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Study of Liquid Cargo Influence on Frequency Characteristics of Tank Wagon Boiler Shell

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ABSTRACT

The article is devoted to the study of the effect of the fill level of liquid cargo on frequency characteristics of the shell of a tank wagon boiler.

The study has applied within its framework an approach used to estimate the frequencies and modes of natural oscillations of steel tanks under the influence of seismic loads. This approach assumes considering two components of natural frequencies: pulse and convective ones. To determine the listed frequencies and modes of natural oscillations, the finite element method using FLUID221 acoustic elements was selected. The choice of the method is justified in the previous studies of the authors.

Using the selected method, convective natural frequencies of oscillations of the free surface of the liquid and pulsed frequencies of natural oscillations with different fill levels of the tank wagon boiler with liquid cargo were studied. Confirmation of reliability of the results for pulse frequencies of the shell containing the liquid is ensured by consistency with the data obtained by the authors in previous works using the semi-momentless theory of shells.

Keywords: *railways, tank wagon, tank wagon boiler, oscillation frequencies, oscillation forms, free surface, convective frequencies, pulse frequencies.*

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INTRODUCTION

In the process of developing railway rolling stock design, the main focus is on conducting comprehensive studies aimed at a thorough assessment of the dynamic characteristics. Such studies are critically important due to the specific operating conditions in which wagon structures operate. In particular, the analysis of natural frequencies of oscillations and their modal forms for cargo wagons becomes an integral element of the design [1], ensuring safe and reliable operation of the wagon structure. Understanding the frequency characteristics of structures allows engineers to prevent dangerous resonance phenomena that can lead to emergency situations.

The main *objective* of the study is to assess the natural frequencies and vibration modes of the tank wagon boiler shell. One of the key problems complicating the process of calculating these parameters is the need to consider the characteristics of the transported cargo. In this regard, the main purpose of the study is to consider the interaction of the cargo with the tank wagon boiler structure, which, as practice and theoretical studies show, has a noticeable effect on the frequency characteristics of the system. In calculation practice, considering liquid in tanks subject to various types of dynamic loads requires special attention during design to ensure safety and reliability of the structure.

REVIEW OF THE SOURCES

Problems of this kind are given much attention in the field of calculations of steel tanks for seismic impacts. The basis for calculating the mathematical model of the «tank – liquid» system was laid in 1954 by G. W. Housner in his work [1]. This approach considered a simplified mathematical model consisting of a system of discrete masses, which made it possible to significantly simplify the process of calculating hydrodynamic forces. The proposed model included two types of kinematic freedom: impulsive, which related to movement of the tank shell together with the main mass of its contents, and convective, associated with movement of waves on the surface of the liquid inside. Based on the assumption that the container walls are absolutely non-deformable, and the liquid is ideally incompressible and has no internal friction, G. W. Housner applied simplified computational approaches to deriving formulas related to a number of different types of containers, including cylindrical ones. Currently, in some countries, the Haroun and Housner model [2] is used for tanks with flexible walls, and the Veletsos and Yang model [3] is used for tanks with rigid walls. In domestic calculation practices, the recommendations developed by I. I. Goldenblat and N. A. Nikolaenko [4] have become widespread.

For the problem under consideration, the expression for determining the splash frequency of the free surface of a liquid is of interest:

$$\omega_n = \frac{g}{R}\lambda_n \operatorname{th}\left(\lambda_n \frac{H}{R}\right), \quad (1)$$

where λ_n are the zeros of the modified Bessel function (to determine the first form of the splash wave, λ_n is taken to be equal to 1,84);

n – oscillation mode,

g – acceleration of gravity,

H – height of a cylindrical tank,

R – inner radius of a tank.

Despite the rather extensive research in the field of estimating the frequencies of liquid tanks, considering both convective and impulsive frequencies, such calculations have not been performed for tank wagon boiler shells. The works [5; 6] consider analytical approaches to estimating the frequency characteristics of tank wagon boiler shells, considering the level of filling them with liquid cargo. The results of these calculations showed satisfactory agreement with the results obtained by researchers earlier [6] and the results obtained based on experimental studies [7; 8].

The authors of the article [9] considered approaches to estimating the natural frequencies of tank wagon boilers and various methods for estimating the effect of liquid on natural oscillations using numerical methods. Such methods include the analysis of natural frequencies using the Acoustic body extension, accounting for liquid as a distributed mass, modelling liquid as a solid body, using the FLUID80 element and applying acoustic elements.

