Dynamics of Tank Trucks with Baffles for Transportation of Viscous Liquids

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***Abstract*—The results of an investigation involving the use of mechanical systems for modeling the dynamics of a tanker truck carrying Newtonian and non-Newtonian fluids are presented. The viscosity effect of a liquid on its temperature under oscillations is analyzed. The reasons for unstable movement of tanks under braking are explained. The optimal baffle design determined based on an analysis of energy dissipation in a single cycle of oscillations is presented.**

***Index Terms*—road tanker, computer modeling, liquid oscillations, equivalent models, baffles, energy dissipation**

I. Introduction

Tanker trucks carry a variety of liquid cargoes. For example, in the agricultural industry more than 20 types of tanker trucks, which differ by type of cargo carried, are used [1]. Dangerous liquid goods make up the bulk of the goods transported using tanker trucks. The analysis in [2] demonstrated that the level of threat to people and environment during the transportation of dangerous liquid goods increases 12 times compared with the level of danger in the transportation of solid goods. Therefore, it is necessary to improve the safety of tanker vehicles.

Tanker trucks can be considered a mechanical system comprising solids and fluids. Many studies on analysis of the dynamics and strength of such vehicles have been reviewed in monograph [3]. After publication of this monograph, further development of the calculation theory for tanker trucks has mainly been related to the use of computer modeling.

Static structural analysis of a water tank as a part of the truck body was performed in [4]. The finite element analysis in [4] was performed using a commercial computer program. Pressure was applied as a nonuniform load (i.e., hydrostatic pressure) with minimal value on the top and maximal value at the bottom. Displacements and stresses were found to be very high in the basic design, so seven modified structures were proposed to find the best one.

In [5], the authors proposed a new method for dynamic simulation of tanker trucks carrying fluids and silo vehicles carrying granulates. The method couples Lagrangian particle methods, such as smoothed particle hydrodynamics for fluids and the discrete element method for granular media, and multi-body systems by using co-simulations. A co-simulation approach was realized by coupling a multi-body system simulation using SIMPACK for the vehicle with a particle-based fluid simulation using the software package PASIMODO for the cargo [6]. Comparisons between different tanker designs show the significant influence of cargo movement and tank design on the driving characteristics of the tanker truck. Subdivisions along the longitudinal direction in the tank have a positive effect on braking stability because they reduce sloshing motion in that direction.

In [7], a methodology for evaluating the interaction dynamics between the sloshing fluid and vehicle is proposed. The fluid and the tank are modeled using the computational fluid dynamics code FLUENT, based on the Navier–Stokes equations and incorporating the Volume of Fluid (VOF) and the moving mesh techniques. Tank motion was determined based on the response of a 14 degrees of freedom (DOF) vehicle model subjected to the forces resulting from sloshing of the fluid. Straight line braking maneuvers and lane change maneuvers were executed to evaluate the effects of fill level, baffles, and tank shape.

Unfortunately, a drawback of the methods proposed in recent works is that the associated calculations are time consuming, which makes it difficult to use them in practical applications. Herein, we report the results of an investigation of tanker truck dynamics and strength carried out at Belarusian State University of Transport.

II. Influence of Liquid Viscosity on Dissipation of its Energy and Temperature

Oscillation of liquid cargo in a roadgoing tank at its transient movement modes may be accompanied by an increase in the temperature of the liquid due to internal friction forces (liquid cargo energy dissipation). A substantial change in the temperature of the transported cargo can cause a change in its viscosity. Energy dissipation of a liquid is divided in two parts: viscous and turbulent. The obtained computational results showed that the viscous energy dissipation accounts for 0.0003–2.5 % of the total liquid energy dissipation for different values of dynamic viscosity. Therefore, it can be neglected in comparison with the turbulent component during the computer modeling of various cases of road tank braking [8]. These and the other finite element modeling results

Manuscript received February 1, 2018; revised April 7, 2018.

doi: 10.18178/ijmerr.7.4.438-443

were obtained using the ANSYS Workbench Software package.

