The Mutual Effect Study of Horizontal and Vertical Loads on the Elastic Tank Partially Filled with Liquid

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Abstract: - Modern equipment elements in the energy, chemical industry, transport, aviation, and space engineering work under conditions of increased technological loads, at high temperatures and pressure levels. At the same time, the equipment is usually exposed to external loads of various natures. Hydroelastic phenomena must also be taken into account in designing and modernizing tanks and storage facilities for flammable and combustible substances. Flammable and combustible liquid accumulation leads to the increased environmental and fire hazard of such objects. The possible dangerous liquid leakage and tank depressurization negatively affect the surrounding area environment state. A fire in the tank is one of the most dangerous emergencies that could lead both to significant material and environmental damage and to human casualties. The paper treats the environmental hazards reducing problem from liquid hydrocarbon spills from storage tanks, which lead to destructive effects on all environment components especially during emergency situations. It has been established for sufficiently thin tank elastic walls, the fundamental frequency during coupled oscillations could be much lower than the frequency of the fluid in the shell with rigid walls. As the thickness of the tank wall increases, this effect becomes insignificant, and the lower oscillation frequency of the shell with liquid approaches the oscillation frequency of the liquid in a rigid tank. Parametric resonance and sub-resonance effects have been treated.

Key-Words: - oil products, flammable liquids, environmental safety, seismic loads, storage tanks

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1 Introduction

Flammable and combustible liquid accumulation leads to the increased environmental and fire hazard of such objects. The possible dangerous liquid leakage and tank depressurization negatively affect the surrounding area environment state. A fire in the tank is one of the most dangerous emergencies that could lead both to significant material and environmental damage and to human casualties.

The paper treats the environmental hazards reducing problem from liquid hydrocarbon spills from storage tanks, which lead to destructive effects on all environmental components especially during emergency situations.

2 Problem Formulation

Modern equipment elements in the energy, chemical industry, transport, aviation, and space engineering work under conditions of increased technological loads, at high temperatures and pressure levels. At the same time, the equipment is usually exposed to external loads of various natures. Hydro and aero-elastic effects are important issues here. These phenomena are inherent in the processes of hydroturbine cover oscillations, hydroturbine impeller blades, and air plant blades, [1], [2], [3]. Hydrodynamic effects are also observed in studying the urban areas flooding phenomena, [4], [5]. Hydroelastic phenomena must also be taken into account in designing and modernizing tanks and storage facilities for flammable and combustible substances, [6], [7], [8]. Rotation shells and composite rotation shells are usually used as tank models, [9], [10]. Tank materials properties have been treated in [11], [12], [13], [14], [15], [16], [17]. The different partition types' effect on the frequencies and tank oscillations amplitudes has been presented in works, [18], [19], [20], [21]. Forced tank oscillations with partially filled liquid have been studied in [22], [23], [24], [25]. It should be noted that the forced liquid oscillations study in tanks in a refined formulation remains an actual issue, as i t makes it possible to determine the movement stability limits, which allows ensuring the reliability and equipment functioning safety. Equipment reliable operation allows the environmental hazards occurrence and emergencies.

3 Problem Solution

Fluid fluctuations in the elastic rotation shell have been studied. It has been assumed the liquid is ideal and incompressible, and its movement, which began from a rest state, is vortex-free (Fig. 1.)

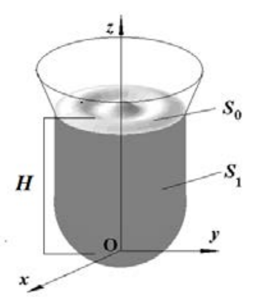

Fig. 1: Elastic rotation shell

The wetted shell surface has been denoted by S_1, and the free surface by S_0, it has been considered the free surface equation at rest is $z=H$. The equation system of shell structure motion with compartments partially filled with liquid has been used in the form