According to the results of the conducted study, the most acceptable approach was to consider the liquid inside the tank using acoustic elements.

The article [10] shows an example of calculating the frequency characteristics, including natural frequencies and oscillation

[1] GOST [Russian state standard] 33788–2016 «Cargo and passenger cars. Methods of testing for strength and dynamic properties». [Electronic resource]: https://docs.cntd.ru/document/1200137251. Last accessed 21.02.2024.

modes of a square tank using the finite element method with the FLUID221 acoustic elements. This approach made it possible to estimate the impulsive and convective frequencies of the tank at different fill levels and under different conditions. The reliability of the approach considered is described in detail in [11; 12] by comparing various analytical and numerical methods for estimating the frequencies of natural vibrations of the «mechanical system – liquid» system or the so-called fluid structure interaction (FSI).

The work [11] considered several options for numerical modelling of considering liquid as an acoustic body, including as the FLUID80 liquid element and as various types of the FLUID30/220/221 liquid acoustic element.

MATERIALS AND METHODS

FLUID80

The FLUID80 element is a single fluid element that uses the material properties of density (DENS) and bulk modulus (EX). Separate but coincident nodes are used to model the fluid–solid interaction at the FSI interface. These nodes are connected to the solid such that they can slide in the tangential direction relative to the body but are bonded in the normal direction. This can be achieved by creating appropriate meshes at the fluid–solid interface and at the solid–fluid interface. The coincident nodes are then connected in the normal direction. These elements have the degrees of freedom UX, UY, and UZ. In [13; 14], this element is applied to model liquid storage tanks. Note that the Block Lanczos method [15; 16] is also suitable for these elements. The element can generate several low-frequency sloshing modes of fluid oscillations that can occur with little or no motion of the solids. Therefore, it is recommended to skip or ignore low-frequency fluid modes when evaluating the pulse frequencies of natural oscillations. These modes can also be identified by their low mass participation coefficient.

FLUID30, FLUID220, and FLUID221

FLUID30 is an acoustic fluid element that shares nodes with neighbouring solid elements. This element uses the fluid density (DENS) and sound velocity (SONC) to define the material properties. Previously, the FLUID30 element used an asymmetric matrix, which required an asymmetric solver. Accordingly, the modal analysis could not be accompanied by forced response and power spectral density analysis. To model the fluid-solid interaction (FSI), two types of FLUID30 elements were used: fluid adjacent to the solid and fluid not in contact with the solid. The fluid adjacent to the solid has the degrees of freedom UX, UY, UZ, and pressure (PRES) to describe the interaction between the solid and the fluid. The fluid that does not interact with the solid has the degree of freedom PRES only to interact with other fluid elements. Later, FLUID30 elements were used, allowing creation of a symmetric matrix. Unlike FLUID80 elements, FLUID30 elements are less sensitive to grid density.

FLUID220 and FLUID221 are higher-order variants of FLUID30.

Based on the analysis of practical calculations, we will use the FLUID221 element, which is a three-dimensional solid 20-node element of higher order (see Pic. 1). The FLUID221 element is used to model a liquid medium and an interface in problems of fluid-structure interaction.

Initial data

Further in the calculations we will use the following initial data, shown in Table 1.

The following assumptions are accepted for further calcualtions:

– The liquid is ideal, incompressible.

– The liquid movement is irrotational.

– The boiler shell has an ideal cylindrical shape with elliptical bottoms.