To analyze the effect of internal friction on the change of the liquid temperature, we performed computations considering liquid cargo with dynamic viscosities of 0.001–300 Pa s sloshing in a roadgoing tank under emergency braking. Dependence of the increase in the average maximum temperature of the liquid on its viscosity is shown in Fig. 1. As can be seen from the figure, when the viscosity of the cargo increases to 1 Pa s, the average maximal temperature increases, and subsequently, as the viscosity decreases, the temperature decreases possibly due to lower relative velocities of the liquid cargo particles. The obtained results show that the maximal change in temperature occurs during the first second after the start of braking. In general, the maximum temperature deviation from the initial value was 1.62 ℃ [8]. Therefore, for computational analysis of roadgoing tanks with liquid cargo, for one cycle of tank transient movement, the process can be considered isothermal.

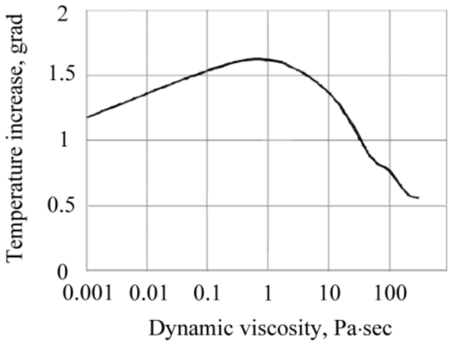


Figure 1. Dependence of average temperature increase on viscosity of liquid cargo [8]

To analyze the influence of tank fill level on liquid energy dissipation values, we carried out simulations of water sloshing (at 20 ℃) in the reservoir filled to 50–90% (Fig. 2) [8]. The results showed that at 80% filling, the values of water energy dissipation were minimal, but at the same time, oscillations of the liquid's center of mass were insignificant, so they did not influence the tank dynamics significantly. If 50–60% of volume of the tank is occupied by liquid cargo, oscillations of the center of mass of the liquid have large amplitudes, and liquid energy dissipation has a local minimum. Similar results were obtained for tanks with internal baffles.

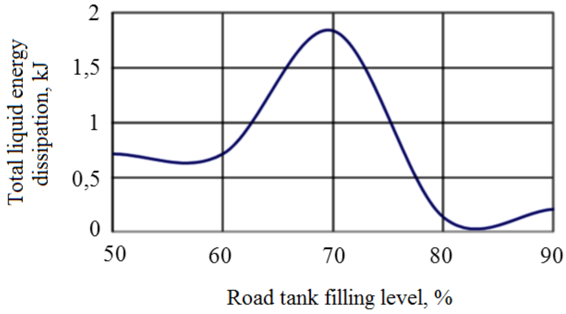


Figure 2. Dependence of total water energy dissipation in first oscillation cycle on tank fill level [8].

III. Analysis of Causes of Unstable Tank Movement at Braking

The results obtained for liquids with different properties demonstrate that the values of hydrodynamic pressure are approximately proportional to the density of the transported Newtonian and non-Newtonian liquids for the first 0.25 s of braking, while viscosity has almost no influence. The summarized liquid energy dissipation for the first cycle of oscillations is generally 5–30% lower with the model of Ostwald de Waele and two and more times higher with Bingham liquids in comparison to the Newtonian model. Therefore, the Newtonian flow results can be used for the flow analysis of non-Newtonian liquids considering the abovementioned correction factors [8].

Assessment of the static and dynamic properties of a tanker truck is crucial, and it is related to three motions: longitudinal (driving and braking), lateral (guidance and steering), and vertical (suspension and damping). In the literature on the dynamics of vehicles, it has been pointed out that the motion of liquid cargo can have both beneficial and negative effects on driving stability and braking performance, but the safest maneuver is braking.