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

where $\mathbf{L}$ and $\mathbf{M}$ are elastic and mass forces operators, $\mathbf{P}$ is liquid pressure on the wetted structure surfaces, and $\mathbf{U}$ is the vector function of displacements. Here and in the future, it has been denoted the normal component of the shell displacements as w. The vector $\mathbf{P}$ is directed normally to the surface since an ideal liquid creates only normal pressure on the wetted shell surfaces. It has been marked $\mathbf{P}$=p $\mathbf{n}$, where $\mathbf{n}$ is the unit external normal to the surface S_1. Since the liquid is incompressible and ideal, and at the initial moment, its motion was vortex-free, it remains vortex-free throughout time. Therefore, there is a velocity potential Φ that satisfies the Laplace equation

$$\nabla^2\Phi=0$$

To find the fluid pressure p on the wetted shell surfaces, it has been used the Cauchy-Lagrange integral

$$p-p_0=-\rho\left[\frac{\partial\Phi}{\partial t}+a_x(t)x+\left(g+a_z(t)\right)\zeta\right].$$

Here p_0 is atmospheric pressure, ρ is liquid density, g is gravity acceleration, $a_x(t)$, $a_z(t)$ are force acceleration, which forces in the horizontal and vertical directions, ζ is a function that describes the liquid free surface movement.

Boundary value problem with correlation to the function Φ has been formulated.

The non-flow on wetted surfaces S_1 condition has been presented

$$\left.\frac{\partial\Phi}{\partial\mathbf{n}}\right|_{S_1}=\frac{\partial w}{\partial t},\ \mathrm{w}=(\mathbf{U},\mathbf{n})$$

On the liquid-free surface, the kinematic and dynamic conditions have been given in the form

$$\left.\frac{\partial\Phi}{\partial\mathbf{n}}\right|_{S_0}=\frac{\partial\zeta}{\partial t},\quad \left.\frac{\partial\Phi}{\partial t}+g\zeta\right|_{S_0}=0.$$

That is, for the velocity potential Φ the following boundary value problem has been obtained:

$$\nabla^2\Phi=0,\left.\frac{\partial\Phi}{\partial\mathbf{n}}\right|_{S_1}=\frac{\partial w}{\partial t},\left.\frac{\partial\Phi}{\partial\mathbf{n}}\right|_{S_0}=\frac{\partial\zeta}{\partial t},\ \ p-p_0|_{S_0}=0. \tag{1}$$

The proper oscillations forms of a tank with liquid in the following form will be searched, [26]

$$\mathbf{U}=\sum_{k=1}^{N}c_k\boldsymbol{u}_k. \tag{2}$$

Here functions $\mathbf{u}_k(x,y,z)$ are eigenforms of empty tank oscillations, $c_k(t)$ and are unknown coefficients that depend only on time t. Note that the ratios are valid, [26]

$$\boldsymbol{L}(\boldsymbol{u}_k)=\Omega_k^2\boldsymbol{M}(\boldsymbol{u}_k)\ ,\quad (\boldsymbol{M}(\boldsymbol{u}_k),\boldsymbol{u}_j)=\delta_{kj}\ ,(\mathbf{L}(\mathbf{u}_k),\mathbf{u}_j)=\Omega_k^2\delta_{kj} \tag{3}$$

Next, it has been searched for the potential Φ in the two potentials form $\Phi=\Phi_1+\Phi_2$, as [23], and has been gained the differential equations system

$$\mathbf{L}\left(\sum_{k=1}^{N} c_k(t)\boldsymbol{u}_k\right) + \mathbf{M}\left(\sum_{k=1}^{N} \ddot{c}_k(t)\boldsymbol{u}_k\right) = -\rho_l\left[\left(\sum_{k=1}^{N} \ddot{c}_k(t)\varphi_{1k} + \sum_{k=1}^{M} \ddot{d}_k(t)\varphi_{2k}\right) + axtx+aztz+\mathbf{Q}, \quad (4)$$

$$\sum_{k=1}^{N} \ddot{c}_k\varphi_{1k} + \sum_{k=1}^{M} \ddot{d}_k\varphi_{2k} + (g + aztk=1Nck\partial\varphi 1k\partial\boldsymbol{n}+k=1Mdk\partial\varphi 2k\partial\boldsymbol{n}+axtx=0.$$

Here φ_{1k} and φ_{2k} are the basis functions obtained in [23].

