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RECENT RESEARCH OF DYNAMICS AND STRENGTH OF TANK VEHICLES

The studies on dynamics and strength of road tankers and tank wagons conducted in the world in the recent ten years were reviewed. The most interesting results of these works are presented. The prospects of development studies which main objective is to ensure the safety of transportation of liquid cargo were the issue under consideration.

Keywords: *road tanker, tank wagon, computer modelling, liquid oscillations, equivalent models, baffles*

1. Introduction. Transportation of liquids, particularly, of drinking water, milk, wine, has been carried out since ancient times. For this purpose, in the past people used barrels, which were installed vertically or horizontally on horse-drawn vehicles. Industrial development and production specialization led to the need of transportation of fluids for long distances. In this respect, in 1865 the first tank wagons were built in the USA. At the beginning of the XX century special vehicles for the transportation of liquids were developed by Ford, GMC, Garford, etc. Now different types of road tankers and tank wagons are used to transport liquid cargos [1, 2]. For example, in agricultural industry more than 20 types of tank trucks, differed by type of cargo, are used [3].

Dangerous goods make up the bulk of tank vehicles transportation. The analysis of the work [4] demonstrated that the level of threat to people and environment increases by 12 times at transportation of dangerous goods compared with the means of transport for the carriage of solid cargoes. In this connection there was a necessity of researches aimed to improve the safety of tank vehicles, and this issue is relevant today.

Tank vehicles can be considered as mechanical systems, including solids and fluids. A peculiarity of such systems is the interconnection of phenomena that determine the dynamics of constructions and their strain-stress state. On the one hand, the dynamics of tank vehicle determines its loading, and on the other hand, as it will be seen further, the deformation of the body can affect tank vehicle oscillations while driving on the road or rails.

A significant number of review materials on analysis of the dynamics and strength of these vehicles are contained in monographs [5–7]. In the present work the results of studies on dynamics and durability of road tankers and tank wagons, conducted after the publication of these books, are discussed.

2. Research of dynamics and strength of tank wagons. Most of the works devoted to the analysis of the dynamics of tank wagons are based on the representation of liquid in the form of an equivalent solid, which is connected with the body by a spring and moves along a longitudinal or lateral axis of the wagon.

A great amount of studies on the dynamics of trains with tanks using such model was made in Dnepropetrovsk (Ukraine). Their main results were summarized in the monograph written by G.I. Bogomaz [5]. In the recent years a number of new challenges for the movement of trains with tanks was solved by his colleagues.

Thus, in the work [8] the calculations of the movement of multi-set trains consisting of tank vehicles and open wagons were made. It is shown that longitudinal forces in the train set consisting of fully loaded tank vehicles are slightly low than in the case of open wagons, which is more favorable for the resistance of a car to lift. As a result of the analysis of inhomogeneous freight train movements it was found that in order to improve the transportation safety of environmentally dangerous goods tractive connection of tank wagons with reservoirs underfill should be positioned in the first half of the train set [9]. An algorithm for constructing of an equivalent model for the case of the spatial movement of the center of mass of the fluid is developed [10].

In the paper [11] it was found that traffic safety of tractive connection of tank wagons on a straightway essentially depends on the level of filling of the tank with liquid cargo. For tractive connections formed from wagons with different loading, dynamic performance of tractive connection is determined by the presence of tank wagons with large underfilling in it, regardless of their place in the tractive connection. Thus, when incomplete filling of the liquid cargo is about 1 m, the permissible velocity can not exceed 65 km/h.

Studies on trains with tank vehicles were also made by other scientists. So, in [12] the lateral dynamic responses of the multibody model of a freight car with partially filled liquid load and an equivalent rigid cargo are evaluated to study the effect of cargo movement on the critical velocity and the wheelset hunting oscillations frequency. Liquid cargo movement within partly-filled tank car could thus yield a beneficial influence on the wheelset hunting. This was evidenced from the phase relationship between the lateral oscillations of the pendulum and the bogie/wheelset. Partially filled tanker resulted in relatively higher critical hunting velocity compared to that of the wagon with equivalent rigid cargo.

