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INFLUENCE OF THE PARAMETERS OF THE PRE-STRESSED WINDING ON THE OSCILLATIONS OF VERTICAL CYLINDRICAL STEEL OIL TANKS

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This paper reports an analysis of the frequencies and shapes of oscillations of the tank with a volume of 3000 m^3 with a winding of high-strength steel wire with a diameter of 3 mm, 4 mm, and 5 mm, applied in increments of 1:3. In addition, for the tension force of the turn in the range from 0.2 to 0.8 of the yield strength of the wire material. The study was carried out on the basis of a finite-element method in the ANSYS software package for a three-dimensional geometric model of the structure. At the same time, the software took into consideration the height-uneven width of the cylindrical wall taking into account the height of the filling to the maximum height and the tension forces of the winding.

It has been established that a change in the diameter of the winding wire does not lead to a significant change in the spectrum for the first ten significant frequencies. And an increase in the tension force of the wire in the winding leads to a decrease in the magnitude of oscillation frequencies. The exception is the sixth frequency. Its values are equal to one-tenth of a Hz for all estimated cases of the force of tension of the turn in the range from 0.2 to 0.8 of the yield strength of the wire material. The oscillation shapes of the tank reinforced by the winding have been determined. The change in the tension force of the wire in the winding does not change the number of waves at the circumferential coordinate at the free edge of the structure. We studied the loss of stability of the tank wall under distributed internal pressure. A comparative analysis of the sixth oscillation shape and the shape of stability loss reveals that they have the same number of waves at the circumferential coordinate.

The results reported here could make it possible to effectively use the pre-stress in order to detune the tank from the resonant frequency when operating in seismically hazardous areas

Keywords: oil tank, tank oscillations, preliminary stresses, winding tension, numerical method

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1. Introduction

Vertical cylindrical steel tanks of large volumes are widely used in the oil refining industry for the storage of oil or petroleum products. During operation, the structure is subjected to a complex static and dynamic effect, as a result of which a stressed-strained state occurs in the tank wall. The main static load acting on the structure is the hydrostatic pressure of oil or petroleum products on the tank wall. Dynamic loads, as a rule, are caused by the influence of the external environment. At the same time, tanks can be operated in areas with different weather and natural conditions, including areas with increased seismic activity. The seismic load leads to fluctuations in the tank wall and the liquid in it [1–3], thereby increasing the dynamic load on the inner surface of the wall.

The production of tanks can not always meet the growing needs for ready-made structures in a timely manner. Thus, the service life of finished tanks can be significantly increased. This increases the likelihood of structural failure of the tank in the areas of bolted joints, dents, welds, and other places of stress concentration [4–6]. To enable long-term and trouble-free operation of tanks of large volumes, technical solutions are implemented aimed at strengthening the durability of structures. Thus, one of the options for strengthening the finished structure is to apply the winding to the outer surface of the wall [7]. In this case, a stressed-strained state occurs on the outer surface of the wall due to the tension of the winding by a given amount. With the correct choice of such winding parameters as the pitch of the winding turn, the thickness of the thread, and the force of its tension, it is possible to determine a preliminary stressed-strained state of the wall of the structure. Such a method partially compensates for the effect of hydrostatic pressure and reduces the likelihood of structural failure of the structure during fluctuations. It should be borne in mind that the presence of the winding and the amount of tension of the filament in it change the frequency spectrum of the tank.

Thus, at the stage of general design, in order to formulate recommendations for the operation of structures in seismically hazardous areas, it is necessary to study the frequency spectrum of the tanks reinforced by winding. At the current level of development of computer technology and software, it is advisable to analyze the influence of prestressed winding parameters on tank oscillations by numerical methods [8]. Therefore, it is a relevant task to conduct studies to investigate this issue.