From correlations (4), after performing the scalar product on $\boldsymbol{u}_l$ and φ_{1j}, it has been obtained as a second-order differential equations system. From this system, the unknown functions of time $c_k(t)$ $d_k(t)$ have been found. For their unambiguous definition, there have been used the initial conditions

$$c_k(0)=c_{k0},\quad \dot{c}_k(0)=c_{k1},\quad d_k(0)=d_{k0},\quad \dot{d}_k(0)=d_{k1}$$

Namely, as a r esult of correlations (3), there have been obtained equation

$$\sum_{k=1}^{N} c_k(t)\Omega_k^2\, \mathbf{u}_k + \sum_{k=1}^{N} \ddot{c}_k(t)\, \mathbf{u}_k = \quad (5)$$

$$= -\rho_l\left[\left(\sum_{k=1}^{N} \ddot{c}_k(t)\varphi_{1k} + \sum_{k=1}^{M} \ddot{d}_k(t)\varphi_{2k}\right) + a_x(t)x + a_z(t)z\right] + \mathbf{Q}$$

In addition, as a result of the last equation (3), there have been gained equation

$$\sum_{k=1}^{M} \ddot{d}_k\varphi_{2k} + (g + aztk=1Nck\partial\varphi 1k\partial\boldsymbol{n}+k=1Mdk\partial\varphi 2k\partial\boldsymbol{n}+axtx=0.$$

Because $\frac{\partial\varphi_{2k}}{\partial\boldsymbol{n}} = \frac{\chi_k^2}{g}\varphi_{2k}\ (k = 1,2,\ldots,M)$, it has been obtained the equation

$$\sum_{k=1}^{M} \ddot{d}_k\varphi_{2k} + (g + aztk=1Nck\partial\varphi 1k\partial\boldsymbol{n}+k=1Mdk\chi k2g\varphi 2k+axtx= 0. \quad (6)$$

It has been multiplied by the scalar equation (5) to $\mathbf{u}_l$ (l= 1, 2,… N), and equation (6) on the functions $\varphi_{2k}\ (k = 1,2,\ldots,M)$. It has been obtained system of differential equations with $\mathbf{Q}$ =0

$$\ddot{c}_l(t) + \Omega_l^2 c_l(t) = -\rho_l \sum_{k=1}^{N} \ddot{c}_k\,(t)(\varphi_{1k}, u_l) + \sum_{k=1}^{M} \ddot{d}_k\,(t)(\varphi_{2k}, u_l) + a_x(t)(x, u_l) +$$

$$\Phi_1 = \Phi_{11}(r,z)\cos\theta\, a_z(t)(z, u_l) = 0, \quad (7)$$

$$\ddot{d}(\varphi_{2l}, \varphi(_{2l}) + (1 + a_z(t)/g)\chi_k^2(\varphi_{2l}, \varphi_{2l}) + \sum_{k=1}^{N} c_k\left(\frac{\partial\varphi_{1k}}{\partial\mathbf{n}}, \varphi_{2l}\right) + a_x(t)(x, \varphi_{2l}) = 0. \quad (8)$$

Note also that the required values will be presented in the form

$$f(r,z,\theta) = f(r,z)\cos n\theta, \quad (9)$$

where n is the harmonic number. The possibility of representation use (9) has been proved in the work, [26], [27].

Numerical results

A cylindrical shell with a flat bottom, with the following geometric parameters and mechanical properties, has been considered: radius R = 1 m, length L = 2 m, Young's modulus $E = 2\bullet 10^5$ MPa, Poisson's ratio ν = 0.3, material density ρ_s = 7800 kg/m^3, liquid density ρ_l = 1000 k g/m^3. The filling level has been taken as follows H = 1.0 m. Various thickness values h have been accepted. It has been assumed that the shell is fixed to the contour, boundary conditions $u_r = u_z = u_\theta = 0$ given at $z = H$ and $r = R$.