In addition, we obtained interesting results in the study on the dynamics of lateral roadgoing tankers. In [9], calculation results pertaining to the braking process of a roadgoing tank were presented. These calculations were based on the analysis of a simplified tank model with liquid cargo as a system with two degrees of freedom and unaccounted wheel weight. In the present work, the interaction force F_{ed} between the liquid cargo and the wall is represented as the sum of the elastic and dissipative components of the interaction force:

$$F_{ed} = cs + \alpha\dot{s}\,. \qquad (1)$$

where c is the coefficient determined by the shape of the tank and the filling level; it is used to consider the effects of the movement of liquid on the tank body cell, and it can be determined as follows:

$$c = c_0 \quad \text{if} \quad s \le s_0, \quad c = c_0 e^{\frac{s-s_0}{3(s_{\max}-s)}} \quad \text{if} \quad s > s_0,. \qquad (2)$$

where c_0 – value of coefficient c for the case of small oscillations of the liquid [10], N/m;

s_0 – coordinate s, when the liquid reaches the cell, m;

$s_{\max}$ – coordinate s, for the case in which all liquid cargo is located near one of the sides of the tank body and its free surface is vertical, m;

α – coefficient, allowing for considering damping of liquid oscillations in a roadgoing reservoir, kg/s.

The dot over the variable hereinafter denotes the derivative with respect to time.

Formula (1) was obtained by approximating the results of liquid cargo oscillations in roadgoing tanks [11], and the results obtained using this formula agreed well with the experimental results [12].

Our calculations showed that for small values of α (this case corresponds to tanks without baffles), there can be observed the alternation of friction with and without sliding (Fig. 3, a). This can cause loss of vehicle controllability and overturning. When the coefficient α increases, friction forces change smoothly (Fig. 3, b). An increase in α can be achieved by setting internal baffles.

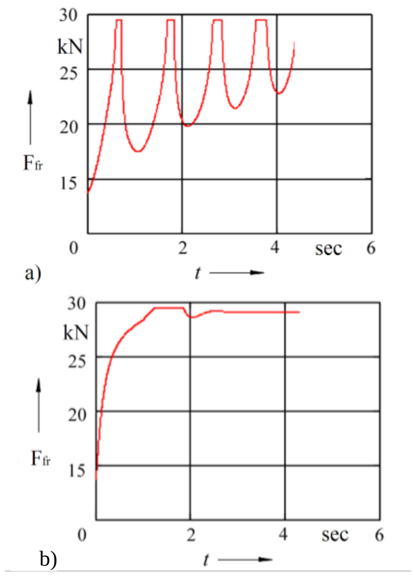


Figure 3. Dependence of friction force between front axle wheels and road on time for: a) α = 2000 kg/s and b) α = 20000 kg/s [9]

In [13], the features of changes in the friction forces between the wheels and the road were determined for the case of tanker truck braking using a more complex model and considering the effects of tank body oscillations on the springs and inertia of the wheels. The analysis performed therein showed that the use of a complex model for describing the oscillations of the liquid in a partially filled tank does not yield significantly different motion kinematic parameters and road–wheel contact forces.

Thus, the performed analysis confirms that there is a need for installing transverse baffles to ensure tank controllability under emergency braking. These partitions allow the rapid damping of the oscillations of liquid cargo or ensuring the best possible dissipation of the energy of moving liquid cargo. In cases when it is impossible to install perforated baffles in existing roadgoing tanks, it is recommended for drivers to use partial (smooth) braking to reduce the oscillation amplitudes of the liquid cargo in a partially filled reservoir. This will help to prevent wheel slippage.

IV. Analysis of Vibrations and Strength of Tanks with Rigid Baffles

According to the investigations described in the literature, the main way to reduce the impact of the oscillations of liquid during transportation on tank dynamics is installing internal damping baffles [14, 15]. Review [16] describes a significant number of modern constructive designs for decreasing the amplitude of oscillations of liquid cargo. These designs are of different sizes and contain various numbers of holes, as well as various hole positions and shapes. Baffles types may be classified according to the scheme shown in Fig. 4 [8].

