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NUMERICAL ANALYSIS OF FLUID MOTION INSIDE PARTIALLY FILLED CONTAINER WHICH IS MOVING IN UNSTEADY WAY

The paper describes the behavior of the liquid in a container that moves with a constant speed along a track consisting of three arcs. Such a complicated track shape generates complex form of inertia forces acting on the liquid and generates the sloshing effect. The behavior of the tank container vehicle is affected by the time-dependent inertia forces associated with the transient sloshing motion of the liquid in the non-inertial frame. These internal excitations, acting on a tank construction, can cause a loss of stability of the vehicle. For that reason, the authors analyze the dynamic loads acting on the walls of the tank truck container. The variation of the position of the liquid cargo gravity center, that depends on the filling level of the container, is also analyzed.

The simulations were performed according to the varying fill level, which was 20%, 50% and 80% of a liquid in the whole tank volume. The simulations were carried out for a one-compartment container. Another aim of this study was the investigation of the influence of container division (tank with one, two and three compartments) on behavior of the liquid. These simulations considered only the half-filled container which was treated as a dangerous configuration prohibited by the law regulations for one-compartment tank. The results of simulation are presented in the form of visualization of temporary liquid free surface shape, variation of forces and moments, as well as frequency analysis. The results of simulation were analyzed, and some general conclusion were derived, providing the material for future investigation and modifications of the law regulations.

1. Introduction

Throughout the world there are transported liquid loads. Among other road vehicles, the tank trucks are moving in an unsteady way under certain driving conditions. During acceleration, deceleration and fast cornering, ad-

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ditional inertia forces are generated that cause motion of the liquid in the partially filled tank compartments.

The result of any disturbance in the partially-filled container movement is the phenomenon known as the sloshing. Depending on the type of disturbance and shape of the container, the free liquid surface assumes various forms. Every vehicle that carries a liquid load is influenced by internal forces resulting from the movement of the liquid inside the tank. Unsteady fluid movement can cause the loss of vehicle stability, which is the reason for many road accidents.

The studies on unsteady fluid motion in a moving container are carried out since the beginning of 1960. That time, the space organization NASA began to devote special attention to this issue. The motivation for the research were problems and adventitious accidents of spacecraft and rockets. One of the first publications dealing with the issue of sloshing for partially-filled liquid containers in space is the monograph [1] by Norman Abramson. Extensive literature review summarizing the work done until 2001 contains an article [11], in which the author cites 1319 literature references. Such a great number of references states that the problem is important and not fully resolved yet. The monograph [12] summarizes the whole scientific achievements in the field of sloshing. Liquid cargo transport vehicle dynamics has been widely studied, taking into account different points of view.

Stability and controllability of such vehicles engaged in various types of maneuvers were the problem on which many researchers focused their attention. It has been found that cargo tanks carrying liquids are more prone to tipping over due to the movement of the load, which is often encountered in vehicle tanks partially filled. The work [21] deals with this issue. One of the recent works on the sloshing of fluid in the vehicle is the work [7].

Long-term works on the sloshing problem have helped to develop a number of analytical and numerical techniques (CFD and FEM methods) aimed at allowing a better examination of characteristics of this phenomenon.

Among them there are:

1. the quasi-static method (eg. [19, 20]),
2. the mechanical analogy method (eg. [23]),
3. the methods based on solutions to the Navier-Stokes equations,
   - the method with linear boundary conditions (eg. [9])
   - the method with nonlinear boundary conditions. ([15, 22])

The element that had a strong impact on the development of these methods is their experimental validation. In a number of papers, ([4, 7, 16, 19, 26]), laboratory tests are accompanied with numerical simulation. The impact of the movement of the gravity center on stability of the tank has been extensively studied using classical mechanics. These types of models, however, do not take into account the transient motion of the moving liquid in the tank.

Numerical simulations are the most important and widely used technique for dealing with this highly nonlinear problem.

The European and the United States statistics show that, in relation to the total number of road accidents, the accidents involving tanks with liquids are quite rare ([4, page 6]). Despite this fact, the statistics say that every day on the roads of the United States and Europe, there occurs at least one accident of rollover, and most of them concern tanks. The main document regulating the conditions of the road transport of hazardous materials is European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR 2009-2011) [17]. It describes the design requirements, material and strength of tanks, and it also determines the permissible degree of filling of the tank. According to this regulation, the tanks having the capacity of not more than 7500 liters, undivided by baffles, should not be filled in the range of 20 to 80% of their volume. The agreement does not specify the conditions for the filling to be met by multi-compartment tanks. The provisions contained in this Agreement pertaining to the filling level motivated the Authors to undertake this work.

Based on information presented in the existing publications, three basic methods have been used in the analysis of the sloshing problem: analytic, numerical and experimental ones. Only few papers [4, 7, 16, 19, 26] represent experimental methods. The fact that the number of experimental work is limited results from the costs of investigation. Most of investigators use numerical methods presented in commercial codes [2, 3, 6, 8, 25].

The analyzed problems are general [1, 4, 9-12, 14, 22, 23, 27, 29] and specific to tank unsteady motion [2, 3, 5, 24].

Many investigations considered only artificial load in the form of sinusoidal functions [8, 15, 16]. Some papers concentrate on presentation of methodology [10-12, 20, 22, 23, 29].

The typical scenario of inertial tank load is limited to braking and lane change [2, 3, 6, 7, 13, 25]. A simple case of the inertial load was considered in [25]. The tank was set into motion by giving an acceleration of 9.81 m/s^2 in the +X direction for 1.5 seconds. The fuel was also under the action of gravity in –Z direction.

In [27] the natural frequencies and the slosh dynamics are obtained numerically for a viscous liquid in a partially filled spinning horizontal cylindrical tank. The tank spins with constant angular velocity around its axial direction, and is placed perpendicularly to its rotational axis in an outer gravity field.

Representative examples are the studies presented in [2]. The dynamic interaction of liquid cargo with the tractor semi-trailer vehicle is evaluated by integrating a dynamic slosh model of the partly filled tank with five-degrees-of freedom of a tractor semi-trailer tank model. The dynamic fluid slosh within the tank is modeled using three-dimensional Navier-Stokes equations, coupled with the volume-of-fluid equations and analyzed using FLUENT software.

A similar problem was presented in [6]. The splash of gasoline inside the partially filled fuel tank when subjected to sudden deceleration could be modeled, analyzed and effectively controlled by reducing pressure intensities inside the tank walls using a coupled fluid structure interaction at a common interface within the fuel tank through commercial CFD codes. This study was concluded by comparing two types of geometries using computational simulations inside the fuel tank considering 40% of fuel and 60% of air inside a 40 liters fuel.

In the doctoral thesis [7], experimental and numerical investigation of a simple maneuver lane change was investigated – a lateral displacement of about 3.5 m operated in 30 m at the constant speed of 50 km/h and a steer angle frequency of 0.5 Hz; tank volume was 50% filled.

The paper [13] presents the three-dimensional quasi-static and dynamic slosh models of the partly-filled clean-bore tank. Initially, there was solved the problem of under ramp-step longitudinal ($g_x = 0.3$) and lateral ($g_y = 0.25$) acceleration excitations for three fill conditions (40, 60 and 80%). The simulations were performed over an extended period of 20 s so as to achieve steady-state values. Simple steady turning case is considered in [18, 20].

The most complicated case of influence of the sloshing phenomena on the directional response of tank vehicles was presented in [21] and [3]. The latter one presents a multiphysics analysis of a simplified tanker truck undergoing a lane change maneuver. Bi-directionally coupled CFD and MBD solvers are used to compute the response of the vehicle during a lane change maneuver. The distribution of the liquid within the cargo tank is computed by the CFD solver AcuSolve using an Arbitrary Lagrange-Eulerian (ALE) mesh motion approach.

A comparison of numerical solutions with literature experimental data was shown in [28]. In the numerical simulations, the free surface shape appearing during sloshing was simulated under small and large amplitude sinusoidal displacements. The results obtained with the use of different software were compared with the results of the experiments reported in literature. Only few papers consider the influence of baffles [9, 13]. Both experimental and numerical studies were presented in [26].

The aim of the present work is the numerical analysis of the liquid motion inside the partially filled compartment during its unsteady motion. The object that can serve as an example is the tanker truck performing a complex maneuver while passing a roundabout. In this work, the test maneuver consisting of motion through three arcs, which in turn determine the entry, transit and exit from the roundabout, is the analyzed scenario of generation of the fluid motion. The vehicle path consists of three quarters of the circle, of which two – entry of the roundabout and the exit from it – have the same radii. Such a complicated, but practical maneuver, has not been considered in the literature.

The simulations are carried out for three filling levels (20%, 50% and 80%) for the volume of the one-compartment tank and half-filled tank in a configuration with one and two baffles. The results of simulation studies representing the variation of position of the center of gravity, the forces acting on the wall of the tank, and their moments, their spectrum and the shape of the free surface were compared and analyzed. The Fluent computational program based on the finite volume method was the tool used in the performed simulations.

2. Description of fluid movement forcing scenario

There are several specific maneuvers, during which the tanks are involved in accidents:

- sudden lane change,
- changing tanker direction of movement by 180 degree,
- driving around a curve,
- sudden braking and accelerating.