2. Literature review and problem statement

The large-sized cylindrical oil storage tank is a thin-walled structure. However, the wall thickness is not constant but decreases from the lower fixed edge of the structure to its upper edge. Due to this feature, studies involving numerical modeling of oscillations and loss of stability are carried out according to two types of models: simplified shell models and three-dimensional finite-element models. Work [9] reviews latest studies into the analysis of thin-walled structures and steel structure. It is shown that when using shell models, in addition to the internal forces and membrane stresses of the shells, the components of the initial strain and imperfection should be taken into consideration in the calculations. The cited work numerically analyzes a steel water tank, which is a typical thin-walled structure. The complex interaction of the initial strain with vertical and horizontal stresses is analyzed in detail. It is noted that the initial strain can reduce the stress in the shell. It is shown that the initial large strains can play an important role in the design of industrial structures, including for thin-walled structural elements. At the same time, the considered shell models assume a constant thickness of thin-walled structural elements. The change in the wall thickness of the thin-walled element is not described by the proposed models. In [10, 11], oscillations of cylindrical shells are investigated using the nonlinear theory of shells. It is shown that the use of nonlinear models is advisable in cases where the mechanical properties of the construction material change in the thickness of the shell. And for thin-walled structures made of isotropic materials, linear models yield adequate results. Both linear and nonlinear shell models generally do not take into consideration changes in shell thickness along the generatrix. And taking into consideration the change in the thickness of the shell along the generatrix leads to a significant complication of the mathematical model, as shown in [12]. At the same time, the simplification of the real geometry of the tank wall to a model of a cylindrical shell of constant thickness leads to unreliable values of the parameters of the stressed-strained state [3]. Based on the foregoing, in this work, the oscillations of vertical cylindrical steel tanks for oil are investigated on the basis of a finite-element method using a three-dimensional geometric model.

A larger number of numerical studies of the vibrations and stability of industrial structures are carried out on the basis of a finite-element analysis. Thus, in works [13, 14], the loss of stability (buckling) of steel cylindrical shells was investigated. The purpose of the cited works was to compare the results of numerical, analytical, and experimental studies. Elastic bulging and the maximum load of these shells were investigated. It is shown that the results of critical load values obtained numerically based on the finite-element method and experimental methods are close. In work [15], thin-walled cylindrical tanks under pressure are investigated. The designs in which the walls of the vessel have a thickness much smaller than the overall dimensions are considered. Based on the finite-element modeling in the standard calculation modules of the ANSYS software package, a number of variable calculations were conducted, taking into consideration the internal level of the liquid, wall thickness, yield strength of the material, and loading conditions. Based on the results, the dynamic behavior of the storage tank design is analyzed. However, the above studies do not address the issue of strengthening structures, as proposed in work [16]. This paper discusses the cylindrical storage tank for petrochemical products. The structure is reinforced with anti-explosion strips. Simulation was carried out at various parameters of the anti-explosion strips during an external explosion. However, the wall of the tank is modeled with a thin shell. Paper [17] reports a comparative analysis of the mechanical properties of structural steels, and work [18] proposes a mathematical model that takes into consideration the influence of the ambient temperature on the process of elastic strain of steel structures. The law of distribution of hydrostatic pressure along the tank wall is considered in [19]. And in work [20] it is argued that the nature of the change in stresses in the tank when filled with petroleum products will depend on the design parameters of the tank, its diameter and capacity, taking into consideration which the load from the weight of petroleum products is calculated. These studies are the basis for determining the hydrostatic pressure on the inner surface of the tank wall. In work [21], an experimental analysis was carried out only for linear structures, taking into consideration the parameters of the preliminary stress. Paper [16] reports the results of modeling the operation of steel cylindrical tanks filled with liquid, and study [22] considers a cylindrical tank for storing petrochemical products. It is noted that a typical tank design has a wall that is modeled with a thin shell. At the same time, the studies described in [16, 20–22] do not cover issues related to the oscillations of the pre-hardened structure. Papers [23, 24] address the issues of repairing dents by carbon fiber reinforcement in order to restore the lost bearing capacity. However, the frequencies and oscillation shapes of reinforced structures are not studied.

Our review of the literature sources showed that the question of the influence of the parameters of the prestressed winding on the oscillations of typical large-sized vertical cylindrical steel tanks for oil, simulated by taking into consideration the change in the wall thickness of the structure, remains poorly understood.

3. The aim and objectives of the study

The purpose of this work is to quantitatively assess the effect of winding parameters on the oscillation frequencies of a vertical cylindrical steel tank with a volume of 3000 m^3, taking into consideration hydrostatic pressure. This will make it possible, when operating a hardened winding structure in seismically hazardous areas, to detune it from resonant frequencies by varying the winding parameters.