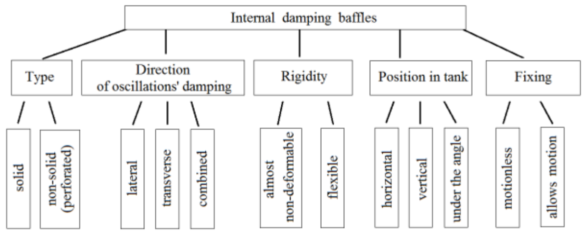


Figure 4. Classification of baffles [8]

However, despite the availability of a wide variety of baffle designs, there is still no consensus about the optimal number and type of internal partitions for best damping the oscillations of liquid cargo transported within tanks in transient movement modes.

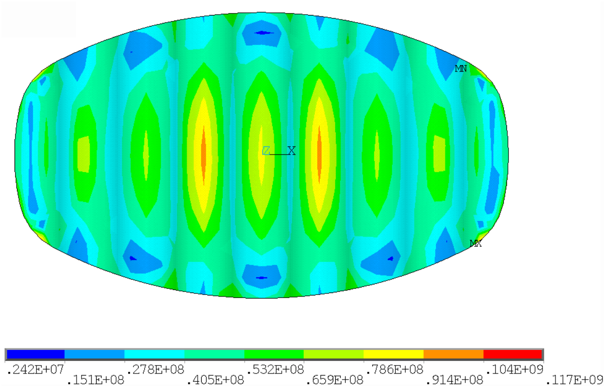
In [17], fluid oscillations in a deformable reservoir with baffles were investigated by modeling the reservoir by using the finite element method and the fluid oscillations by using boundary elements. This approach reduced significantly the time required to calculate the natural oscillation frequencies of the system.

In [18], the results of finite element modeling of fluid oscillations in a reservoir with baffles of different sizes and different distances from the bottom location are compared. Good agreement was found between the results of calculations and measurements of the wave height and vibration frequencies. Notably, the baffle efficiency increased in the resonance zones. Moreover, it was found that the greatest decrease in wave height occurred when large baffles were located near a free surface mimicking a state of rest.

Real-world data of roadgoing tanker trucks with internal baffles show that cracks in the connection tank shell and the baffle area appear over time. This indicates that the stress values exceed the fatigue limit of the material.

In [19] we have analyzed solid partitions of various configurations. The liquid pressure forces acting the tank body due to hydroimpact were calculated analytically. The pressure forces acting the tank body were calculated using the one-dimensional wave equation. The stress distributions for partitions of various configurations were computed in the ANSYS software environment. For creating a model of the reservoir, a drawing of roadgoing tank with volume of 12 m^3 that is currently produced at Grodno Mechanical Plant was used. The design scheme included a block of two compartments, each measuring 1.5 m in length. The disadvantage of the partitions used in this model was the small corrugation radius of the curvature, which can induce large stresses. Therefore, we been decided to develop an additional partition model with a corrugated surface. When this partition is viewed from the end, it appears to be shaped like a sinusoid with an amplitude of 5 cm to meet requirements of the standard [20].

The calculations results show that the stresses in the most loaded part of the reservoir with the existing corrugated baffle exceed more than twice the yield strength of the material; this coupled with the action of dynamic loads can lead to material fatigue and cracking. Replacement of the existing partition with the waved baffle led to a fourfold reduction in the maximal stresses and a twofold reduction in deformations compared to the existing corrugated partition (Fig. 5).