The tank dynamic characteristics under the simultaneous action of vertical and horizontal loads with different excitation frequencies will be considered (Table 1 and Table 2).

Table 1. Frequencies of empty and liquid-filled elastic tanks, n = 0, Hz

$n = 0$				
K	n_S	n_L	Shell without liquid	Shell with liquid
1		1		0.9739
2		2		1.3208
3		3		1.5909
4		4		1.8209
5		5		2.0249
6	1	1,2	23.233	7.6591
7	2,1		91.101	43.308
8	3,2		205.25	117.03

Table 2. Frequencies of empty and liquid-filled elastic tanks, n = 1, Hz

	$n = 1$			
K	n_S	n_L	Shell without liquid	Shell with liquid
1		1		0.6418
2		2		1.1509
3		3		1.4564
4		4		1.7054
5		5		1.9212
6	1,2		48.520	21.902
7	2,1		139.70	79.712
8	3,2,1		232.44	178.42

Here, the coefficients n_S, and n_L indicate the shell forms number and liquid taken into account in the coupled oscillations, and K is the number of the oscillations coupled form. Shell oscillations in four forms and sloshing in five forms have been used for numerical simulation.

From the Table 1 data regarding liquid sloshing in the tank, the lowest frequencies are $\omega_{11} = 0.6418$ Hz and $\omega_{01} = 0.9739$ Hz.

The frequencies of empty and liquid-filled tanks of different thicknesses have been shown in Table 3 and Table 4 below:

Table 3. Dependence of frequencies on shell thickness

k	An empty shell, Hz			
	h, м			
	0.01	0.005	0.003	0.0015
6	23.233	11.838	7.1805	3.6308
7	91.101	46.271	28.023	14.153
8	205.25	100.01	62.922	31.747

Table 4. Dependence of frequencies on shell thickness

k	Shell with liquid, Hz			
	h, м			
	0.01	0.005	0.003	0.0015
6	5.5213	2.8187	1.7096	0.8644
7	43.769	22.249	13.479	7.0064
8	119.14	58.148	36.587	15.716

In Table 2 the number K = 6 corresponds to the first axisymmetric form of elastic bottom vibrations. The frequencies given in Table. 2 for the thickness h=0.01m h=0.005 m, h=0.003 m, are higher than the sloshing frequency.

Results in Table 2 indicate that the lowest frequencies of elastic shells decrease with decreasing shell thickness. Therefore, for very thin elastic tank walls, the first frequency of elastic wall oscillation could be much smaller than the oscillation frequency of the fluid in the shell with rigid walls. As the tank wall thickness increases, this effect becomes negligible. However, the use of such thin shells as e lements of responsible structures operating under intense external loads requires careful analysis of the stress-strain state to avoid stability loss.

In work, [22], the conditions have been obtained when the sloshing impact becomes insignificant in studying the elastic shell vibrations. Thus, to estimate the lowest oscillation frequencies of the liquid-filled shell, it is advisable to limit the study to rigid shells, at least if the ratio of the thickness to the shell characteristic size is greater than 0.003.

The data in Table 2 indicate the lowest oscillations frequency of the elastic cylindrical tank walls is equal to $\Omega_1 = 0.8644$ Hz at a thickness of $h = 0.0015$ m. The simultaneous action of horizontal and vertical loads with accelerations will be considered

$$a_x(t) = a_h \cos\omega_h t\ , a_z(t) = a_v \cos\omega_v t\ .$$

Note that the lower frequency of sloshing corresponds to the first harmonic, and the lower oscillation frequency of elastic walls corresponds to axisymmetric bottom oscillations. It follows that$(x, u_1) = 0$, since $x = \rho\cos\theta$. Therefore, only vertical excitation will be present in equations (7). Nevertheless, in equation (8), all terms responsible for the influence of the external load will be non-zero.

It has been assumed that ω_h=ω_v = 0.8644 Hz. The functions $d_l, c_l, l = 0{,}1$ have been calculated and plotted the change in the level of the tank-free surface at the point with coordinates z=H, R=1, θ=0, shown in Fig. 2.