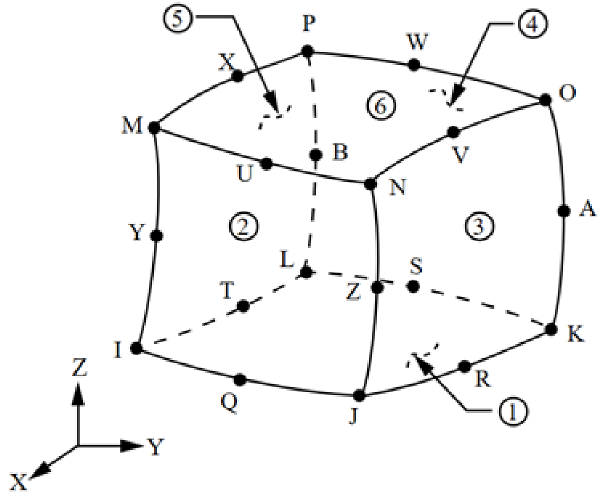
RESULTS AND DISCUSSION

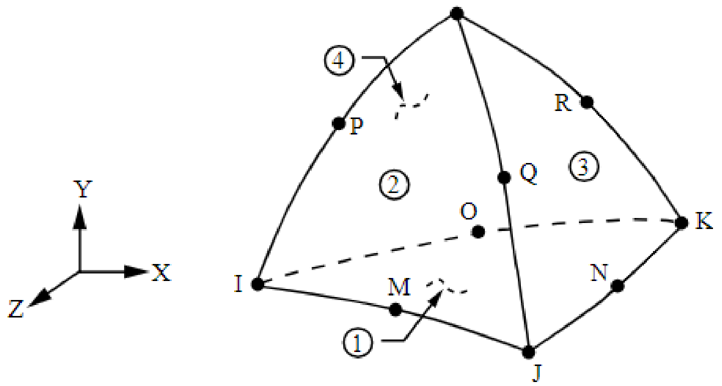
Pics. 2 and 3 show the solid model under study.

For clarity, the Pic. 3 shows a model cut in the XOY plane, and the fill level corresponding to 90° (or a fill factor of 0,5).

The model was divided into elements as follows: elements of the SOLID187 type were used for the solid body, elements of the FLUID221 type were used for the liquid, and the contact between the solid body and the liquid was provided using CONTA174 elements. The CONTA174 element is necessary to create a sliding contact between the elements of the solid body and the liquid.

The first forms of oscillations of pulse and convective frequencies are shown in Pics. 4 and 5, respectively. Table 2 shows the results obtained using the finite element method and the energy approach [9] proposed by the authors using the semi-momentless shell theory. When comparing the calculation results, it was found that they





Pic. 1. Geometry, location of nodes and coordinate system of the FLUID220 element (left) and FLUID221 element (right) [https://www.mm.bme.hu/~gyebro/files/ans_help_v182/ans_elem/Hlp_E_FLUID220.html; https://www.mm.bme.hu/~gyebro/files/ans_help_v182/ans_elem/Hlp_E_FLUID221.html].

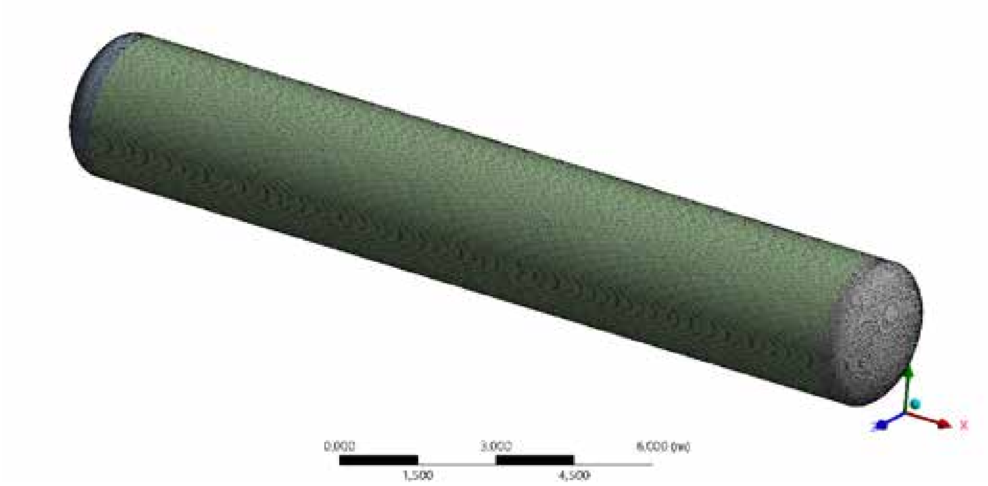
correlate fairly well with each other and are in the same frequency range. We consider these results satisfactory.