In the paper [13] mathematical model is defined for the entire freight car, including the bogies with primary suspensions, the tank and a discrete number of equivalent models positioned at different places along the longitudinal axis of the tank. This model is used to simulate the dynamics of the tank for a variety of curve geometries, train velocity and fill levels. Results show that sloshing can increase significantly the risk of tank rollover whereas its influence on the risk of derailment is minor.

Dynamic analysis of a partially filled tanker train travelling on a curved track is studied in the paper [14]. For three classes of tracks, rail irregularities are randomly generated by using Monte Carlo simulation. An equivalent dynamic system is used to model the sloshing motion of the fluid. Two derailment indexes, i. e., derailment quotient and unloading ratio, are obtained numerically as safety indicators. A parametric study is carried out to investigate how different parameters such as the operational velocity, fluid modelling, rail irregularities, and fluid density may affect the derailment potential. It is found that ignoring the sloshing may lead to 18 % and 25 % error in the calculation of derailment quotient and unloading ratio, respectively. It is also found that lowering the centre of gravity and consequently reduction of the moment arms is more dominant than the oscillating forces due to sloshing motion.

In the paper [15] a two-degree-of-freedom model representing the sprung mass and the sloshing cargo in a vehicle is used to simulate the dynamic wheel forces on the rails as a result of lateral perturbations derived from turnings along the railway path and the resultant cargo sloshing. The results of the calculations showed that the fluid oscillation on the track section with rapid change in radius of curvature may increase the lateral strength by 20 % and more compared with the solid cargo. It is also found that the damage increases with the square of the velocity, and that sloshing damping can reduce the rail damage to one-half when the traveling velocity is 70 km/h.

In the work [16] the dynamic model of Y25 tank wagon bogie is created in ADAMS/RAIL engineering software. The mass-spring system is used for the modeling of the longitudinal sloshing of the liquid in the tank. The calculated forces and track irregularities applied to a model of the frame in ANSYS LS-DYNA Finite Element Method engineering software. The study of the stress history of the bogie indicated two types of fluctuations. Irregularities of the track cause stresses with smaller amplitudes at higher frequencies. The liquid sloshing causes stresses of higher amplitudes and smaller frequencies. The stress at the 50 % filling ratio, rather than others, is highly sensitive to track irregularities. This can be attributed to the larger free surface that becomes available for this case.

In the work [17] sloshing coefficient as prominent parameter in tank wagons designing has been investigated. For purpose of derivation of this coefficient, Arbitrary Lagrange–Euler method was applied and results were compared with equivalent mechanical method. So, to simulate fluid sloshing inside the tank two different approaches, finite element method and multibody dynamics were exploited. In lateral and longitudinal simulations, tanker is analyzed in traveling curved track and accelerating respectively. Also, the effects of velocity, irregularities of track and fill ratio on sloshing coefficient were studied.

Alongside with investigation of motion on rails considerable attention is paid to calculations of cars mutual collision. So, in the work [18] dynamic model of wagon and the tank containing fluid has been studied as a 3 degree of freedom vibrational system which is in first vibrational mode. Effect of tank fluid sloshing on the amount of energy absorption in collision was assessed by simulating in the LS-DYNA software. Analysis of the results revealed that the fluid height has a negative effect on energy absorption, so that this amount for a semi full fluid tank is 18 and 36 % more than for the tank filled with 75 and 99 % fluid, respectively.

Authors of the paper [19] have built a railway tank car model with a scale ratio of 1:5. The longitudinal impact and vibration characteristics of this model with different filling ratios of tanker were studied based on the method of random decrement technique and Morlet transformation. Morlet wavelet transformation was applied to analyze free longitudinal responses of the railway tank car model while these free longitudinal vibration signals were obtained with the random decrement technique, thus the system's longitudinal resonance frequencies and damping ratios were identified.

To analyze the longitudinal oscillations of the tank car in a program «Universal mechanism» [20] the three-dimensional solid-state dynamic model of the tank car 15-1443 was developed in Belarusian State University of Transport (BelSUT). Liquid sloshing was modelled by the rigid mass moving on same curve path of fluid body centre of mass (figure 1). Resistance force was also considered in model. It was determined that the movability of a fluid in a copper makes essential impact on vertical displacement of a head of the automatic coupler equipment (figure 2). The gained effect can become principal at formation of uncoupling of coaches that is inadmissible at operation.