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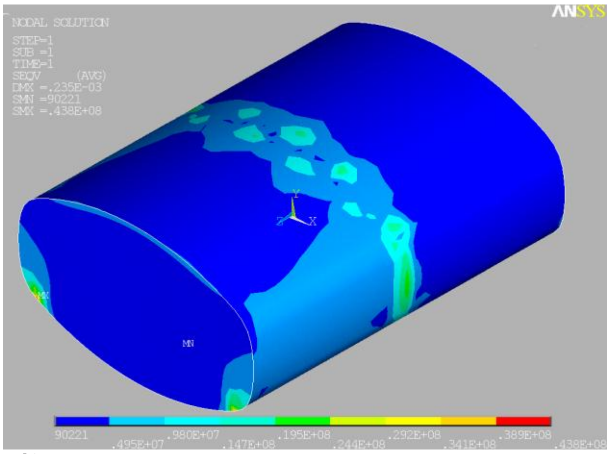
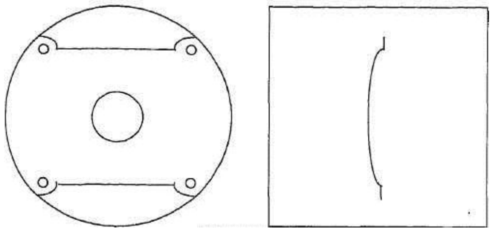


b)

Figure 5. Distribution of stresses in (a) partition and (b) tank reservoir with a wavy partition

V. Dynamic Properties of Tanks with Perforated Baffles

Analysis of the effect of the shape and dimensions of perforated baffles on tanker dynamics will be performed in a separate study. In [21], the baffles installed inside the container had different shapes and different hole patterns (Fig. 6, a). One of them had perforations of size 3 mm. The mass of such a baffle is lower than that of a solid baffle, but the perforation size was insufficient to significantly improve the damping of vibrations in the tank during transient and other driving regimes. In [22, 23], the baffles installed inside the container were spherical, and there was an opening in their centers. In [24], baffles of various types with or without holes were proposed (Fig. 6, b).



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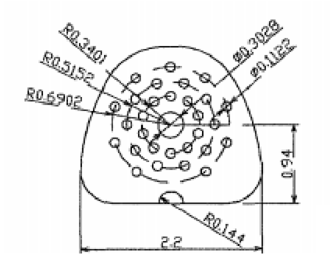


b)

Figure 6. Types of baffles presented in [21, 24]

In [25], we proposed a method for analyzing the efficiency of the liquid cargo damping based on the calculation of liquid energy dissipation. In this regard, many studies have been carried out to analyze the influence of various factors on the parameters characterizing the oscillations of liquids in tanks. Later, a similar approach was applied in [26]. The calculations performed in [26] showed that an X-shaped baffle is more efficient that a baffle shaped as a “+” sign.

In [27, 28, 29], the influence of the configuration of lateral baffles installed in the reservoir of a roadgoing tank on the sloshing characteristics of liquid cargo in the reservoir under emergency braking were analyzed. The results showed that for the considered problems of liquid movement in tanks, it was preferable to use a two-parameter k–ε turbulence model. 3D finite element modeling of the sloshing of liquid cargo in the reservoir was performed using the ANSYS CFX software package.

Furthermore, oscillations of water in a cylindrical tank measuring 2 m in diameter and 4 m in length with internal baffles of different configurations, as well as without baffles, for different tank fill levels were simulated [28]. The results showed that a simultaneous increase in the total energy dissipation of the liquid cargo and reduction of the maximum values of the hydrodynamic pressures and tank shell loading can be achieved only by using perforated baffles (Fig. 7).

The computational results helped to elucidate the relationship between the summarized liquid energy dissipation and size of perforations (Fig. 8, a). According to this relationship, the best damping of liquid cargo oscillations is achieved by using a baffle with perforations measuring 18–22 cm in diameter in a tank with a reservoir measuring 2 m in diameter and 4 m in length. The effect of the perforations appeared when the area of holes was greater than 30% of the area of the partition. A further increase in hole area leads to a slight increase in energy dissipation.