Let us estimate the effect of the liquid on the frequencies of natural oscillations of the shell itself, that is, on the so-called pulse frequencies. Table 2 clearly shows that with an increase in the filling level, the natural frequency of oscillations decreases. For example, when the fill level changes from 0° to 171°, the natural frequency

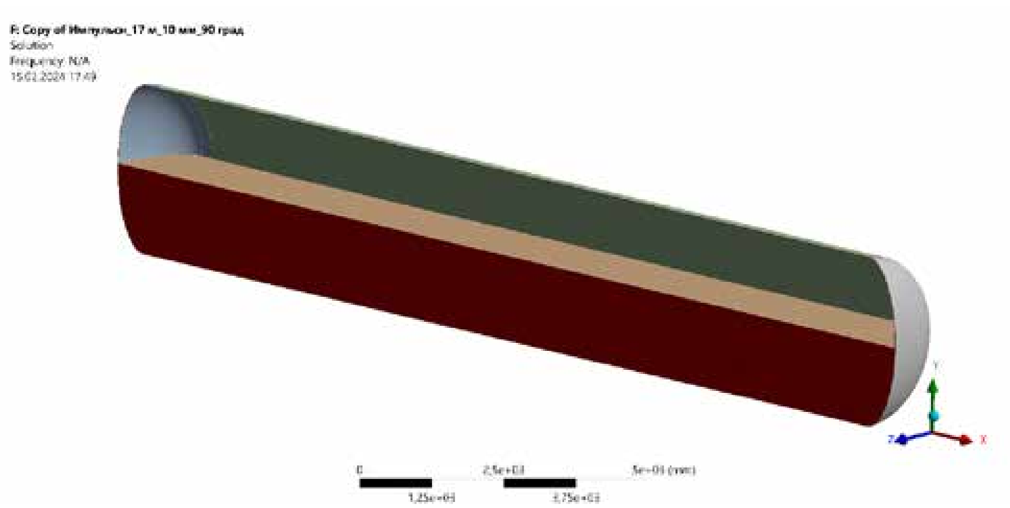
Table 1

Initial data (performed by the authors)

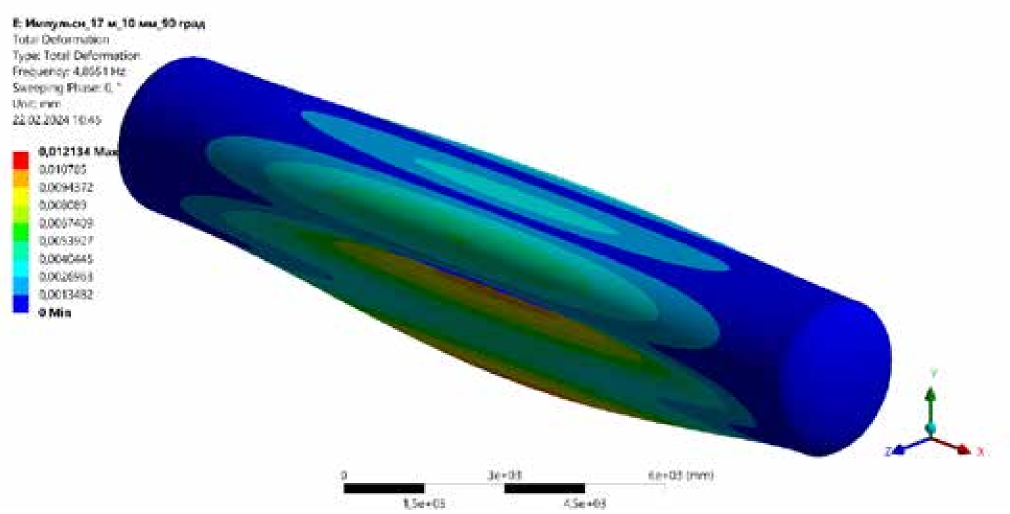
Designation	Name	Parameter	Dimension
E	Modulus of elasticity of the boiler material	210	GPa
μ	Poisson's ratio	0,3	–
g	Acceleration of gravity	9,81	m/s^2
ρ_{st}	Density of the shell material	7850	kg/m^3
ρ_l	Density of liquid cargo material	1000	kg/m^3
C	Velocity in the acoustic environment of liquid cargo	1435	m/s
D	Inner diameter of the cylindrical part of the shell	3	m
h	Boiler shell thickness	10	mm
L_c	Length of the cylindrical part of the shell	17	m
L_{bot}	Length of the elliptical bottom overhang	0,45	m
β_{fill}	Liquid cargo filling angle	0° – 180°	–