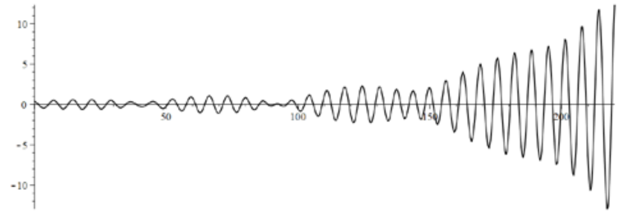

Fig. 2: Lift level of the free surface provided that ω_h=ω_v =0.8644 Hz

From the data shown in Fig. 2, the approach of the frequency of forcing forces to a lower oscillations frequency of elastic walls leads to a loss of motion stability.

Next, the case when ω_h=ω_v = 0.9739 Hz has been considered. The change in the level of the free surface over time has been shown in Fig. 3.

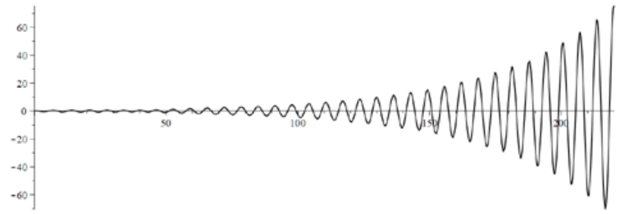

Fig. 3: The level of free surface increasing under the condition ω_h=ω_v =0.9739 Hz

From the data shown in Fig. 3, i t has been concluded that the frequency approximation of forcing forces to a lower frequency of liquid axisymmetric vibrations leads to stability loss. At the same time, the results do not depend on the frequency of horizontal excitation, as evidenced by the data shown in Fig. 4.

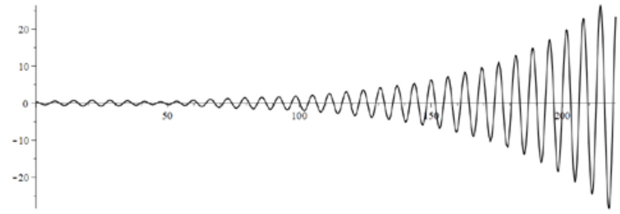

Fig. 4: The level of free surface increasing under the condition ω_{v} = 0.9739 Hz, ω_{h} = 0.4 Hz

Note also the parametric resonance presence. The corresponding data have been shown in Fig. 5.

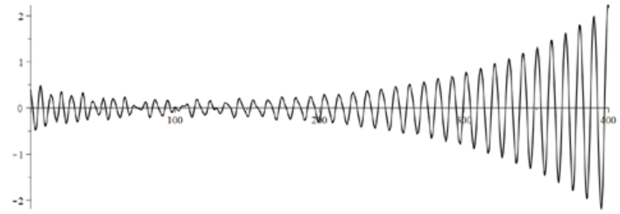

Fig. 5: The level of free surface increasing under the condition ω_{v} = 1.2856 Hz, ω_{h} = 0.4 Hz

Fig. 5 corresponds to the vertical load frequency, which is equal to the doubled fundamental frequency, namely ω_{v} = 2 0.6418 Hz = 1.2856 Hz.

In the system "elastic shell - liquid" there are also so-called subresonant oscillations when the sum or difference of the frequencies of vertical and horizontal excitation is equal to the fundamental frequency.

The corresponding results have been shown in Fig. 6 and Fig. 7. At the same time, Fig. 6 shows the graph of the free surface increasing level under the condition ω_{v} = 0.2418 Hz, $\omega_{\hbar}$ = 0.4 Hz.

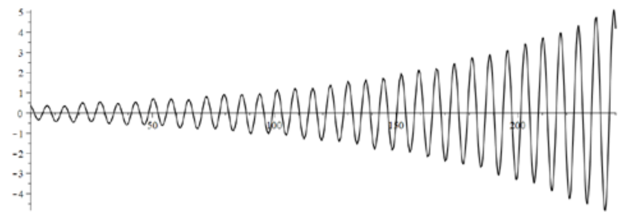

Fig. 6: The level of free surface increasing under the condition $\omega_{\hbar}+\omega_{v}=\omega_{11}$.