In this paper, we consider a tanker truck movement scenario in which the liquid under the alternately changed lateral acceleration can generate the oscillating motion of the liquid in the tank. The driving maneuver analyzed in this work is the passage with the constant speed through the quarter of a roundabout. The tanker truck moves with velocity $v = 3$ m/s on a trajectory consisting of three arcs with radii of $R = 20$ and $r = 7$ m. A simplification of the movement model is used. It is assumed that the velocity vectors of the front and rear axles of the vehicle are tangent to the described path. On this basis, the speed of the tank movement and rotation is determined. The basic parameters of the vehicle trajectory are shown schematically in Fig. 1. The car with tank is making a typical maneuver in which direction of inertial forces is changing rapidly in opposite direction. One can notice a complicated variation of the value and direction of centrifugal acceleration during the tank motion (Fig. 1 right sketch). In literature, such a complicated sequence of inertia force variation has not been considered.

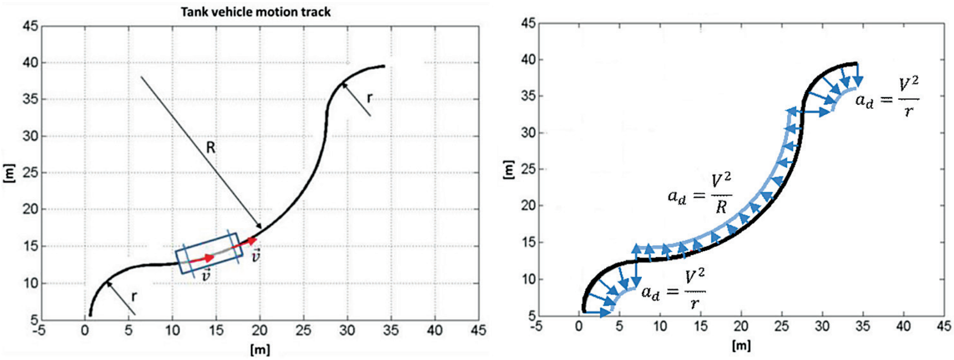

Fig. 1. Parameters of the tank truck trajectory (left) and resulting acceleration (right)

The tank vehicle container volume was discretized and logically divided into the gaseous and the liquid part. The tank movement was implemented into the program Fluent using the user-defined function (UDF). The Fluent macro "define_zone_motion" can be used for that purpose. The movement of any object can be analyzed using the "Mesh Motion" or the "Reference Frame Motion". The first function enables direct simulation of the movement of the container in space, which requires updating the location of grid nodes in each subsequent time step. This procedure is computationally expensive. The option of "Reference Frame Motion", where the issue is resolved relative to the reference non-inertial system, was used in the present study, due to the higher speed and effectivity of computation.

The convention adopted in the Fluent requires description of inertial system (*X*, *Y*, Z*)* motion (Fig. 2) in relation to a non-inertial system (x', y', z'). The UDF code describes the relation of the tank speed components in the reference system *X*, *Y*, *Z*.

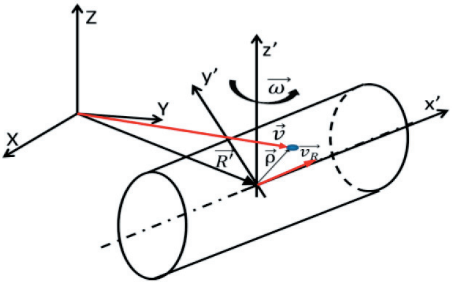

Fig. 2. Motion of the tank non-inertial system

Velocity and acceleration vectors are expressed by the following relations

$$\vec{v} = \vec{v}_r + \vec{\omega} \times \vec{\rho}\,, \tag{1}$$

$$\vec{R} = \vec{R}' + \vec{\rho}\,, \tag{2}$$

$$\frac{d\vec{R}}{dt} = \frac{d\vec{R}'}{dt} + \vec{\omega} \times \vec{R}' + \frac{d\vec{\rho}}{dt}\,, \tag{3}$$

$$\frac{d^2\vec{R}}{dt^2} = \frac{d^2\vec{R}'}{dt^2} + \vec{\omega} \times (\vec{\omega} \times \vec{R}') + 2\vec{\omega} \times \frac{d\vec{R}'}{dt} + \frac{d\vec{\omega}}{dt} \times \vec{R}' + \frac{d^2\vec{\rho}}{dt^2}\,. \tag{4}$$

Figure 3 shows the convention rule adopted in the Fluent.

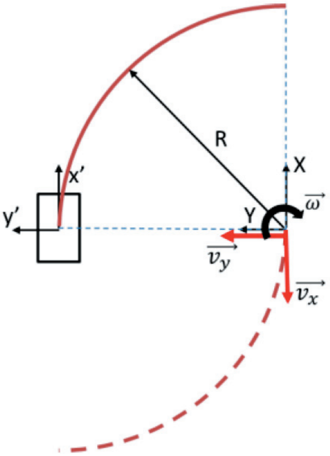

Fig. 3. Scheme of the notation convention used in Fluent

Then, the constraint in the form of a linear velocity field and the rotation can be written in the UDF code as follows:

$$\vec{V} = \left[-V\cos\left(\frac{Vt}{R}\right),\ V\sin\left(\frac{Vt}{R}\right),\ 0 \right] \quad \vec{\omega} = \left[0,\ 0,\ -V/R\right]. \tag{5}$$

3. Method of analysis

The volume of fluid (VOF) technique is a numerical method that allows tracking and determining the shape of the free surface between the immiscible fluids. If the case of multiphase flow with free surface is considered, the Navier–Stokes equations describing the flow motion have to be supplemented with equations describing the VOF (*Volume of Fluid*) technique. The VOF method was described for the first time in [10].

After setting on the VOF technique, it is necessary to select the method of geometry interpolation of the free surface between the phases. In the present case, the shape of the free surface is built with the Fluent program using the technique of geometric reconstruction (geo-reconstruct). Its scheme is based on the volume fraction of liquid's phase in each cell. The phase interface is approximated for each cell separately, using the linear function, as it is shown in Fig. 4.

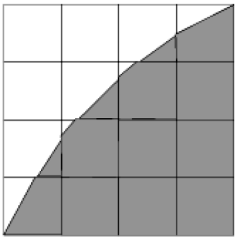

Fig. 4. Approximation of the free surface by piecewise linear function [30]

4. Numerical model

4.1. Geometry

The circular cross-section of the tank of diameter D = 3 m and length L = 6 m has been assumed, as it is shown in Fig. 5.

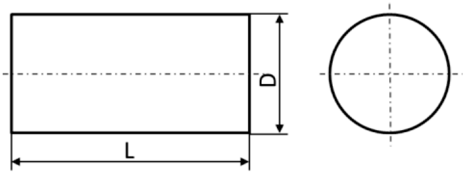

Fig. 5. Tank geometry

To investigate the influence of baffles and fill level, the one-compartment tank and the baffled tank were considered. The scheme of the baffles assumed for the simulation is presented in Fig. 6.

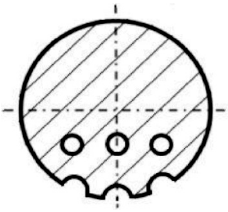

Fig. 6. Baffle geometry

The baffle is a full wall with three holes located in the bottom half of the tank and three slots located in the vicinity of the wall.

4.2. Mesh

For the purpose of simulation of the liquid's motion inside the container without baffles, its volume was discretized into 229878 QUAD elements using the “Sweep Method” option included in Ansys Fluent environment. It created a uniform mesh in each of the cross sections of the container.

In another case, the simulation involved the division of the tank truck container. Its volume was divided into TETRA finite elements. It was assumed that the partition wall was completed with three holes of a diameter equal to 30 cm, and three slots at the bottom with a diameter of 40 cm allowing the liquid to drain from the tank. The mesh on the baffle is shown in Fig. 7.

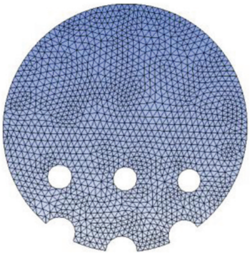

Fig. 7. Example of mesh used on the baffle surface

When the tank is half-filled, the holes are located in its bottom part which is filled with liquid. In this case, the mesh consists of 303116 elements. Mesh density was chosen on the basis of known solutions and own experience of the authors in the analysis of similar problems.

4.3. Fluid model

The multiphase domain chosen for this simulation consisted of water and air, which were homogenous and isotropic. The physical and mathematical model of the phases takes into account the viscosity and incompressibility of the fluid. In the case of the one-compartment tank, the turbulence was modeled with the use of the one-equation Spalart-Allmaras model. This model solves the transport equation for turbulent viscosity and is usually used for aerodynamic flows, especially when the boundary layer is considered ([5]). Since it is effective for low Reynolds numbers, it was used in this analysis.

In the study of a baffled tank simulation, the selected turbulence model was based on the theory of Scale-Adaptive Simulation [5]. This model, in the case of the baffled tank, was more effective than Spalart-Allmaras model. It shortened the computation time and reduced the problems associated with the convergence of the solution.

4.4. UDF procedure

UDF is a user-defined function, which can be loaded in FLUENT program to extend the possibilities of standard functions. It can specify boundary conditions, initial conditions or material properties for a given problem. UDFs are written in the C programming language with the use of a text editor or Visual Express compilers and saved with the extension "*.c".

The Fluent Software defines types of macros that can be implemented in the UDFs code. It is crucial to select the right type of macro functions, because it changes the method of solving given problem. The macro DEFINE_ZONE_MOTION was used to define the movement of the tank.

