ON LOADING OF A TANK CAR SHELL UNDER HYDRAULIC IMPACT

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ABSTRACT

A mathematical model of shunting collision of a tank car is offered, taking into account the possibility of installing automatic couplers with absorbing devices of various types, fluctuations of transported liquid cargo in tank shell at incomplete filling and the likelihood of hydraulic impact. Calculations resulted in proposed choice of rational parameters and of a shape of tank shell bottom which allow increasing carrying load and volume of the tank shell. Scientifically sound limits for impact speed were determined for certain types of shunting operations with tanks to ensure safe working conditions, minimization of environmental risks.

Keywords: railway, environmental safety, tank, shell, bottom, hydraulic impact, variational method, finite element method.

Background. *To create modern designs of tank cars it is necessary to implement in practice more advanced engineering calculations, measurement methods of loading of tank shells by the action of various dynamic forces generated during operation and shunting operations. In the latter case the most heavily loaded part of the tank shell is its bottom, the maximum pressure to which from liquid cargo at certain impact speeds is determined by the magnitude of hydraulic impact. Given that shunting operations, despite the requirements of technical operation rules, for several reasons are still performed in excess of the impact speed, the magnitude of this pressure is quite high.*

Collisions at high speeds lead often to damage to the cars. Damage resulting in spillage of dangerous goods transported in tanks is harmful to the environment and may pose a threat to human life or health.

Objective. *The objective of the authors is to investigate loading of tank shell at hydraulic impact.*

Methods. *The authors use general engineering methods, finite element method, nonlinear differential equations of hydrodynamics with derivatives, method of characteristics, simulation.*

Results.

Research methods. *From a mathematical point of view the movement of the liquid in the tank shell is described by a system of nonlinear differential equations of hydrodynamics with derivatives, analytical solutions for which in some cases are still pending. Therefore, in engineering practice methods are used, based on the use of hypotheses, simplifying the initial construction. These equations are solved by spectral or numerical methods. In addition, methods based on the model of mechanical liquid cargo analogue are commonly used [1, 2]. Influence of fluid on dynamics and loading of the tank shell is taken into account by means of hydrodynamic coefficients determined by a variety of theoretical and semi-empirical methods. Calculation of coefficients is quite complex and, of course, we have to correct them when changing the filling level of the tank shell.*

In applied mathematics various numerical methods for solving nonlinear equations of hydrodynamics are developed. Some of them are the basis for commercial software packages, the most famous of which are STAR-CD, FLUENT, ANSYS CFX and domestic FlowVision.

Works of scientists of Belarusian State University of Transport (Gomel) are known, which used the method of solving the problem of railway tank shells loading described in [3, 4]. However, it requires significant computational resources; otherwise the time required for calculation will be significant. In other words, in designing process requiring multivariate calculations, this method becomes very time consuming.

In MIIT at the department of Cars and cars facilities for simulation of fluid motion in the tank shell a hydraulic approach was used, based on the equations of «shallow water», the integration of which was performed by the method of characteristics [5, 6]. Using this method permits to avoid the above mentioned problems. This article uses the same approach, but in integration of equations a variational method was applied.

The calculation of the structural strength of the tank shell will be performed using finite element method (hereinafter referred to as FEM), the most effective in our opinion among existing methods.

Tasks. *To achieve this goal, two main tasks were solved.*

a) Study of the impact of liquid cargo in the form of pressure on the tank car's shell bottom during shunting collisions at different speeds, which involves: 1) simulation of collisions of tanks during shunting operations; 2) simulation of shock absorbers of absorbing devices mounted on the car; 3) simulation of the behavior of liquid cargo in a tank car's shell; 4) simulation of hydraulic impact occurring in the tank shell under certain conditions.

b) A study of stress-strain state (hereinafter SSS) of tanks' shell bottoms, involving as input values previously determined pressure values that involve the creation of computational model of the tank shell and the study of its expected properties in the action of the applied load.

Simulation of the collision of a tank car

Several options of shunting collision of a tank car were considered: a stroke of a tested tank car into a fixed nondeformable stop (scheme № 1), a stroke of a tank car into a stop through an intermediate car (scheme № 2), and a stroke into a free-standing car on a straight section of track (scheme № 3).