To accomplish the aim, the following tasks have been set:

– to analyze the effect of changing the size of the diameter of the steel wire of the winding on the frequencies of oscillations of a large-sized tank, maximally filled with oil, as well as assess the change in the magnitude of the movements when the value of the winding diameter changes;

– taking into consideration the hydrostatic pressure of oil, to investigate the frequencies and oscillation shapes of the tank with a winding of high-strength steel wire, applied in 1:3 increments, for various variants of coil tension. It is also necessary to determine the shape of loss of stability of the tank wall under the influence of the load on the external surface.

4. The study materials and methods

A study into the influence of the tension force of the winding thread on the oscillations of a large-sized cylindrical tank for oil storage is a continuation of research into the features of the stressed-strained state and oscillations of the structure strengthened with winding [3]. Numerical studies are carried out on the basis of the finite-element method in the ANSYS software package. Static strength, in the Static Structural calculation module, and oscillations, in the Modal calculation module, of the tank wall, simultaneously loaded with internal pressure from oil poured to the maximum height, and external distributed pressure created by the tightened winding, were investigated. When determining the frequencies and oscillation shapes of the wall of the tank with winding, the change in the mass and thickness of the wall of the structure was taken into consideration. In this study, oscillations of only the tank wall were considered while the influence of the bottom was simulated by the condition of rigid fixation of the lower part of the wall.

For the calculation, a three-dimensional geometric model is used, which accurately takes into consideration the change of 1÷2 mm in the thickness of the tank wall in height. The geometric parameters of the tank wall are as follows: inner diameter, 18.38 m; height, 11.92 m. In height, the tank wall consists of four belts: the lower – with a thickness of 8 mm and a height of 1.49 m; the second – 6 mm thick and 1.49 m high; the third – with a thickness of 5 mm and a height of 2.98 m; top – with a thickness of 4 mm and a height of 5.96 m. The maximum height of liquid filling in seismically hazardous areas is 11.08 m. At the place of attachment of the tank wall with the bottom, the boundary conditions of rigid fastening are set. This model of fastening is widely used in the numerical analysis of the strength and vibrations of the tank wall [6].

The finite-element model of the structure uses a grid with a maximum finite-element size of 0.1 m. The results of checking the convergence of the solution for the grid used are reported in work [3].

The tank is made of C245 steel: modulus of elasticity, E=2.1·10^{11} Pa; Poisson's coefficient, υ=0.3; density, ρ=7850 kg/m^3; yield strength, $\sigma_{0.2}$=245 MPa. The appearance of zones of plastic flow of the material is considered unacceptable.

Previously conducted variable studies into the strength of the pre-stressed winding of the structure showed that winding the tank wall with steel wire or composite filament makes it possible to change the stressed-strained state of the wall and remove the localization of stresses in its ring layers [3]. It was established that winding with steel wire in increments of 1:3 gives the lowest maximum equivalent stresses in the structure. Therefore, this study considered this very type of winding. The wire is made of 65T steel with a yield strength of $\sigma_{0.2}$=785 MPa.

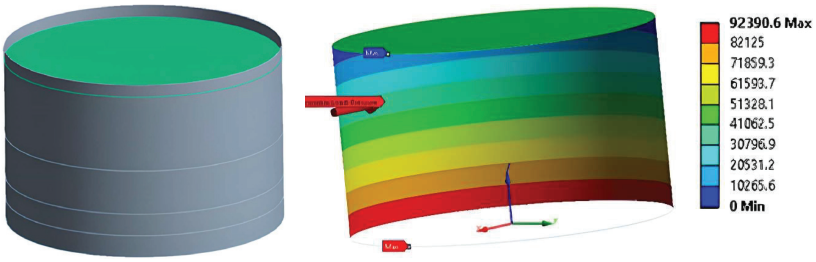
The value of the tension force of the thread is determined from the following dependence [3]:

$$N=0.25\pi d^2 H\, k\cdot\sigma_{pr}, \qquad (1)$$

where d is the diameter of the wire; H is the height of the cylinder wall on which the winding is applied; k is the coefficient of tension of the thread, $0<k<1$.

The distributed internal pressure on the tank wall from oil poured to the maximum height is shown in Fig. 1.

A decrease in the height of oil loading leads to a decrease in internal pressure according to a linear law [3].