5. Simulation results

The three-dimensional simulations of transient sloshing motion of a liquid inside the partially filled container were performed while the truck is riding on a quarter of the roundabout. The velocity of the tank truck was constant and equal to 3 m/s. Taking into account formal regulations prohibiting the use of tank trucks containers filled in the range 20%-80%, some test have been done to check the liquid dynamics in this area. The results were obtained for the tank without baffles in three cases of the container filling – 20%, 50% and 80% of the tank volume. Then, half-filled tank was divided by baffles into smaller compartments. The simulations were performed with the tank container divided into two and subsequently three equal compartments. The accepted scenarios of tank truck motion in the simulations allowed comparing the influence of different filling levels of the container and the influence of the container division on forces, moments and the center of mass coordinates of the liquid cargo.

In order to control the differences in the free surface behavior, its shape was monitored in the characteristic points of the route shown in Fig. 8. The following points of the tank movement were set and marked in Fig. 8:

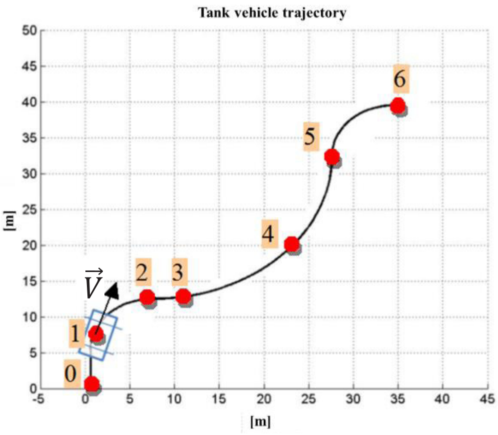

Fig. 8. Tank truck trajectory with characteristic points

0. beginning of the maneuver,
1. entrance to the roundabout,
2. leaving the entrance arc,
3. entrance to the main arc of the roundabout,
4. riding on the roundabout,
5. leaving the roundabout to the exit arc,
6. leaving the roundabout and the end of simulation.

5.1. Base tank model simulation

This section shows simulation results referred to the case when the tank is half-filled. However, it is worth mentioning that the results of the liquid's free surface form, for the case when tank is 20% and 80% filled, are quite similar. The main differences are noticeable in absolute values of dynamic impacts acting on the tank. Therefore, the case of half-filled tank is treated as most dangerous and basic for the two simulation scenarios. Further, the shape of the liquid's free surface is shown in the characteristic point on the track marked in Fig. 8.

Figure 9 shows the container geometry and free surface of the liquid when the tank truck is located at the beginning of the entry to the roundabout (point "0"). The liquid is in the steady state. The velocity vector of the tank is parallel to the *x* axis shown in Fig. 9.

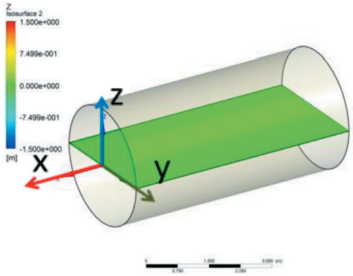

Fig. 9. Geometry of the container. The free surface form at the beginning of the roundabout (50% of filling)

The shape of free surface visualizes a hydrostatic pressure distribution and is the clearest information type for understanding distribution of forces acting on the tank walls. In Figs. 12-17, instantaneous free surface shape in characteristic phases of the analyzed tank maneuver for all considered tank geometries are collected for direct comparison.

In the first column of Figs. 12-17, the form of free surface in the one-compartment tank vehicle is visualized in characteristic points of the track shown in Fig. 8, and compared with other cases.

Liquid cargo moves to the rear wall of the tank and on its right side, as it is seen in Fig. 12. This motion is caused by the inertia forces that start acting when the vehicle enters the curve. At the entrance, at point 2 (Fig. 13), we can observe further accumulation of the liquid on the back of the tank. The wave, reflected from the back wall of the tank moving toward the front, is also visible in Fig. 13. Figures 14-15 refer to points 3 and 4 on the tank truck route. Figures 14 and 15 depict free surface shape during the typical sloshing phenomenon – the liquid is reflected from the front and rear walls of the tank and, in effect, the waves of high amplitudes are formed. This is occurring during the ride on the arc of the biggest radius. Figures 16 and 17 show next stages of sloshing during the vehicle's maneuver.

When the vehicle enters the exit curve of the roundabout, the vector of the normal acceleration to the vehicle's trajectory changes its direction. As a result, the liquid reflects from the side walls of the tank, and these waves are small.

5.2. Two-compartment tank simulation

This section corresponds to the situation when the tank is half-filled and divided into two compartments of volume equal to 21.2 m^3. Figure 10 shows geometry of the container and the shape and location of a baffle as well free surface of the liquid inside the half-filled tank when no excitations act on vehicle. The tank is located at the beginning of the entry arc (point "0" in Fig. 8) and the liquid is undisturbed.

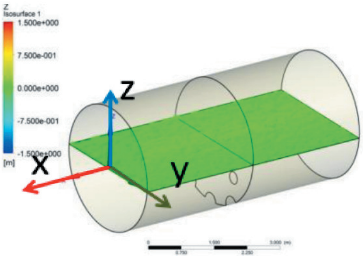

Fig. 10. Geometry of the container and internal baffles. The free surface form at the beginning of the roundabout (50% of filling)

As it is visible in Fig. 10, the baffle is located in a half of the tank length and the holes and slots are under the liquid level. In the following Figs. 12-17, in the second column, there is shown the free surface shape in characteristic locations on the roundabout.

When we consider each compartment separately, the division of the tank into two compartments doesn't make major changes in the free surface shape of the liquid in the initial stage of the movement (Fig. 12). For the case of one-compartment tank, for simulation time 1.37 s, one can notice a slight deviation in the free surface of the plane defining the position of the free surface of the liquid at rest (see Fig. 12, first column). However, this deviation is larger for the baffled tank.

Entering in the main arc of the roundabout (Figs. 13-15) brings important changes in the free surface shape. The liquid rapidly reflects from the walls of the tank. The new form of movement can be noticed, which is the separation of the liquid portion lapping up on the baffle. While sloshing, a wide range of motion types of the liquid can be observed.

It cannot be noticed in the pictures, but the animation of free surface shape modification makes it clear that the changes in free surface occur with a higher frequency. Figures 16 and 17 illustrate the simulation results obtained for the final stage of the movement of the tank.

Figures 16 and 17 show that the shapes of the free surface as well as its changes are non-linear. It means that the free surface cannot be approximated by a part of a plane. It seems that in the case of the one-compartment tank, it was possible to understand the shape of free surface, or more or less predict its next form. In the case of the divided container it is a more difficult problem because of much more complex motion. These results give also a view on the capabilities of the numerical solution performed by a CFD. The non-linear feature of the wave motion is partially related to the internal flows between tank compartments, which depended on the second power of velocity, and partially due to higher amplitude of oscillation influencing in nonlinear way the speed of surface waves, which depended on the square root of the local liquid depth.

5.3. Three-compartment tank simulation

The results in this section correspond to the situation when the tank is half-filled and divided into three compartments with baffles located every 2 m of the tank length. In Fig. 11, container geometry and form and distribution of baffles is presented.

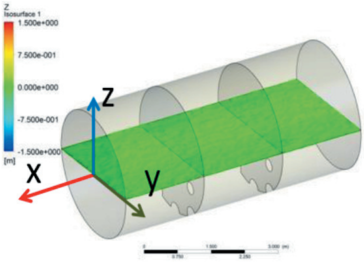

Fig. 11. Geometry of the container and internal baffles. The free surface form at the beginning of the roundabout (50% of filling)

In the initial stage (Fig. 12 right side column) of the movement, the division into three compartments doesn't make major changes in the free surface shape of the liquid – the deviation from the steady position of the liquid is similar as in other cases of half-filled tank. Here one can note that the inclination of the free surface in each compartment is growing with decreasing distance to the rear wall of the tank. The free surface can be approximated as a part of a plane. Figure 13 shows further growth of the inclination and initiation of deformation of the free surface.

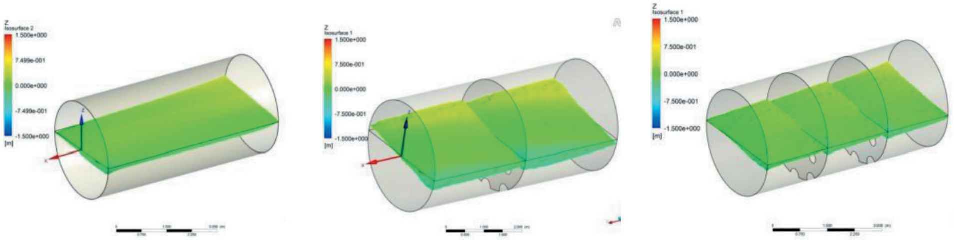

Fig. 12. $t = 1.38$ s, point „1"

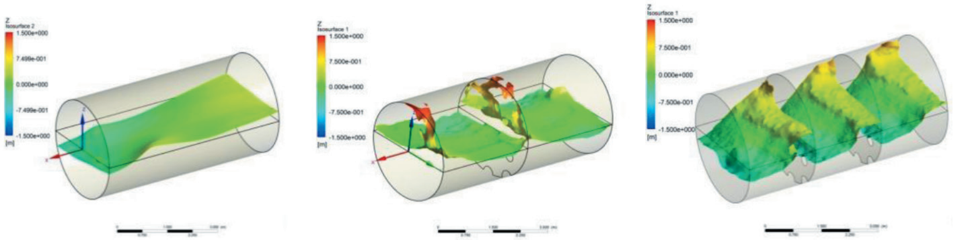

Fig. 13. $t = 3.68$ s, point „2"

Figure 14 shows the liquid's surface after reflection from the walls, which can be also seen in the case of the two-compartment tank shown in Fig. 14 – central column. The shape of the free surface of the liquid, for the case of driving on a main arc of the roundabout, is presented in Figs. 14 and 15.