Shunting collision of cars was represented by single-mass models, connected by elastic links. It was taken into account that draft gears are installed in series with elastic elements of cars, that is, elastic properties of the structure were shown when absorbing devices were closed. It was also assumed that the deformation of cars elements obey Hooke's law. The inertia forces of parts of intercar links and viscous friction in relations were not taken into account. The action of liquid cargo on the tank car shell was set via the magnitude of horizontal projections of the total pressure of the liquid on left and right bottoms.

Reactions of connections were determined by the dependencies that characterize the work of shock absorber of absorbing device mounted on the car.

Simulation of shock absorbers

Currently, all domestic tanks for transportation of dangerous goods must be equipped with absorbing devices of the class not lower than T2 according to OST 32.175-2001. We have modeled the work of two such devices produced by «LLMZ-KAMAH»: 73ZW class T2 with a constructive course of 90 mm and 73ZWU2 class T3 with a constructive course of 110 mm.

We used a mathematical model proposed in [5]. It is built by analyzing the properties of a shock absorber of absorbing device and takes into account the force of initial tightening, elastic properties of the shock absorber, dry friction and viscous friction (due to overflow of elastomer in compression of absorbing device).

The mathematical model parameters were determined on the basis of experimental power characteristics of the device according to VNIIZhT data [5].

Simulation of liquid cargo vibrations

In a collision of a single tank with another car the magnitude of forces acting on the tank shell is affected mainly by longitudinal oscillations of liquid cargo. Therefore, it is appropriate to consider only the longitudinal motion of the liquid in the tank shell. A mathematical model of an oscillating liquid in the tank shell is based on the equations of the theory of «shallow water» at the assumption that the liquid is ideal and incompressible, with constant density [7]:

$$\left.\begin{aligned} \frac{\partial^2 w}{\partial t^2} - gh_0\frac{\partial^2 w}{\partial x^2} &= -h_0\frac{\partial a}{\partial x}; \\ \frac{\partial^2 v}{\partial t^2} - gh_0\frac{\partial^2 v}{\partial x^2} &= a, \end{aligned}\right\}, \qquad (1)$$

where $w=h-h_0$ is deviation of the point of free surface from the primary level; $v=\int_0^t u\,dt$ is movement of cross-section along the axis of tank shell; u is speed of longitudinal movement of the fluid, the same in all points of cross-section in accordance with the theory of «shallow water»; h=h(x, t) is equation of free surface of liquid; h_0 is level of free surface of liquid in an undisturbed condition; g is acceleration of gravity; x is longitudinal coordinate of a tank shell; t is time.

The initial conditions are as follows: t = 0; v = 0; w = 0.

To solve a system of equations a variational method [7] was applied, so that the system (1) splits into m separate, unrelated equations:

$$\frac{d^2 v_m}{dt^2} + \omega_m{}^2 v_m = \frac{2}{l}\int_0^l a\sin\frac{m\pi x}{l}dx, \qquad (2)$$

where $\omega_m = \frac{m\pi}{l}\sqrt{gh_0}$ is natural frequency.

If $a(x) = const$, after integration we get

– at m = 1, 3, 5: $\frac{d^2 v_m}{dt^2} + \omega_m{}^2 v_m = \frac{4}{m\pi}a;$ (3)

– at m = 2, 4, 6: $\frac{d^2 v_m}{dt^2} + \omega_m{}^2 v_m = 0.$ (4)

Initial conditions have a form:

$$t = 0;\ v_m = 0;\ \frac{dv_m}{dt} = 0. \qquad (5)$$

Based on the type of initial conditions (5), the equations (4) will have solutions, identically equal to zero. Therefore, solutions for equations (3) were sought by numerical Euler method.

Simulation of hydraulic impact

In determining the hydrodynamic loading of the tank shell in a mathematical model of oscillations of liquid cargo the value of hydraulic impact pressure was taken into account. The results of the study of the distribution of pressure change in liquid cargo in railway tank shell at hydraulic impact were published in [8]. The solution of differential equations of hydraulic impact, obtained by N. E. Zhukovsky was applied:

$$P_{hi} = \rho|u_b|c, \qquad (6)$$

where u_b is rate of flow of fluid to the border of filled area, equal in absolute value to speed of border movement and aimed in the opposite direction; c is speed of movement of wave surface; ρ is fluid density.