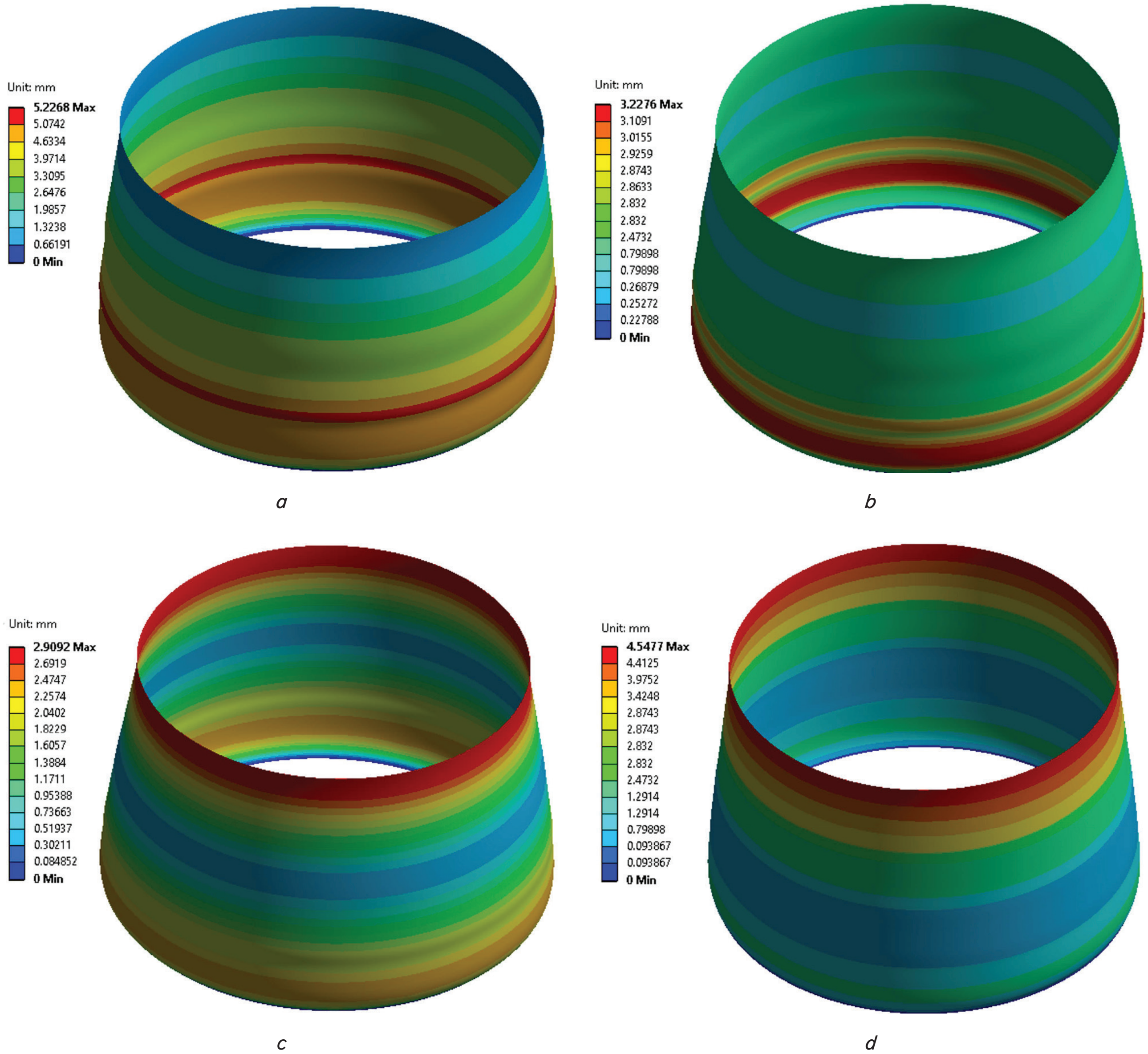
a *b*

Fig. 1. Oil-filled tank model: *a* — general view of the maximally filled vertical cylindrical tank; *b* — distribution of oil pressure on the inner surface of the tank wall

5. Results of the analysis of the influence of prestressed winding parameters on the oscillations of vertical cylindrical tanks

5. 1. Analyzing the effect of the diameter of the steel wire of the winding on the frequencies of oscillations of the maximally filled tank