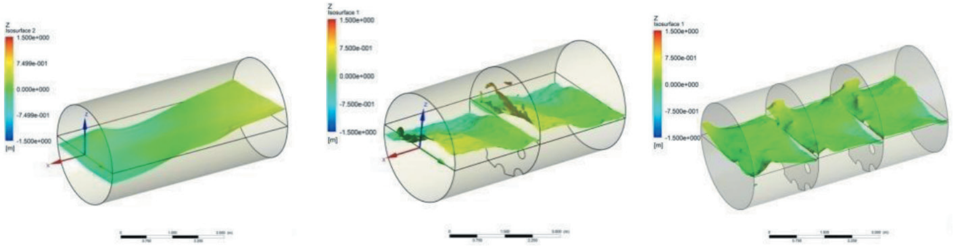

Fig. 14. $t = 5.24$ s, point „3"

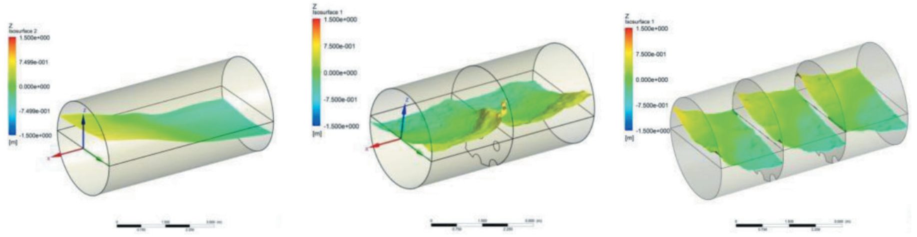

Fig.15. $t = 11.78$ s, point „4”

Comparing these shapes of the free surface with two-chamber geometry, we cannot distinguish portioning of the liquid cargo. However, the changes in the shape of the free surface occur with a higher frequency. Figures 16 and 17 illustrate the simulation results obtained for the final stage of the tank movement.

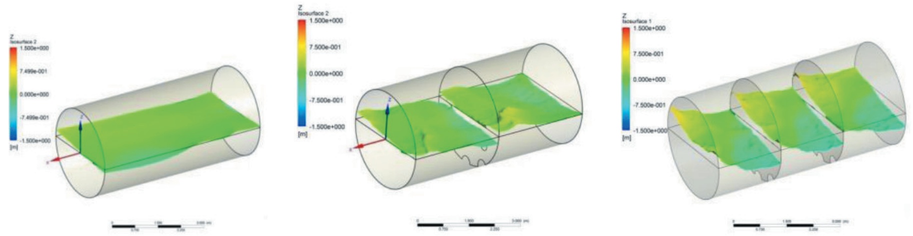

Fig. 16. $t = 14.78$ s, point „5”

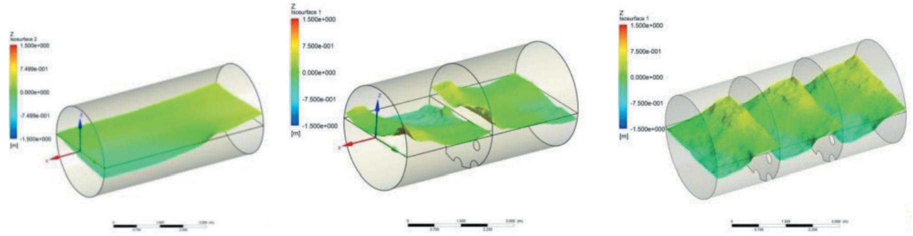

Fig. 17. $t = 17.3$ s, point “6”

Figures 16 and 17 show that after subsequent maneuvers of the tank on the track, the liquid is reflected from the walls and tilts in the plane OXZ. It can be assumed that, in the examples presented in these Figures, the free liquid surface can be approximated by a plane. Comparing these results with free-surface shapes corresponding to the end stage of maneuver of the two-compartment tank, one can notice that the shapes of the liquid surface are different. This confirms the notion that sloshing motion solved numerically with the use of VOF technique is highly non-linear.

For easier interpretation of the results of simulations, the forms of the free-surface of liquid for all considered tank geometries are presented in a compact way. Figures 12-17 present the shape of free surfaces for three considered tank vehicle container configurations (single, double and triple compartment) at time instances corresponding to characteristic points of the tank track shown in Fig. 8.

6. The quantitative comparison of simulation results.

The complex maneuver of the vehicle leads to the transient motion of the liquid inside the tank and changing location of the liquid's mass center. The moving mass of the liquid generates the varying dynamic loads acting on the tank walls. The simulation studies performed in Fluent program were used to track the movement of the liquid in order to derive the three components of the forces acting on the walls of the tank and position of its center of gravity. The components of the forces and the coordinates of the center of gravity are described in the non-inertial reference system associated with the tank.

This chapter presents the results concerning:

- force components F_x, F_y, F_z and their moments for the three levels of tank filling,
- changes of three force components and their moments for half-filled tank in the case without the baffles, two-compartment and three-compartment tank,
- the spectral analysis of force signals in cases of baffled and non-baffled tank.

These numerical results will be compared for each case of partial-filling and compartment division.

6.1. Influence of the liquid level in tank on the unsteady forces acting on the tank

The influence of liquid filling value on a tank system can be estimated on the basis of the changes of the force components and moments acting on the tank. It should be recalled that, in accordance with the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR 2009-2011), the non-baffled tanks with a capacity of no more than 7500 l shall not be filled in the range of 20% – 80% of their volume. Therefore, simulations for different levels of filling of the tank have been carried out for the acceptable values and for 50% of filling being in the middle of prohibited range.

The maximum value of F_x force acting on the walls in the x-axis, shown in Fig. 18, increases with the increasing volume of the liquid in the tank. This is consistent with intuition. It should also be noted that the increase of tank filling increases the difference between the minimum and maximum value of this force component.

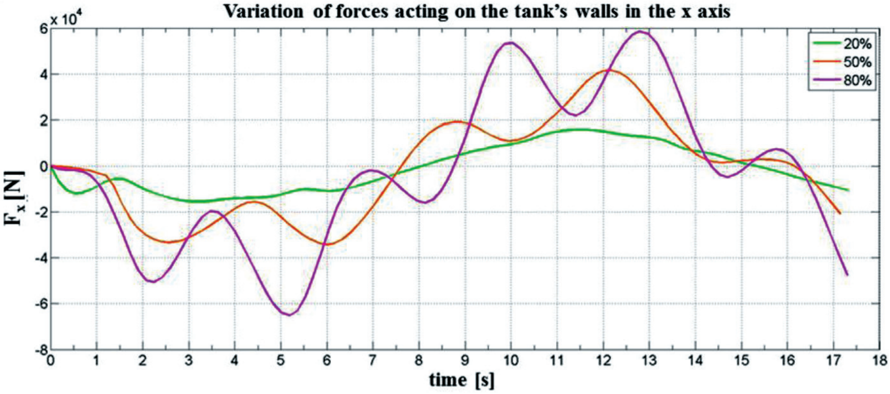

Fig. 18. Comparison of the unsteady forces acting on the tank wall in the direction along longer axis of the tank, for different tank filling level

For the 20% filled tank, the force acting on the front and rear wall of the tank varies from –16 to 17 kN, in the case of half filled tank the range is from –33 to 41 kN, and in the case of 80% filled tank it varies from –65 to 60 kN. Figure 18 shows clearly also the wave nature of sloshing – forces acting on the walls of the tank have oscillatory characteristics. The increase in fluid level generates also higher harmonics of the force acting on tank walls.

Figure 19 depicts the results of the spectral analysis for the F_x force component in all cases of tank filling. Spectral analysis describes how the signal is distributed over the frequency. The largest amount of energy is transmitted at the frequency of 0.06 Hz. This frequency depends on the time of maneuver.

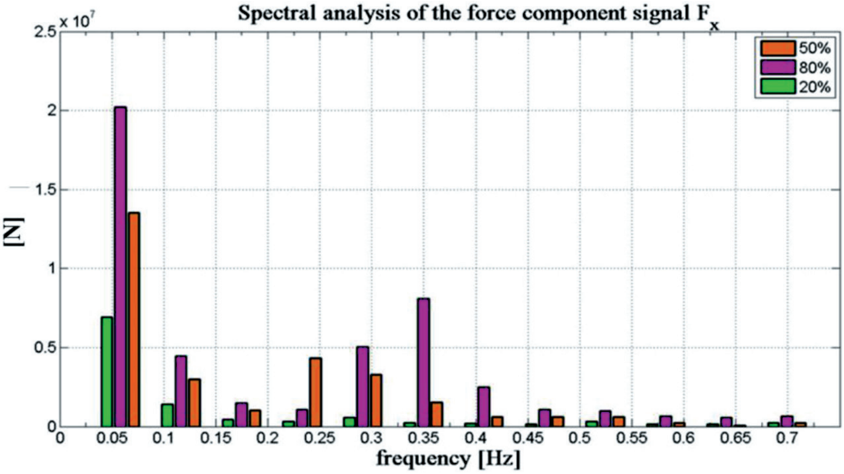

Fig. 19. Spectral analysis of the force acting on the tank wall in direction of the longer axis, for three levels of tank filling

Increasing speed of a car carrying tank reduces this frequency, but increases the inertia forces. Of course, its value decreases as the filling of the tank is reduced. When the tank is 80% filled, an additional frequency of approximately 0.34 Hz appears. The reason of that is probably connected with an increase in surface waves speed due to higher local depth of the liquid.