The velocity of the wave surface:

$$c = \sqrt{\frac{E_f}{\rho\left(1+\frac{D}{e}\cdot\frac{E_f}{E}\right)}}, \qquad (7)$$

where E_f is modulus of volume elasticity of fluid; E is modulus of elasticity of the tank shell material; D is inner diameter of the cylindrical part of the tank shell; e is thickness of walls of the tank shell.

The results of collision simulation

Mathematical model of shunting collision of a railway tank in view of oscillations of liquid cargo is implemented in a software application created in integrated environment of Borland C ++ Builder.

The reliability of the results of the application of the program is confirmed by comparison with experimental results and calculations of other authors [1, 2]. The similarity of the results can be considered satisfactory.

The program has been used to study the shunting collision of a tank model 15-1443 for transportation of gasoline and light oil products in three variants of schemes.

The tank had a statutory filling 98%, and the car in stay bar (scheme № 2) and free-standing car (scheme № 3) were assumed to be filled (gross weight of 92 tons). In calculations a tank shell was considered, which was filled with oil density ρ = 827 kg/m³, for which the volume elasticity modulus E_f = 2100 MPa. Impact speed varied, at the same time as absorbing devices were used models class T2 and T3-73ZW and 73ZWU2.

According to the results of calculations dependencies of maximum effort into automatic coupler and pressures of liquid cargo on the bottom of the tank from impact speed were obtained and analyzed. By the condition of the strength in the effect of the maximum longitudinal load [9] values of the permissible impact speed and maximum pressure of liquid cargo on the bottom arising at these speeds were determined. These data are summarized in Table 1.

Study of SSS of tank shell bottoms

Stress-strain state of tank shell bottoms will be determined with the use of software complex MSC.NASTRAN, realizing FEM [10]. The calculation scheme is a finite element model of the tank shell, which takes into account the symmetry of a transverse vertical plane, i.e. considered half of the capacity obtained during dissection of the plane. When building a finite element scheme two-dimensional finite elements were used of quadrangular and triangular shape (at the pole of bottoms). The boundary conditions (links) were introduced in view of the symmetry of the structure. A detailed description of the model is given in [11].

Study of SSS of tank shell bottoms was performed in several stages. At the first stage selection of rational parameters of the bottom of the tank shell was used: design shape (outline of the meridian), gap, thickness.

A similar study at the action of the pressure of 0,4 MPa is illustrated in [11]. However, in accordance with [9], in assessing the strength of the tank shell it is neces-

Table 1

Permissible impact speed and pressure on the bottom under the influence of maximum longitudinal load

Type of absorbing device	Number of collision scheme	Maximum permissible impact speed, m/s	Pressure of hydraulic impact on the bottom, MPa	
			left	right
73ZW	1	1,67	0,37	0,21
	2	3,32	0,37	0,38
	3	3,56	0,38	0,39
73ZWU2	1	1,97	0,37	0,21
	2	3,67	0,32	0,38
	3	3,94	0,36	0,38

Table 2

The dependence of volume and holding capacity from the gap of the bottom

Gap of the bottom, m	Shape of the bottom	Volume of the tank shell, m^3	Holding capacity, t
0,48	superellipse	74,26	60,837
0,48	ellipse	73,83	60,487
0,61	ellipse	73,1	60,000

Table 3

Permissible impact speeds on the condition of tank shell strength

Type of absorbing device	Number of collision schemes	Permissible impact speed, m/s	Pressure on the bottom, MPa	
			left	right
73ZW	1	1,66	0,487	0,347
	2	3,23	0,487	0,507
	3	3,43	0,507	0,507
73ZWU2	1	1,96	0,507	0,347
	2	3,57	0,427	0,507
	3	3,83	0,477	0,507

sary to perform the calculation at the maximum design pressure:

$$P = P_1 + P_2, \qquad (8)$$

where P_1 = 0,147 MPa is pressure of liquid vapors, which is taken by adjusting the value of safety valve for the tank model 15-1443; $P_2 = N\frac{Q_f}{Q_{gr}S}$ is pressure of hydraulic impact; Q_f is mass of fluid in the tank shell; Q_{gr} is gross weight of the car; S is square of cross-section of the bottom; N is maximum impact force.