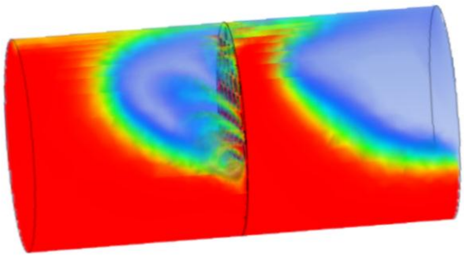
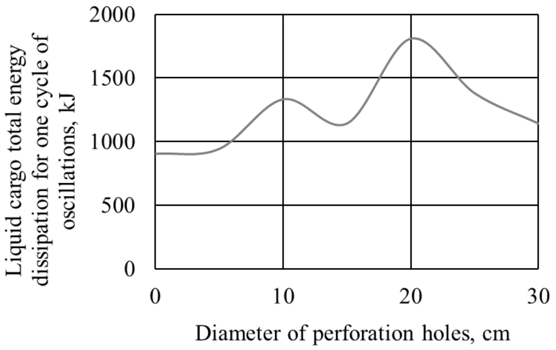


Figure 7. Position of water free surface in tank with perforated partition (perforation diameter is 15 cm) at 0.07 s after initiation of braking.

The analysis of the sloshing of liquid cargo in partially filled tanks with evenly perforated baffles (perforation diameter = 16–25 cm) demonstrated a significant decrease in hydrodynamic pressures values (Fig. 8, b).



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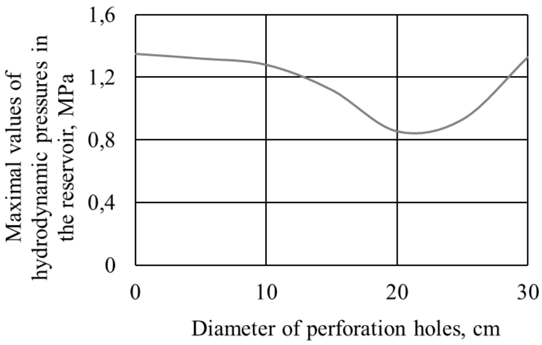

b)

Figure 8. Liquid energy dissipation (a) and maximal hydrodynamic pressures (b) in tank with perforated baffles for 50% reservoir fill level

The rational configuration was considered to obtain the minimal values of the maximal equivalent stresses in the construction under liquid cargo loading. The canonical form of the genetic algorithm was used as the problem-solving method. The analysis results showed that the minimal stresses appeared in the case of a perforated partition of convex shape with a large radius of curvature in the central part and a considerably smaller radius near the connection to the tank shell (Fig. 9). The proposed solution reduces the stresses in the baffle and in the shell of the road tank.

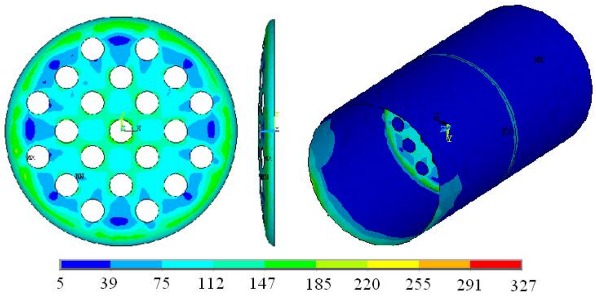

Figure 9. Stresses (MPa) in perforated convex baffle with perforations of diameter 20 cm

VI. Conclusions

1. Under the current conditions, the share of analytical and experimental research is gradually reducing compared to that of virtual computer simulation of tank vehicles. However, despite their relatively simplified nature, analytical studies help to discover new effects that cannot often be revealed in computer simulation due to the abundance of output parameters. Experimental studies remain the main criterion for determining the adequacy of the developed models.

2. A moving tank with liquid cargo is a complex dynamic system, and special attention should be paid to the relative displacement of liquid cargo, which can lead to loss of vehicle stability and controllability. Moreover, the sloshing of liquid in the reservoir of a tanker truck leads to redistribution of stresses and strains in the structure of the vehicle, which should be considered in the process of vehicle design.

Acknowledgment

The authors wish to thank Volha N. Filimonchyk for translation of this work.

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