Fig. 7 corresponds to the following data ω_{v} = 0.7418 Hz, $\omega_{\hbar}$ = 0.1 Hz.

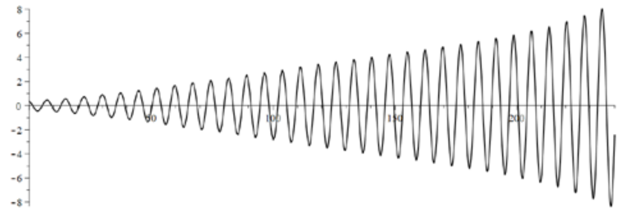

Fig. 7: The level of free surface increasing under the condition $\omega_{\hbar}+\omega_{v}=\omega_{11}$

Note that the frequencies of forcing forces, which are close to the frequency of axisymmetric oscillations ω_{01}=0.9739 Hz and the oscillations frequency of the elastic bottom ω_{07}=0.8644 Hz, although they do no t coincide with the specified frequencies, also leads to a stability loss.

Fig. 7 shows the change in the liquid-free surface level under the condition $\omega_{v} = \omega_{\hbar}$=0.9 Hz. From the results, there has been concluded stability loss.

Fig. 8 shows the change in the free surface level at the frequency $\omega_{v} = \omega_{\hbar}$=0.2 Hz, which is not close either to the lower frequencies of sloshing or to the lower frequency of elastic wall oscillations. Lastly, the level of free surface increasing provided $\omega_{v} = \omega_{\hbar}$=0.2 Hz as presented in Fig. 9.

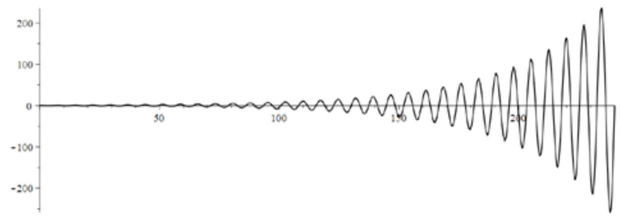

Fig. 8: The level of free surface increasing under the condition $\omega_{v} = \omega_{\hbar}$=0.9

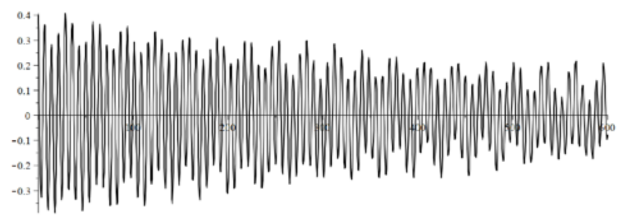

Fig. 9: The level of free surface increasing provided $\omega_{v} = \omega_{\hbar}$=0.2 Hz

4 Conclusion

The most dangerous frequencies of external influence are those that approach the frequencies of elastic wall oscillations, which in turn are close to the free surface oscillations frequencies. That is, in this case, the frequency spectra of elastic wall oscillations and liquid-free surface oscillations are not separate, and the influence of the elasticity of the walls couldn't be neglected.

It has been established for sufficiently thin tank elastic walls, the fundamental frequency during coupled oscillations could be much lower than the frequency of the fluid in the shell with rigid walls. As the thickness of the tank wall increases, this effect becomes insignificant, and the lower oscillation frequency of the shell with liquid approaches the oscillation frequency of the liquid in a rigid tank.

Parametric resonance and sub-resonance effects have been treated.

The practical application could be in the environmental hazards reducing problems from liquid hydrocarbon spills from storage tanks and preventing emergency situations.

Future research will be concerned with different reservoir forms and horizontal and vertical partitions consideration.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

-Olena Sierikova carried out the conceptualisation, data curation, formal analysis, methodology.

-Elena Strelnikova carried out the simulation and the optimization.

-Denys Kriutchenko carried out the visualization, data curation.

-I. Hariachevska carried out the simulation and the optimization.

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Conflict of Interest

The authors have no conflict of interest to declare.