Figure 20 illustrates the variation of the F_y force component acting on the tank walls in the y-axis. Here, the fluid acts on the cylindrical wall in the direction along the y-axis in non-inertial frame, which is lateral to the velocity vector of the moving vehicle. This direction of the acting force has the strongest influence on the vehicle stability. One can distinguish the changes in the direction of the acting force associated with the location of the vehicle on the route – there are negative and positive values depending on the roundabout arc. Similarly as the force component acting in the x axis, the force reaches a higher value for higher filling level. For 20% filled tank, the range of force changes is equal to –10 to 21 kN, for half-filled tank the forces change from 20 to 48 kN, in 80% filling the maximum force is 3.5 times higher than in the case of 20% filling. Analyzing this data, one can conclude that, from the point of view of generating vehicle instability, a more dangerous case is that of 80% filling in comparison with 50% filling.

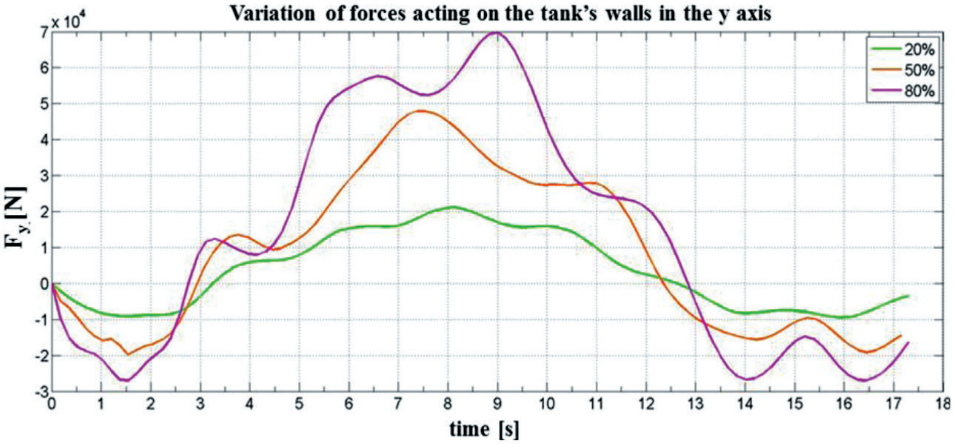

Fig. 20. Comparison of the unsteady forces acting on the tank wall in direction normal to the longer axis of the tank (lateral force), for different tank filling level

The changes in the value of the force component in the z-axis are negligible – we can notice only small oscillations around the value that specifies the weight of the liquid in the tank. Figure 21 shows the results for different levels of filling.

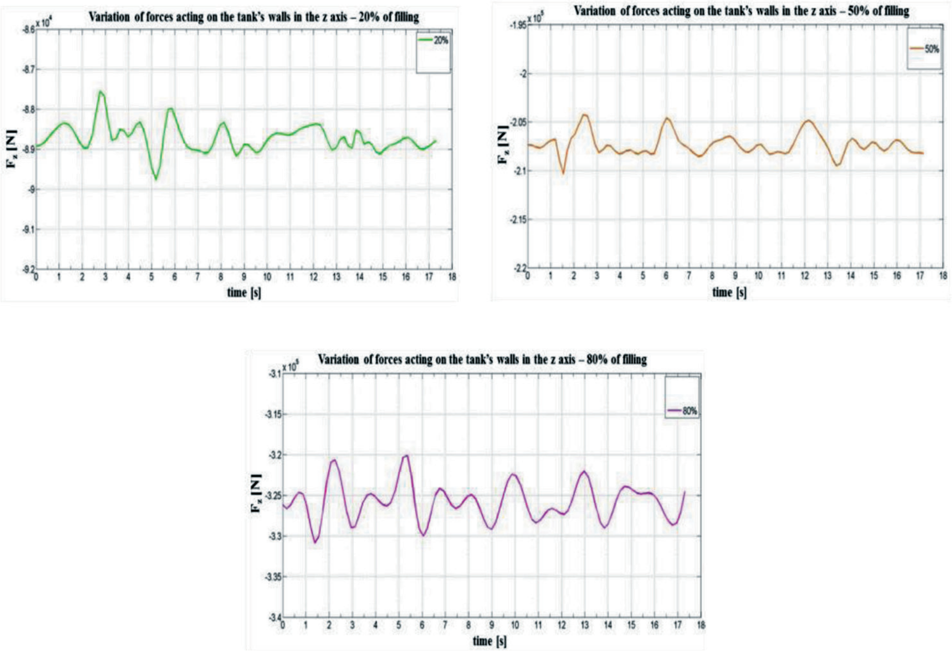

Fig. 21. Comparison of the unsteady forces acting on the tank wall in vertical direction for different tank filling level (20%, 50% and 80%)

The next step of result analysis was the calculation of the force moment. Besides the forces, it depends on the position of the center of gravity of the liquid. The moment acting on the system with respect to the *x* axis is presented in Fig. 22.

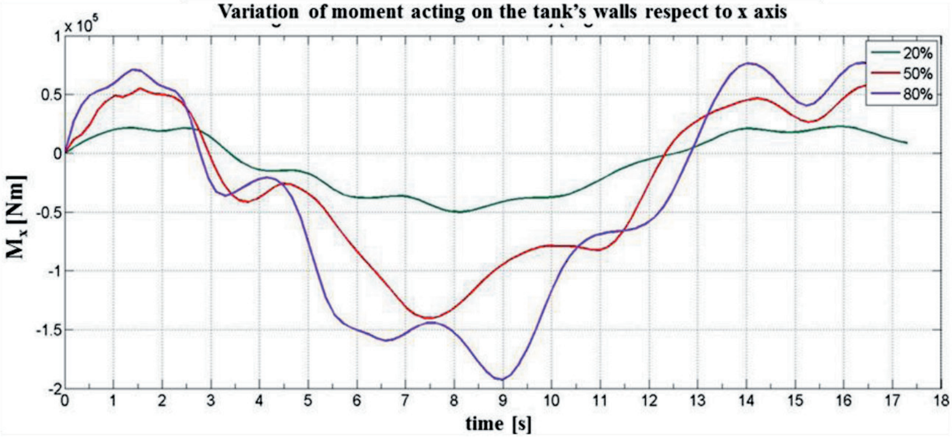

Fig. 22. Comparison of the unsteady forces moments acting on the tank wall with respect to the direction along the longer axis of the tank, for different tank filling level

The highest values of the M_x moment were obtained for the highest level of filling. The moment was equal to approx. 180 kNm and occurred while driving on the roundabout, on the arc with the largest radius. Although the centrifugal force is greater at the entrance and exit of the roundabout (the radius of the track curvature is a smaller), the time of riding on these arcs is too short to obtain high values of the moment.

Figure 23 illustrates the M_y pitching moment with respect to the y axis. According to these results, it turns out that the values for the highest degree of filling are similar to those of the half-filled tank, but the changes occur more frequently at 80% filling. The highest value of the force moment can be noted on the main arc of the roundabout and it is equal to 220 kNm.

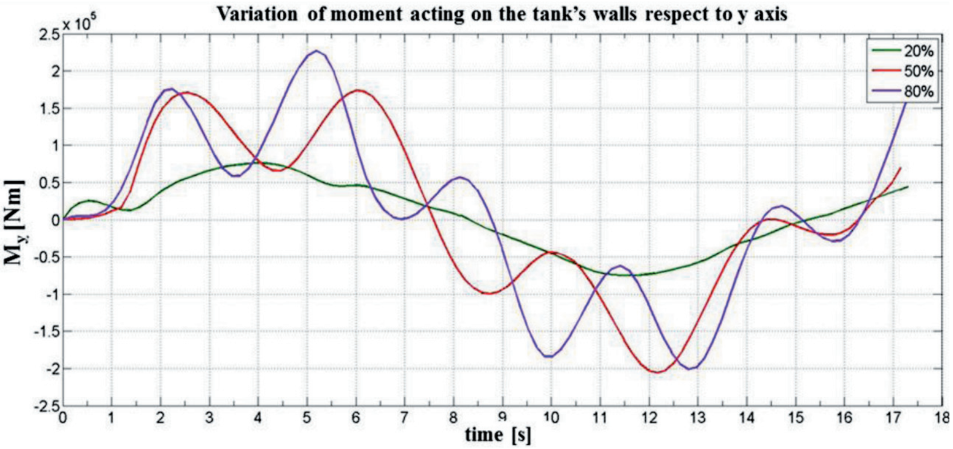

Fig. 23. Comparison of the unsteady forces moments acting on the tank wall respect to direction nornal the longer axis of the tank, for different tank filling level

One can notice that the force moment M_y appears to be determined mainly by the variation of the force F_x (see Fig. 18). This is due to the fact that the changes in the force F_z, which also influences the value of this moment, are insignificant.