Thus, for the first design mode [9] it is necessary to evaluate the strength of the tank shell model 15-1443 from internal pressure:

$$P = 0{,}147 + 3{,}5\cdot\frac{60}{83{,}2\cdot 3{,}14\cdot 1{,}5^2} = 0{,}504\,MPa.$$

The calculation results showed that the dependence of maximum stress in the bottom from the gap and the stress distribution in the bottoms with different values of gap obtained in [11], is preserved, but the magnitude of gaps are specified.

It turned out that in gap value of elliptical part of the bottom 0,48 m maximum equivalent stresses are 284,8 MPa (given further quantities should be seen as gaps of elliptical part of the bottom). The specified gap value was accepted rational on the condition of strength.

Varying the thickness of the bottom has led to the fact that with the sheet thickness of 13 mm at the bottom with a gap of 0,45 m it is possible to further reduce the amount of the maximum equivalent stress from 385,7 to 292,3 MPa, and thus to accept this version of the tank shell as rational. However, the question of the use of the bottoms for oil and gasoline tanks remains controversial, since it is difficult to avoid an increase in metal intensity of construction.

At the second stage was performed a study on the impact of the possible outline of the meridian of the bottom on SSS of tank shell under the influence of maximum design pressure of 0,504 MPa. In [11] it was proposed to describe the outline of the meridian of the bottom with the equation of generalized superellipse, which has the form:

$$\left|\frac{x}{a}\right|^m + \left|\frac{y}{b}\right|^n = 1, \qquad (9)$$

where a=0,48 m is optimal from the condition of strength gap value of the bottom; b=1,5 m is a radius of cylindrical part of the tank shell; m, n are positive numbers, larger than 1.

For the purpose of a comparative analysis options of bottoms were explored, where the meridian was given by the equation (9). In [11] it was shown that the greatest stresses at the bottom occur in places of a sharp change in the curvature of the meridian, and the most efficient on the condition of strength meridian option will be a curve that is close to an ellipse, but its curvature, cannot be disregarded, in the joint at the transition from the cylinder *to the ellipsoid does not change abruptly. In this regard, the curves were considered, in which the index of m degree varied in the interval 2-3 at a constant n=2. For these values of m it is characteristic, that the curvature of the generating in the form of superellipse in the transition zone to the cylindrical section becomes zero. As a result, the most efficient on the condition of strength is version of the curve with parameters m=2,7 and n=2.*

To visualize the effect of reducing the gap of the bottom and the shape of its meridian, for the tank model 15-1443 were identified such important technical and economic indicators, as the volume of the tank shell and the holding capacity of the car. As a result of the calculations shown in Table 2 were prepared dependences of volume and holding capacity from the gap of the bottom.

At the third stage, within the finite element model studies of SSS of tank shell bottom were conducted with a rational outline of the meridian. The initial data were hydraulic impact pressure values determined using the developed program of shunting collision. Additional accounting of liquid vapor pressure allowed finding the maximum allowable impact speed on the condition of tank shell strength (table 3).

Conclusions.

1. The mathematical model of shunting collision of tank cars was offered, which takes into account the ability to install automatic couplers with absorbing devices of various types on the car, fluctuations of liquid cargo transported in the tank shell with incomplete filling, and the emergence of hydraulic impact.

2. On the basis of the proposed mathematical model in the environment Borland C ++ Builder a simulation program of shunting collision of a railway tank filled with liquid cargo was developed.

3. Permissible impact speed of the tank with regulatory filling of tank shell was determined on the basis of the condition of strength under the action of the maximum longitudinal load for three collision schemes taking into account the possibility of installing absorbing devices of various types on the tank.

4. The stress-strain state of the elliptical bottom of the tank shell model 15-1443 was investigated under the action of the internal pressure with the use of specialized software that implements the finite element method.

5. The choice of rational parameters of the bottom of the tank shell was justified, the analysis of its possible structural forms was conducted.

6. The shape of the meridian of bottom was found, which allows more efficiently use the useful volume of the tank shell. The obtained results clarify the results of previous studies.

7. Shunting impact speeds, permissible under the given conditions of strength, were determined.

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