The study evaluated movements in the wall of the maximally oil-filled tank when using a winding with different thread diameters. To this end, we studied movements in the tank wall under the action of hydrostatic pressure of oil at the maximum level of loading. The results of these studies are shown in Fig. 2. For the visualization of the image, auto-scaling is used. Cases of a wall without winding (Fig. 2, *a*) and three winding options were simulated. For the first version, the wire diameter was taken d_1=3 mm (Fig. 2, *b*), for the second – d_2=4 mm (Fig. 2, *c*), and for the third – d_3=5 mm (Fig. 2, *d*). The magnitude of the tension force of the thread in all three versions of the winding was taken to be equal to $N=0.75\cdot\sigma_{pr}\, 0.25\pi d^2 H$. The winding was applied to the entire outer surface of the wall.



a *b*

c *d*

Fig. 2. The results of modeling the movements of the tank wall under the action of maximum hydrostatic pressure: *a* – the tank without winding; *b* – the tank with winding, diameter d_1=3 mm; *c* – the tank with winding, diameter d_2=4 mm; *d* – the tank with winding, diameter d_3=5 mm

The results of our calculations show that a change in the diameter of the winding thread leads not only to quantitative but also to qualitative changes in the field of movement in the structure. Maximum movements in the tank without winding exceed 5 mm and are observed in the zone of connection of the second and third belts of the wall. Applying a winding in all three cases makes it posible to get rid of this dangerous effect during operation. Applying a winding with a wire diameter of 3 mm does not compensate in full for the hydrostatic pressure at the bottom of the structure. Movements in the lower belt of the wall are 3 mm. The winding with a wire of diameters of 4 mm and 5 mm to a greater extent compensates for the expansion of the wall in the lower part of the structure. However, the winding with a wire of diameter of 5 mm causes movements of more than 4.5 mm in the upper unloaded part of the wall. And maximum displacement for a wire-wrapped tank with a diameter of 4 mm is less than 3 mm.

The frequencies of oscillations of the tank, reinforced by a winding of steel wire of different diameters, were investigated, taking into consideration the maximum hydrostatic pressure. The effect of changing the diameter of the thread on the oscillation frequencies of the prestressed tank was evaluated. The tension coefficient of the thread in formula (1) was assumed to be k=0.75. For comparison, the case of a tank without winding loaded with maximum hydrostatic pressure was also considered. Table 1 gives the results of the first ten significant frequencies of the tank.

All frequencies given in Table 1 are paired, which is caused by the axisymmetry of the loads acting on the tank wall.

Fig. 3 shows the change in the frequencies of the tank oscillations depending on the diameter of the winding wire.

It should be noted that the sixth frequency for all four estimated cases, including the tank without winding, has close values.

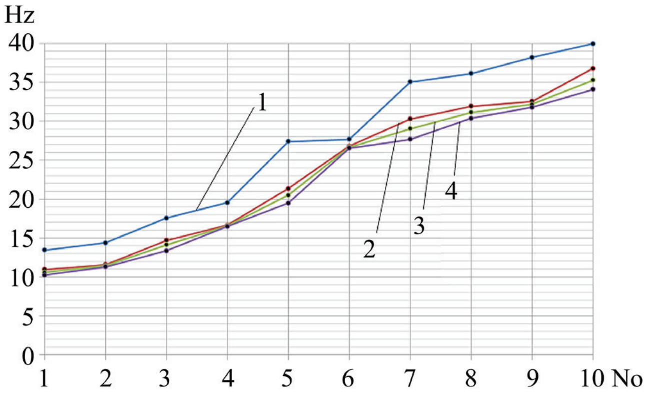


Fig. 3. Frequencies of oscillations of the tank, at maximum hydrostatic pressure: 1 – tank without winding; 2 – tank with a winding with a diameter of d_1=3 mm; 3 – tank with a winding with a diameter of d_2=4 mm; 4 – tank with a winding with a diameter of d_3=5 mm

Table 1

Oscillation frequencies of the tank, reinforced by a winding of steel wire of different diameters, taking into consideration the maximum hydrostatic pressure, Hz

Frequency No.	Tank without winding	A steel wire wound tank with diameter		
		d_1=3 mm	d_2=4 mm	d_3=5 mm
1	13.44	10.933	10.581	10.238
2	14.375	11.56	11.426	11.283
3	17.539	14.677	14.123	13.367
4	19.545	16.649	16.548	16.459
5	27.401	21.357	20.505	19.475
6	27.676	26.791	26.66	26.545
7	35.033	30.276	29.038	27.67
8	36.128	31.91	31.136	30.368
9	38.185	32.543	32.171	31.786
10	39.946	36.777	35.28	34.069