Figure 24 presents the yaw moment M_z with respect to the z axis. The highest value of this moment and its biggest range of changes were obtained for a half-filled tank. Nevertheless, the maximum value of this moment is 10 times smaller than the previously mentioned moment components. M_z moment values for the half-filled tank are in the range of –18 kNm to 12.5 kNm and the difference between this maximum values is higher than in other cases of filling.

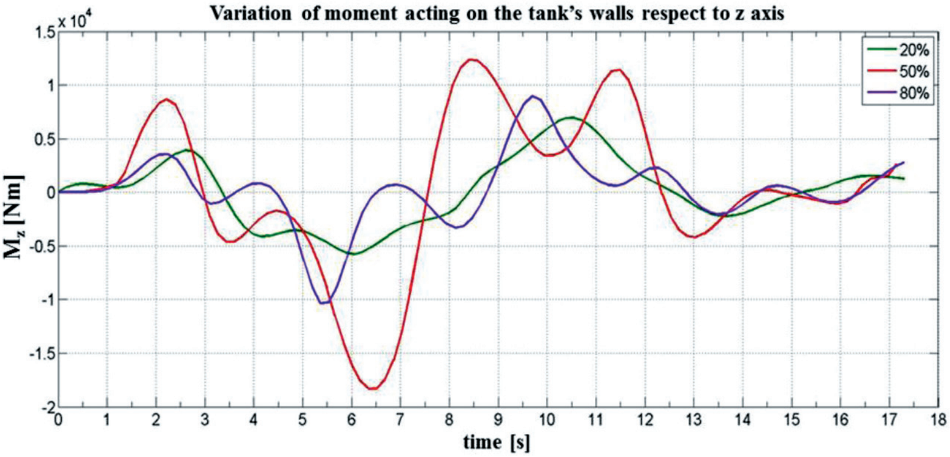

Fig. 24. Comparison of the unsteady forces moments acting on the tank wall respect to direction of vertical axis of the tank, for different tank filling level

Figure 25 shows the trajectory of motion of the center of gravity for three filling levels of the tank. Although the variation of position of the center of gravity for the filling level equal to 20% is the biggest one, the forces acting in this case are so small that the changes in the center of gravity are not the most important factor influencing the variation of force moments.

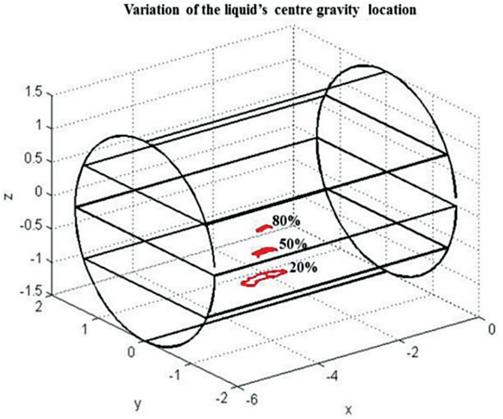

Fig. 25. Changes of the center gravity position on the filling level considered

After the simulations of the transient motion of a fluid in a one-compartment tank driving on a roundabout, we can refer to regulations on transporting hazardous materials. For a tank with a much larger volume than that stated in the ADR, the results indicate that the transport of liquid in a tank filled to 80% generates a greater impact on the tank's dynamics than the not allowed half-filled tank. Only once, the yaw moment M_z with respect to the z axis was the biggest in the case of half-filled tank. It is, however, the smallest moment among other moment components, so consequently an assumption of negligible impact of tank dynamics can be supposed. It must be noted that the simulations were performed at relatively low velocity of the tank. It seems that the confrontation of reasonability of these regulations must be preceded by broad simulations regarding different vehicle's velocities, different maneuvers and smaller tank volume.

6.2. Influence of baffles

Basing on the results presented in this chapter, we can estimate the effect of the tank division on dynamic impacts acting on the tank. The analysis of these results concerns the simulations performed for the half-filled tank. The forces and their moments for the one-compartment tank are compared with the results for the two- and three-compartment tank. The influence of baffles on the dynamics of the system is discussed also with the use of the Fast Fourier Transform and spectral analysis for the obtained force components. Figure 26 shows the force component in the x axis.

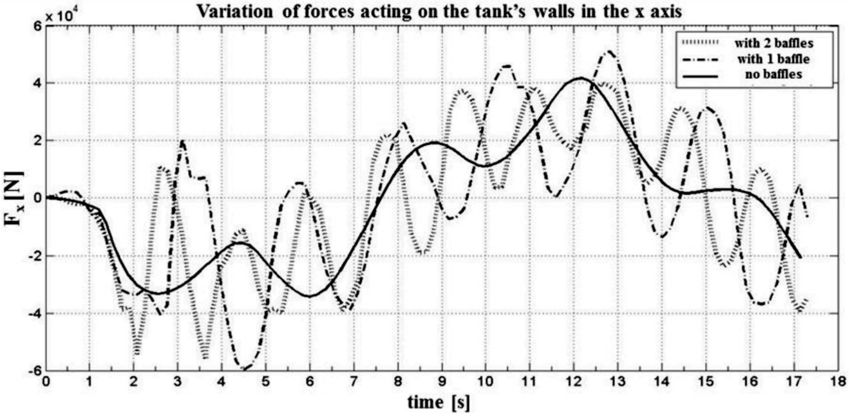

Fig. 26. Comparison of the unsteady forces acting on the tank wall in direction along longer axis of the tank, for different tank internal configuration

When the tank is non-baffled, the force F_x varies in the range of –35 kN to 40 kN. When the division is introduced, the range of the force F_x definitely expands – from –60 kN to 50 kN. Inserting the second baffle causes that the force F_x changes from –55 kN to 40 kN.

In Fig. 26, it can be seen that the more divisions, the greater increase in the changes of frequency of the force F_x. This is due to the shorter waves of the liquid surface reflecting from the walls. Spectral analysis presented in Fig. 27 clearly shows the effect of baffles on liquid sloshing.

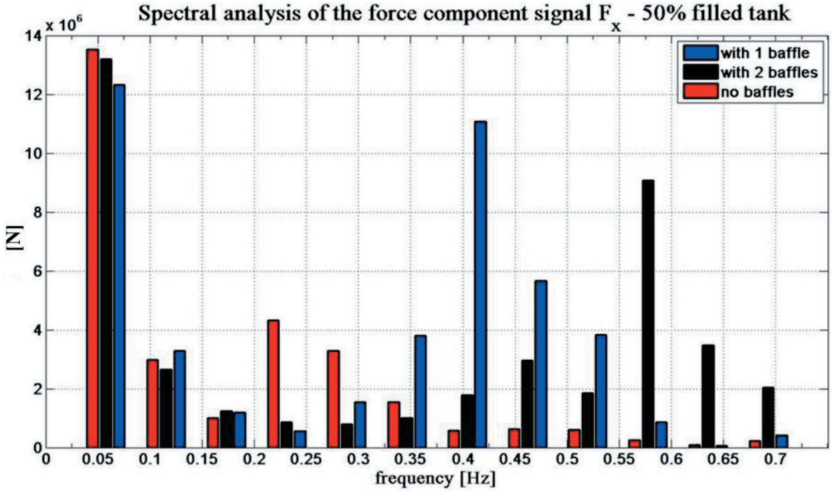

Fig. 27. Spectral analysis of the force acting on the tank walls in longitudinal direction, presented for three tank internal configurations

All the cases have a common frequency equal to 0.06 Hz. Inserting a baffle in the middle of the tank length causes that there appears an additional higher frequency of approx. 0.41 Hz, at the same time the value for the common frequency is reduced. The presence of two baffles shifts the peak to even higher frequencies, i.e. 0.57 Hz.

Figure 28 shows the force component along the *y* axis.

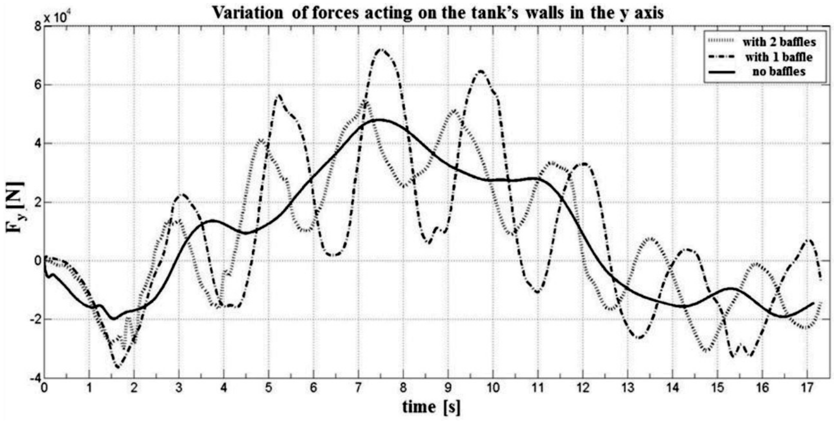

Fig. 28. Comparison of the unsteady forces acting on the tank wall in direction normal to longer axis of the tank, for different tank internal configuration

Introduction of two baffles reduces the range of the force F_y (–30 kN and 50 kN) in relation to the tank with one baffle (–35 kN to 70 kN). However, they are still higher than those for the undivided tank (–20 to 50 kN). Spectral analysis for component F_y is shown in Fig. 29.