Paper [21] present the results of original investigations tackling special features of car bodies' interaction with security arrangements fixing them relative

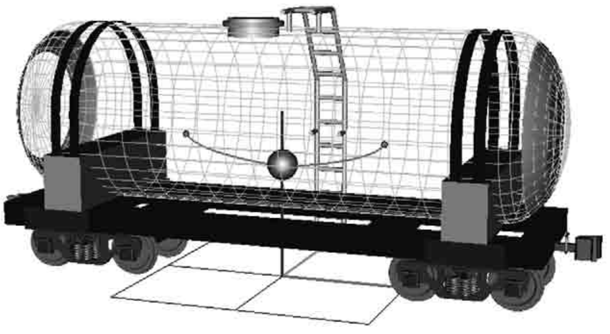


Figure 1 — Model of the partially filled tank car 15-1443 with equivalent solid body [20]

to the railway ferry-boat decks. There were examined most essential freight car vibration motion patterns under the sea disturbance conditions affecting its stability as relative to the ferry-boat deck. There were carried out supporting members' strain-stress state calculations of car bodies transported by railway ferry-boats under sea disturbance conditions.

The development of computer engineering and software solutions to meet the challenges for fluid dynamics has led to emergence of new works, in which fluid is considered to be a continuous medium. So, in the work [22] to study the fluid motion–vehicle dynamics interaction, a model of four, liquid filled two-axle container freight wagons was set up. The railway vehicle has been modelled as a multibody system (MBS). To include fluid sloshing, an equivalent mechanical model has been developed and incorporated. The influence of several factors has been studied in computer simulations, such as track defects, curve negotiation, train velocity, wheel wear, liquid and solid wagonload, and container baffles. SIMPACK has been used for MBS analysis, and ANSYS for liquid sloshing modelling and equivalent mechanical systems validation. Simulation results showed that, for certain combinations of type of liquid, filling level and container dimensions, the liquid cargo could provoke an undesirable, although not hazardous, release of the unused coupling screw from its hanger. The coupling screw's release was especially obtained when a period of acceleration was followed by an abrupt braking manoeuvre at 1 m/s^2. It was shown that a resonance effect between the liquid's oscillation and the coupling screw's rotary motion could be the reason for the coupling screw's undesired release.

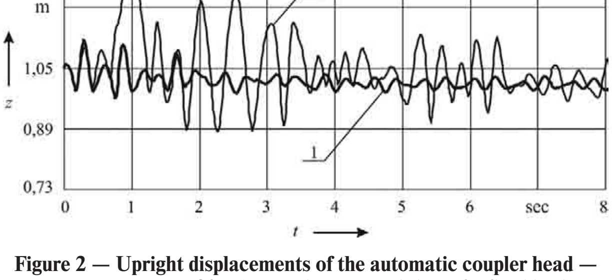


Figure 2 — Upright displacements of the automatic coupler head — time dependences [20]: 1 — without movability of a fluid body; 2 — taking into account movability of a fluid body

In the work [23] the tank car finite element model is integrated with a three-dimensional railroad vehicle using computational non-linear MBS framework where the wheel/rail interaction is formulated using a three-dimensional elastic contact formulation that allows for the wheel/rail separation. The effect of the coupling between different modes of displacements is demonstrated by comparing the results of the simulations of the flexible and rigid tank car models. The effect of the flexibility and plate thickness of the tank car on the vehicle critical velocity and dynamic characteristics are examined. The analysis presented in this paper shows that there is a strong dynamic coupling of different oscillations modes of the tank car wheel wear with the plate thickness and the wheel–rail contact parameters.

In the paper [24] lateral and longitudinal surface movements of liquid are modeled and simulated. In the proposed methodology, part of the liquid is isolated in a tube in order to provide the essential inertia in passive and active vibration absorbers. The performance of different vibration-absorbing systems including the tuned mass damper, delayed resonator and nonlinear energy sink are evaluated in a variety of loading situations. Dynamic stability is measured in terms of Nadal's criterion and the unloading quotient is determined as an auxiliary index and compared with limiting criteria. It is found that an appropriately designed and installed control system can passively absorb and locally dissipate a major portion of the kinetic energy of the car body, up to an optimal value of 65 %.

