 967	0.86 938	0.86 938	0.97 553	1.02 43

From the given data there has been drawn the conclusion of the obtained results probability. Note that the splash frequencies are the lowest, they do not depend on the choice of material, at least at the selected ratios between the geometric characteristics of the shell.

Thus, the second system of basic functions has been built.

The third system of basic functions definition will be obtained. To do this, it has been performed the calculation in the hydroelastic formulation. Note that it has been proposed to search for the velocities potential in the form of the sum of two potentials $\varphi = \varphi_1 + \varphi_2$. In this case, the potential φ_2 corresponds to the definition of free surface splashes, i.e. it has been found as the basic functions linear combination of the second system. The potential φ_1 corresponds to the oscillations of the elastic shell with the liquid, but without taking into account the movements of the free surface and is depicted as the linear combination of basic functions of the third system. FEM and BEM could also be used to define these basic functions.

Here the calculation has been performed with the FEM help. Fig. 5 shows the corresponding oscillations forms.



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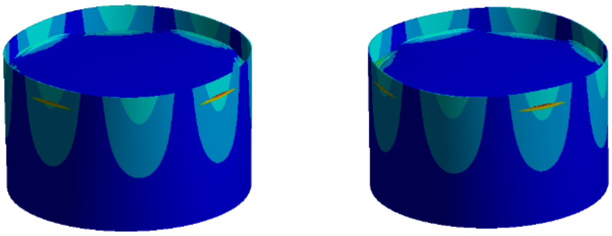

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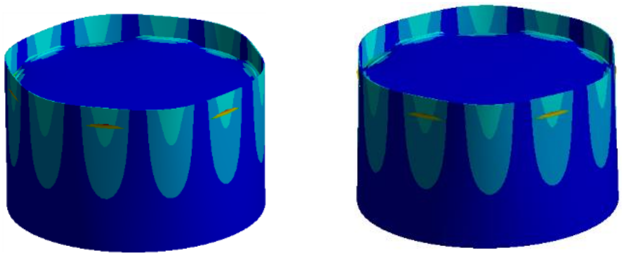

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Fig. 5. Shell oscillations modes taking into account the walls elasticity

Table 3 shows the natural frequencies of shell oscillation, taking into account the walls elasticity.

Table 3. Eigenfrequencies of hydroelastic oscillations of the shell, Hz

Mater ial/ Frequ ency numb er	Alumi num	Comp osite, steel bullets	Comp osite, steel fibers	Comp osite, carbon fiber	Comp osite, steel sphere s
1	48,02 9	50,565	50,625	43,828	43,692
2	48,05 5	50,593	50,653	43,85	43,716
3	51,60 7	54,672	54,722	47,343	47,014
4	51,61 7	54,682	54,732	47,349	47,023
5	54,90 2	57,646	57,723	49,792	49,851
6	54,94 8	57,694	57,722	49,829	49,891

From the above results the oscillations forms of shells of different materials are the same, and the difference in oscillation frequencies reaches 5-7 percent, which may be significant when conducting resonance tuning.

4 Conclusion

The composite materials using with nanoinclusions in tanks for storage liquid hydrocarbons, allows to increase the reliability of tanks under seismic loads and extend their service life under the influence of natural and technogenic influences of various origin. The results of the calculations have been shown that the use of composite materials with nanoinclusions in the steel spheres form is the best option for environmentally friendly operation of tanks under seismic loads.

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

Olena Sierikova: conceptualisation, data curation, formal analysis, methodology.
Elena Strelnikova carried out the simulation and the optimization.
Kirill Degtyarev: visualization, data curation.

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