5. 2. The frequencies and shapes of tank oscillations at different winding tensions, taking into consideration hydrostatic pressure

The frequencies and corresponding oscillation shapes of a prestressed tank with a winding of high-strength steel wire with a diameter of 4 mm, applied in 1:3 increments, were investigated. A case was considered when the winding is applied to the entire outer surface of the wall. It was assumed that the inner surface of the tank wall was subject to hydrostatic pressure corresponding to the pressure of oil poured to the maximum level. The tension of the wire coil in the winding varied for four estimated cases. For the first calculation, in formula (1), the coefficient of tension of the thread k was chosen equal to k_1=0.2; for the second – k_2=0.4; for the third – k_3=0.6; for the fourth – k_4=0.8. Table 2 gives the results of the first ten significant frequencies of the tank. All frequencies shown in the table are paired.

The oscillation shapes corresponding to the first six frequencies, given in Table 2, are the same and do not depend on the tension force of the wire in the winding.

The oscillation shapes corresponding to the first four frequencies are the same for all the estimated cases of the tank with the winding. They are shown in Fig. 4.

The first four shapes of oscillations are shown in Fig. 4.

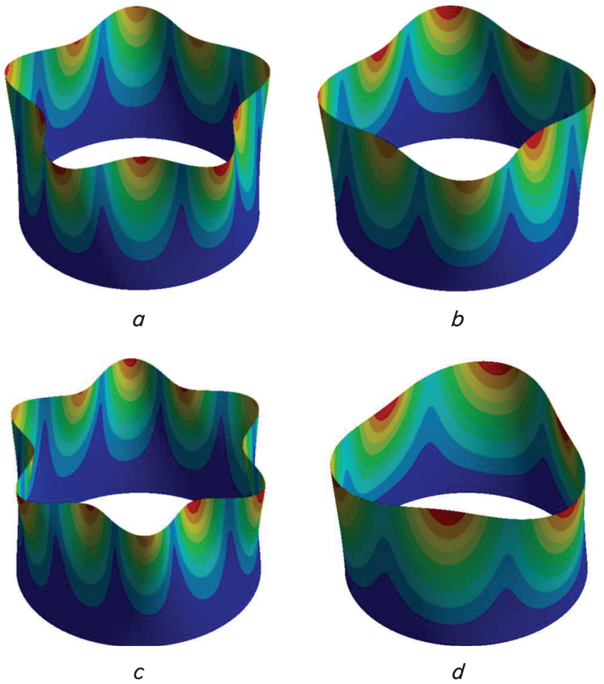


Fig. 4. Oscillation shapes of a tank reinforced with a winding of high-strength steel wire, taking into consideration the maximum hydrostatic pressure: *a* – the first shape; *b* – the second shape; *c* – the third shape; *d* – the fourth shape

Table 2

Oscillation frequencies of the tank, reinforced by a winding of steel wire with different thread tension, taking into consideration the maximum hydrostatic pressure, Hz

Frequency No.	Coefficient of thread tension in the winding			
	k_1=0,8	k_2=0,6	k_3=0,4	k_4=0,2
1	10.441	10.992	11.516	12.015
2	11.346	11.661	11.967	12.267
3	13.968	14.58	15.168	15.734
4	16.52	16.631	16.74	16.85
5	20.356	20.945	21.518	22.076
6	26.654	26.677	26.7	26.723
7	28.902	29.441	29.967	30.479
8	31.072	31.326	31.579	31.831
9	32.128	32.3	32.473	32.651
10	35.204	35.51	35.813	36.113

Fig. 5 shows the change in the first six oscillation frequencies as a function of the tension force of the wire in the winding. Frequencies from the first to the fifth decrease with an increase in the tension force of the wire in the winding. For the fourth frequency, this increase does not exceed 0.11 Hz. And for the sixth frequency with an accuracy of one-tenth of Hz, they are equal for all four estimated cases.

The shape of the buckling mode of the tank wall under distributed internal pressure was investigated. Fig. 6 shows the sixth oscillation shape.

Fig. 7 shows the study's result.