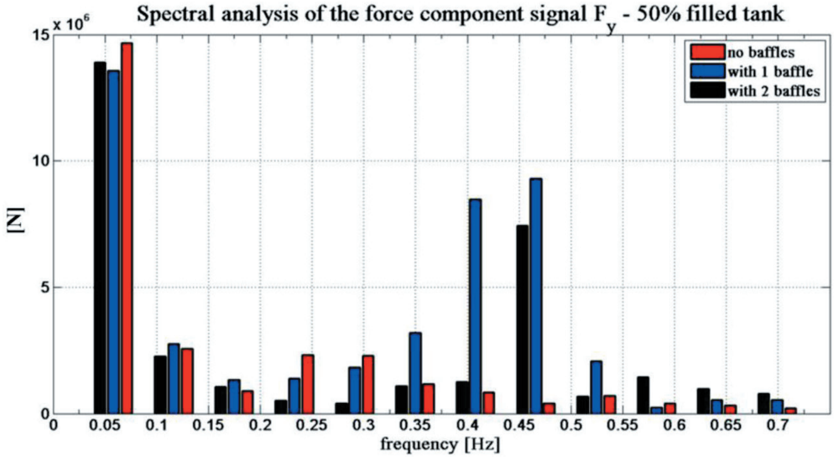

Fig. 29. Spectral analysis of the unsteady forces acting on the tank wall in direction normal longer axis of the tank, for different tank internal configuration

The use of baffles causes that there appear, except the basic frequency of 0.06 Hz, an additional frequency equal to approx. 0.4 Hz and 0.46 Hz. The presence of more baffles decreases only the value of the spectral component of the force for the basic frequency.

Figure 30 depicts the force component along the *z*-axis.

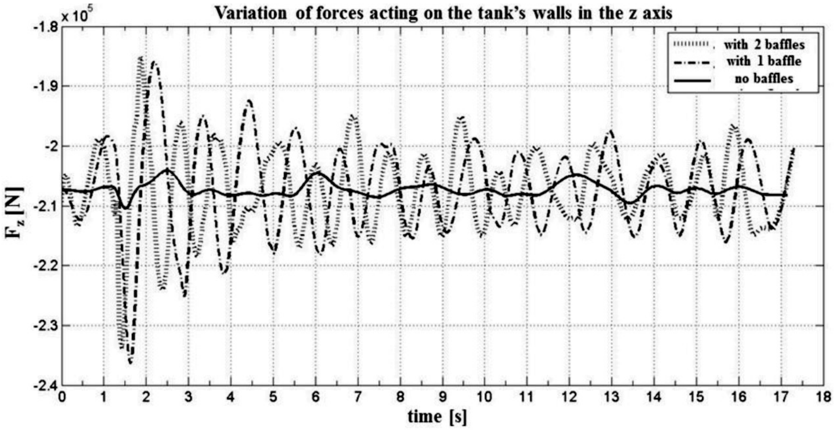

Fig. 30. Comparison of the unsteady forces acting on the tank wall in vertical direction, for different tank internal configuration

The baffles inserted in the tank increase the amplitude variation of the force F_z. Regardless of the number of baffles, this force takes similar values (in the range from –232 to –187 kN). Figure 12 seems to indicate that this change is caused by the reflection of the liquid from the tank wall and the temporary portioning of the liquid caused by its chaotic motion.

Figure 31 shows the tilting moment M_x, with respect to the x axis.

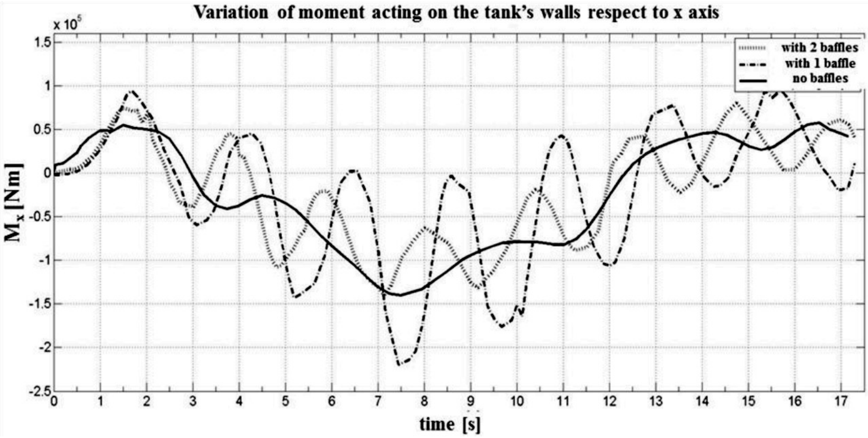

Fig. 31. Comparison of moments of the unsteady forces acting on the tank wall along longitudinal axis, for different tank internal configuration

The highest moment value is obtained for the two-compartment tank. It is equal to approx. –220 kNm and occurs when driving on the arc with the largest radius. For the same location on the track, in the case of three-compartment container, the value of this moment is twice lower. Although the centrifugal force is greater at the entrance and the exit of the roundabout (there is a smaller radius of the track curvature) and it can be expected that the tank will be impacted by the bigger dynamic loads, the time of passing through these arches is too short, so the liquid cannot move or alter significantly. The pitching moment M_y is shown in Fig. 32 which shows that tank division reduces the maximum values of M_y while driving on a roundabout.

In the case of the single-compartment tank, the moment M_y takes the range of variation from –200 to 170 kNm. For a two-compartment tank it is the range from –160 to 160 kNm, while for the three-compartment tank the range narrows, and takes the values from –150 to 125 kNm. It should be noted that in the initial stage of the movement (approximately up to 1 s), the values in the graph illustrating this moments are very close, regardless the number of divisions.

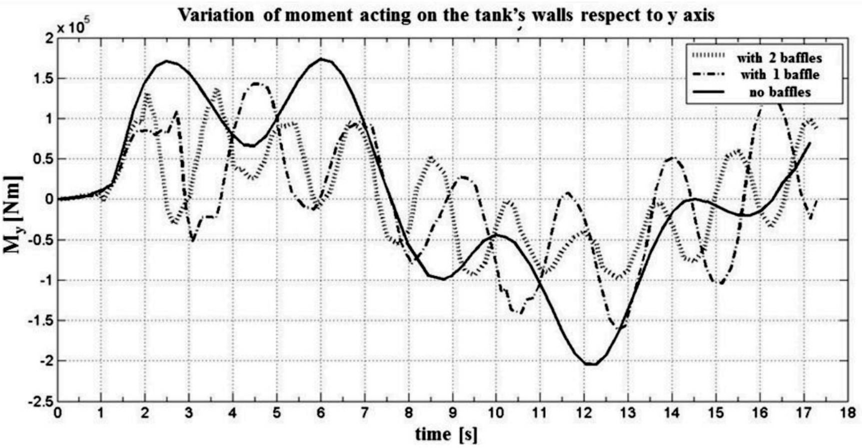

Fig. 32. Comparison of the unsteady forces moments acting on the tank wall normal longitudinal axis, for different tank internal configuration

Figure 33 presents the yaw moment M_z. The highest value of this moment was obtained in the case of one-compartment tank and it was equal to –18 kNm.

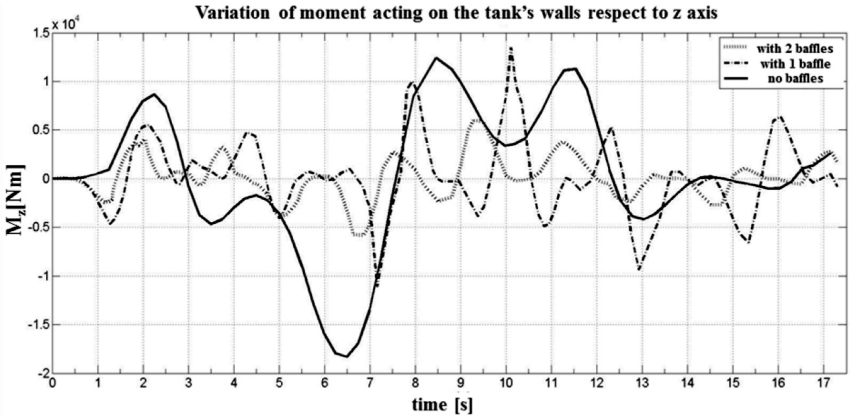

Fig. 33. Comparison of the unsteady forces moments acting on the tank wall along vertical axis, for different tank internal configuration

The graph in Fig. 33 shows that baffles reduce the maximum moment with respect to the *z* axis. In the case of one baffle, the maximum value of the M_z is equal approx. 14 kNm, while for the two baffles it is around 6 kNm. Again, the moment M_z is in general 10 times smaller than the moments M_x and M_y.

The influence the tank division is visible also in the motion trajectory of the gravity center of the liquid. It has been found that the effect of baffles is significant especially in the *x*-axis. The variation of center gravity coordinate in the *x*-axis for the one-compartment tank ranged between –3.5 m to –2.5 m, for the two-compartment tank between –3.2 to –2.8 m, and for the three-compartment tank it was in the range between –3.1 to –2.9 m. It means that introducing one baffle reduced the variation of *x* coordinate of gravity center more than twice.

7. Concluding remarks

The paper describes the behavior of the liquid in the tank which moves with a constant speed along a track consisting of three arcs. The tank can be treated as an example of a tanker truck passing through a roundabout. The behavior of such a vehicle is affected by the inertia forces associated with the transient sloshing motion of the liquid in the non-inertial frame. These internal excitations acting on a tank construction can cause a loss of stability of the vehicle. For this reason, the paper analyzes the dynamic loads acting on the walls of the tank and also the variation of the position of the gravity center of the liquid cargo, depending on the filling level of the tank. Such a complicated inertia load of the tank has not been analyzed and described in literature.