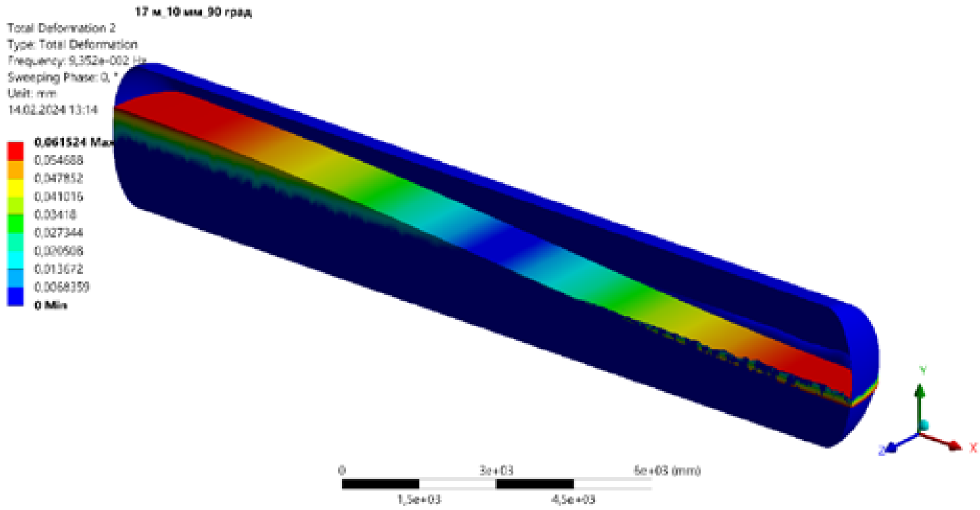
Pic. 2. General view of the solid model [performed by the authors].



Pic. 3. Finite element model of the boiler shell [performed by the authors].



Pic. 4. The first natural form of pulse oscillations of the shell of a tank wagon boiler filled with liquid [performed by the authors].



Pic. 5. The first convective form of oscillations of the free surface of a liquid [performed by the authors].

of oscillations of the shell of the model under consideration decreases by more than 50 %.

Convective frequencies deserve special attention. The study of liquid splashing in the boiler of a tank wagon is an urgent and rather complex task. In Table 2, opposite each fill level, two frequencies of pulse oscillations of the free surface of the liquid f_{conv} are presented. The first frequency corresponds to one half-wave of oscillations of the liquid in the longitudinal direction, the second – to one half-wave of liquid oscillations in the transverse direction. In our opinion, these types of liquid oscillations are easily excited when a tank wagon moves along uneven track surfaces. For example, if the tank wagon boiler is filled to a filling angle of 153° and forced oscillations occur with a galloping frequency of 0,19 Hz, this can lead to liquid movements that affect the dynamics of the wagon.

CONCLUSIONS

The frequencies and modes of natural oscillations of the tank wagon boiler shell were calculated considering different levels of filling it with liquid cargo. The calculation was performed using the finite element method, in which the FLUID221 element was used. This approach made it possible to obtain two types of natural frequencies – pulse and convective ones. The calculation results showed satisfactory convergence with the approaches proposed by the authors for solving similar problems in their previous works based on energy approaches and shell theory.

Based on the results of the studies, the following conclusions can be made:

– The use of the finite element method and the energy approach based on shell theory gives similar results in estimating the pulse frequencies of natural oscillations.

Table 2

Calculated values of pulse and convective frequencies [performed by the authors]

Fill level	Natural frequency of the shell considering the liquid (pulse frequency)		Natural frequency of the free surface of a liquid (convective frequency)	
β_{fill}	f_{pulse}, Hz		f_{conv}, Hz	
	Energy approach	FEM	FEM	
171°	4,12	4,24	0,32	–
153°	4,17	4,35	0,19	0,83
126°	4,15	4,52	0,13	0,59
90°	5,45	4,86	0,093	0,47
54°	7,69	6,21	0,057	0,42
0°	10,81	10,89	–	

– The approach used in the study allows us to estimate the convective natural frequencies of the free surface of the liquid, which are significantly lower than the pulse frequencies.

– Filling the tank wagon boiler with liquid cargo significantly reduces the natural frequency of its shell. For the case under consideration, filling with liquid leads to a decrease in the natural frequency of the boiler by more than 57 %.

– The convective frequency of the free surface of the liquid increases with the increase in the fill level of the liquid cargo.

– In the strength calculations of tank wagon boilers, attention should be paid to the change in the natural frequency of its shell when they are filled with liquid cargo.

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