A comparative analysis of the sixth oscillation shape and the stability loss shape shows that they have the same number of waves at the circumferential coordinate of the cylinder. It is seven.

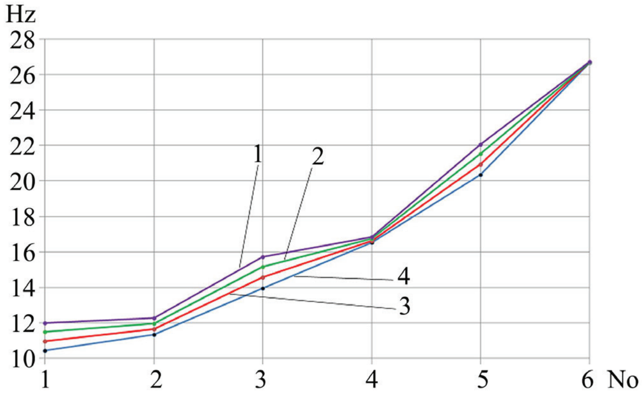


Fig. 5. Change in the first six frequencies of oscillations depending on the tension force of the wire in the winding: 1 – at k_1=0.2; 2 – at k_1=0.4; 3 – at k_1=0.6; 4 – at k_1=0.8

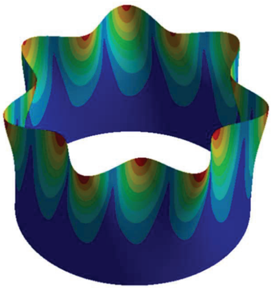


Fig. 6. The sixth shape of oscillations of the tank reinforced with a steel wire winding, taking into consideration the maximum hydrostatic pressure

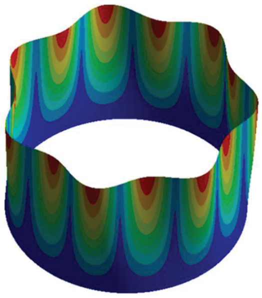


Fig. 7. The shape of stability loss by the tank wall under distributed internal pressure

6. Discussion of results of investigating a winding-reinforced vertical oil tank

In order to assess the effect of a wire winding with different diameters on the oscillation frequencies of the tank at maximum hydrostatic pressure, a comparative analysis of the movements in the structure was carried out (Fig. 2). The results of the calculations were compared for three variants of the winding and without it (Fig. 2, *a*). The diameter of the winding thread was chosen so that for the first option it was less than the wall thickness in the upper part of the tank (Fig. 2, *b*). For the second option, it was equal to the thickness (Fig. 2, *c*), and for the third – exceeded it (Fig. 2, *d*). In the absence of a winding in the lower part of the wall near the attachment zone with the bottom and in the zone of connection of the belts, the walls with a thickness of 6 mm and 5 mm of movement in the radial direction reach significant values. When using all options for winding, their value decreases, there is no wave-like increase in the magnitude of movements at the junction of the second and third belts of the tank wall. In this case, the use of wire with a diameter of d_1=3 mm does not give a satisfactory result in the lower part of the tank wall. And the use of a winding with a diameter of d_3=5 mm leads to large movements in the upper part of the wall not loaded with hydrostatic pressure. The best result is observed when winding with a wire with a thread diameter of d_2=4 mm. Along the tank wall, there are no ring zones with large movements. Movements in the maximum loaded lower belt of the structure do not exceed 30 % in wall thickness, and the unloaded upper layer of the structure is shifted to a value less than the wall thickness. Based on the analysis of the result, it can be concluded that the application of a wire winding with a thread diameter of d_2=4 mm for the design of the tank with the geometry in question is more preferable.

The frequencies of oscillations of the tank for three variants of winding and without it were analyzed (Table 1). The presence of a winding can significantly reduce the frequencies of oscillations of the tank (Fig. 3). At the same time, a change in the diameter of the winding wire does not always lead to a significant change in the frequency spectrum. Thus, for the estimated cases considered, the second, fourth, sixth, and ninth frequencies are close. And the sixth frequency has similar values for all four estimated cases, including the tank without winding.

The frequencies of oscillations of the tank were analyzed taking into consideration the maximum hydrostatic pressure, reinforced by a winding of steel wire with different thread tension (Table 2). Four estimated cases were considered:

1) at k_1=0.2;
2) at k_2=0.4;
3) at k_3=0.6;
4) at k_4=0.8.