The simulations were performed according to the varying fill level, which was respectively 20%, 50% and 80% of a liquid in the whole tank volume. These simulations were carried out for the one-compartment tank.

Another aim of this study was the investigation of the influence of tank division (tank with one, two and three compartments) on the behavior of the liquid. These simulations considered only the half-filled tank which is treated as a dangerous configuration, prohibited by the law regulations in the one-compartment tank case.

The following conclusions can be drawn on the basis of the obtained results:

1. The biggest variation of the gravity center coordinates occurs for the tank filling level equal to 20%. (see Fig. 25).
2. The summary of the changes in forces and moments gathered in Table 1 shows that the maximum value of the force and torque acting on the tank increases with the increase in the filling level of the liquid in the tank. The difference between the minimum and maximum force also increases. We can also note that the ratio of the force component range related to the weight of the liquid cargo is equal to approx. 1/3.

Table 1.
The summary of the force components acting on the tank walls in three cases of liquid's level in the tank

filling level	F_x, kN				F_y, kN				F_z, kN			
	Min	Max	diff.	ratio of F_x to weight [%]	Min	Max	diff.	ratio of F_y to weight [%]	Min	Max	diff.	ratio of F_z to weight [%]
20%	–16	17	33	37	–10	21	31	34.8	–89.8	–87.5	2.3	2.6
50%	–33	41	74	35.6	–20	48	68	32.7	–210	–204	6	2.8
80%	–65	59	124	38	–27	70	97	29.75	–331	–320	11	3.4

filling level	M_x, kNm			M_y, kNm			M_z, kNm		
	Min	Max	diff.	Min	Max	diff.	Min	Max	diff.
20%	–50	25	75	–70	75	145	–6	7	13
50%	–140	60	200	–210	175	385	–18	12	30
80%	–190	80	270	–200	225	425	–11	8.5	19.5

- The spectral analysis of F_x force shows that the largest portion of energy in all studied cases of tank filling occurs at the same frequency of 0.06 Hz. This frequency depends on the time of maneuver. The increasing speed of a car carrying tank will increase this frequency and increase the inertia forces. Obviously, its value decreases as the filling of the tank is reduced. In the 80% filled tank, there appears an additional frequency of approx. 0.34 Hz.
- What can be observed, is the significant effect of the baffles on the liquid's behavior. It strongly influences the liquid's gravity center coordinates during the sloshing. The tank's division into two compartments have decreased the range of the variation of *x*-coordinate more than twice. The higher inclination in XZ plane of the free surface occurs when the tank is non-baffled.
- The summary of forces and moments collected in Table 2 shows that the temporary values of forces are higher for the two-compartment tank than for one-compartment. However, the introduction of the second, additional baffle reduces the force values in comparison with a two-compartment tank, leaving the range of variations still higher than that of the one-compartment tank. Generally, addition of baffles slightly reduces low frequency force components but generates significant high frequency components (see Fig. 27 and Fig. 29). In relation to the moments, such a clear conclusions can not be reached. The values of the moments M_y and M_z decrease when the number of baffles increases. The moment M_x has the biggest variation range for the two-compartment tank. For one-compartment and three-compartment tank, the values of moment M_x are comparable. The ratio of

the force component range to the weight of the liquid cargo has been also considered. The tendency of the increase in the value of this ratio and its subsequent decreasing can be noticed.

Table 2.
The summary of the force components acting on the tank walls for three cases of tank division when the tank is half-filled

no of baffles	F_x, kN			ratio of F_x to weight [%]	F_y, kN			ratio of F_y to weight [%]	F_z, kN			ratio of F_z to weight [%]
	Min	Max	diff.		Min	Max	diff.		Min	Max	diff.	
0	–33	41	74	35.6	–20	48	68	32.7	–210	–204	6	2.9
1	–60	52	112	53.8	–35	72	107	51.4	–235	–187	48	23
2	–55	40	95	45.7	–30	55	85	40.8	–235	–186	47	23

no of baffles	M_x, kNm			M_y, kNm			M_z, kNm		
	Min	Max	diff.	Min	Max	diff.	Min	to	Max
0	–140	60	200	–210	175	385	–18	12	30
1	–220	100	320	–160	145	305	–12	13	25
2	–140	75	215	–100	140	240	–6	7	13

- The spectral analysis of the F_x forces shows that in all cases the peak of the spectrum appears at a frequency equal to 0.06 Hz. Setting the baffle in the middle of the tank length results in the appearance of an additional, higher frequency of approx. 0.41 Hz, along with simultaneous reduction in the spectrum values for the basic frequency. Inserting two baffles into the tank shifts the peak of spectrum value to even higher frequency equal to approx. 0.57 Hz. Addition of baffles slightly reduces low frequency force components but generates significant high frequency components (see Fig. 27 and Fig. 29). One can notice a high frequency component comparable to low frequency one in the case of tank with single baffle (see Fig. 27).

The performed calculations can also lead to conclusions concerning modeling of the liquid in the tank. The viscosity of the fluid has no significant effect on the resulting force. The most important role belongs to the fluid inertia, and consequently to the expression related to the dynamic pressure acting on the walls of the tank by the fluid. It should be also noted that the viscosity of the liquid in the present case has a little impact – the forces associated with fluid viscosity amount to only 0.02% of the total force. In the present case, two turbulence models were used. The SAS model (Scalable Adaptive Simulation) allowed us to obtain results in a shorter computational time (there were no problems with the convergence of the solutions) than that required when using the Spalart-Allmaras model.

Simulation studies have not confirmed the validity of the regulations referring to the allowed liquid's levels in the one-compartment tank. A wider study is then required.

The results show, only to some extent yet, that a two-compartment tank at a certain level of filling may experience worse sloshing dynamics than the one-compartment tank. On the contrary, the further introduction of baffles can possibly improve the vehicle's dynamics. However, the statement that a further increase in the number of baffles improve vehicle dynamics requires confirmation that will require additional simulations.

Generally, it can be claimed that the increase in the number of baffles in the tank results in the oscillations of the forces characterized by higher frequencies. It seems that the increase in the number of tank baffles will cause that the frequencies of the parametric excitation initiated by fluid motion in the vehicle will move away from the low-frequency motions of the maneuvering vehicle.

The behavior of the liquid in the tank, and consequently the results of the simulation, are affected by numerous parameters, such as tank geometry, velocity and vehicle's trajectory, as well as the type and number of baffles. It is advisable to develop studies on different configurations of these parameters and settings of numerical solution.

The results show that the numerical analysis performed with the use of VOF (Volume of Fluid) technique in the Fluent programme allows one for a more accurate modelling of the fluid's behaviour than the calculations based on the quasi-static, or mechanical analogy methods. Fluent programme solution captures the non-linear phenomena, such as separation of the liquid's portion from the free surface, or non-planar, chaotic motion.

It is worth remembering, however, that the movement of the vehicle on the road is accompanied by the excitations having their origin in the road irregularities or aerodynamic forces. Therefore, this is a convoluted problem, leading to a set of coupled equastion, and the solution to it is not an easy task. There is no commercial code, which could solve coupled equations of motion of vehicles dynamics and the equations of motion of the liquid. Hence, the phenomenon of sloshing is very difficult to deal with and requires a lot of work due to the lack of available tools. The most interesting issue, according to the authors, would be coupling of the vehicle's dynamics equations of motion with the equations of liquid's motion and investigating their mutual impact on the entire system. The last, but not the least question that arises from this problem is whether the active or semi-active suspension would help to reduce the sloshing phenomenon.

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Analiza numeryczna zachowania się cieczy wewnątrz częściowo wypełnionego zbiornika poruszającego się ruchem nieustalonym

Streszczenie

Artykuł opisuje zachowanie się cieczy wewnątrz zbiornika, który porusza się ze stałą prędkością wzdłuż toru składającego się z trzech łuków. Na zachowanie zbiornika cysterny mają wpływ siły zależne od czasu związane z nieustalonym ruchem cieczy w układzie nieinercjalnym. Wewnętrzne wymuszenia działające na konstrukcję zbiornika mogą spowodować utratę stabilności pojazdu. Z tego powodu w artykule przeanalizowano obciążenia dynamiczne działające na ściany zbiornika pojazdu cysterny, a także zmianę położenia środka ciężkości przewożonej cieczy, w zależności od stopnia napełnienia zbiornika.

Symulacje zostały przeprowadzone dla różnych stopni napełnienia przewożonym ładunkiem, tj. 20%, 50% i 80% cieczy w całkowitej objętości zbiornika. Dla tych stopni napełnienia rozpatrywano zbiornik jednokomorowy. Kolejnym celem badań było sprawdzenie wpływu podziału zbiornika (na jedną, dwie i trzy komory) na zachowanie się cieczy wewnątrz zbiornika. W tym przypadku rozważano zbiornik wypełniony cieczą w połowie, co uważane jest jako niebezpieczny stopień napełnienia zabroniony według regulacji prawnych dotyczących przewozu materiałów w cysternach ze zbiornikiem jednokomorowym. Wyniki symulacji zostały przedstawione w postaci kształtów powierzchni swobodnej, przebiegu sił i ich momentów działających na ściany zbiornika a także analizy częstotliwościowej tych sygnałów. Wyniki zostały przeanalizowane i na ich podstawie wyciągnięto wnioski, które dają podstawę do dalszych badań w tym temacie i dyskusji nad możliwymi zmianami w regulacjach prawnych dotyczących przewozu cieczy w cysternach.