It has been established that an increase in the tension force of the wire in the winding leads to a decrease in the values of the frequencies of oscillations (Fig. 5). The exception is the sixth frequency. Its values are equal for all four estimated cases with an accuracy of one-tenth of Hz.

Oscillation shapes have been obtained for all estimated cases of a winding-reinforced tank (Fig. 4, 6). Changing the tension force of the wire in the winding does not change the number of waves along the circumferential coordinate of the cylinder on the free edge of the structure.

We studied the loss of stability in the tank wall under distributed internal pressure. The shape of the loss of stability was established (Fig. 7). A comparative analysis of the sixth oscillation shape and the shape of the loss of stability shows that they have the same number of waves at the circumferential coordinate, equal to seven.

Quantitative assessment of the frequencies of oscillations of a pre-stressed tank makes it possible to estimate the probability of the appearance of resonant frequencies during the operation of the structure in seismically hazardous areas.

The results of our research are planned to be used in the operation of the strengthened winding of the structure in seismically hazardous areas to detune it from resonant frequencies by tensioning the winding thread by a given amount. Note that this requires initial data on the frequency characteristics of the expected earthquakes in a particular area of operation. It should also be noted that for the natural frequency with the oscillation shape corresponding to the shape of the loss of stability of the structure, detuning from resonance should include a number of additional studies on the choice of winding parameters: the material and thickness of the thread, the step of applying the coil in the winding, the tension force of the thread.

The continuation of this study may involve analysis of forced oscillations of the tank under the influence of seismic loading.

7. Conclusions

1. We studied the effect of the tension force of the wire in the winding of a vertical cylindrical steel tank with a volume of 3000 m^2 filled with oil on the frequencies of its oscillations. The frequencies and oscillation shapes of a tank with a winding of high-strength steel wire with a diameter of d_1=3 mm, d_2=4 mm, and d_3=5 mm were established, applied in 1:3 increments, with different tensile strength of the coil. The effect of hydrostatic pressure on the inner surface of the tank wall from oil poured to the maximum height was taken into consideration. For numerical analysis, a finite-element method in the ANSYS software package was used. The geometric model of the structure takes into consideration the change in the width of the wall in height. And the analysis of the effect of changing the diameter of the steel wire of the winding on the oscillation frequencies of a large-sized tank, maximally filled with oil, showed that a change in the diameter of the winding wire does not always lead to a significant change in the frequency spectrum. Thus, for the estimated cases considered, the second, fourth, sixth, and ninth frequencies are close. And the sixth frequency has similar values for all four estimated cases, including the tank without winding.

Based on the analysis of the change in the magnitude of the movements with a change in the size of the winding diameter, it can be concluded that the application of the winding with a wire with a thread diameter of d_2=4 mm for the design of the tank with the geometry in question is more preferable.

2. The frequencies and oscillation shapes of the tank with a winding of high-strength steel wire, applied in increments of 1:3, taking into consideration the maximum hydrostatic pressure of oil, have been investigated. Estimation cases for the following coefficients of wire tension relative to its tensile strength were considered:

1) at k_1=0.2;
2) at k_2=0.4;
3) at k_3=0.6;
4) at k_4=0.8.

It was determined that an increase in the tension force of the wire in the winding leads to a decrease in the values of the frequencies of oscillations. Thus, an increase in the tension force coefficient of the thread in the winding from 0.2 to 0.8 of the tensile strength of the winding material leads to a decrease in the first oscillation frequency by 13.1 %, the third – by 11.2 %, the second and fifth – by more than 7.5 %, the fourth frequency is reduced by 2 %. The exception is the sixth frequency. Its values are equal for all four estimated cases with an accuracy of one-tenth of Hz.

The oscillation shapes for all estimated cases of the tank reinforced by winding were obtained. Changing the tension force of the wire in the winding does not change the number of waves along the circumferential coordinate of the cylinder on the free edge of the structure. The first oscillation shape is characterized by five waves at the circumferential coordinate, the second – by four, the third – by six, and the fourth – by three waves at the circumferential coordinate.

We studied the loss of stability by the tank wall under distributed internal pressure. The shape of the loss of stability by the structure was established. A comparative analysis of the sixth oscillation shape and the shape of the loss of stability shows that they have the same number of waves at the circumferential coordinate, equal to seven.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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