In BelSUT the finite elements models of the tank body shell and internal volume with liquid cargo were created for the railway car model 15-1443 [25]. These two models were created in parallel: the car body model in package ANSYS Workbench and volume with liquid in package CFX. The algorithm of the problem solution includes several steps. On the first step the strength calculation at hydrostatic pressure on the internal tank surface is performed. Then the obtained results for deformation $\{u\}$ are transmitted to CFX module for hydrodynamics problem solving. The results for liquid pressures $\{p\}$ on the interacting surface are transmitted to the strength module where the calculation of the forces system matching to a new liquid location is performed. Further the information about structural deformation is transmitted to the hydrodynamics computation module and the computational cycle and information interchange repeats until the final time is achieved (figure 3).

As a result of computations two groups of results were formed: the stress-strain condition for the car body shell and hydrodynamic characteristics of the transported liquid. Figure 4 shows liquid position in the reservoir after 0.3 sec from the beginning of an impact considering normative liquid filling level (90 %). It was established that the maximal liquid pressures are achieved in different moments of time for various filling levels of the reservoir. The obtained results showed that

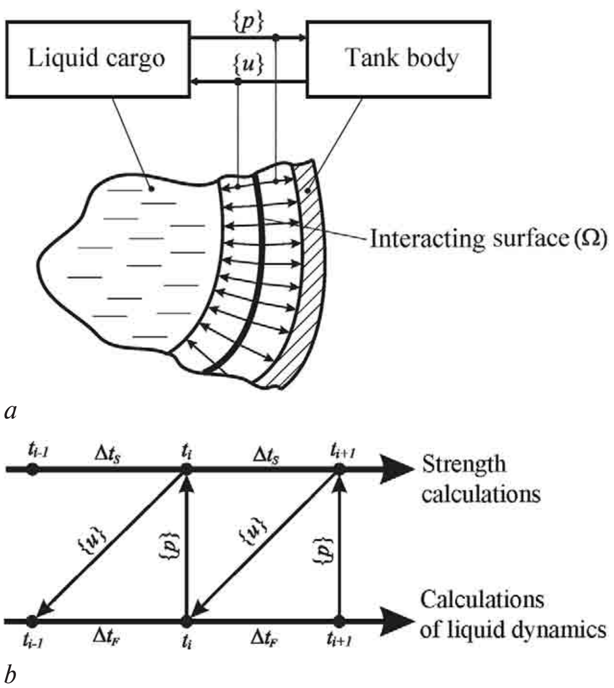


Figure 3 — Schemes of liquid-tank body interaction (*a*) and of solution process (*b*) [25]

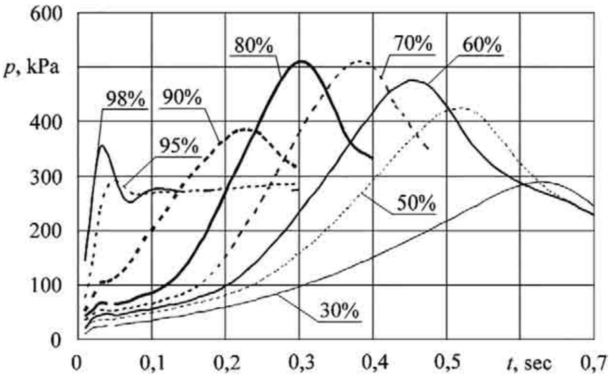


Figure 5 — The dependence of liquid cargo pressure in the control areas on time [25]

when the tank is filled by 70–80 % the greatest values of liquid pressures on the bottom of the reservoir are observed (figure 5). At the initial time liquid pressures are 55 % different in the case of solid reservoir in comparison with the values obtained by taking into account the tank body deformation. At the same time in the manhole area there is a significant dis-tinction in the discrepancy between the results.

Also it is necessary to pay attention to the number of works devoted to the analysis of strength of constructions of tank wagons, where the fluid impact on reservoir is considered to be known in advance.

In the paper [26] a dynamic nonlinear finite element analysis, carried out with ABAQUS is used to simulate a moving striker colliding against a stationary hazmat tank car. The results of the simulations show the ability of the damage delocalization technique to signiicant reduce of the pathological mesh dependency issues while predicting satisfactory hazmat tank car impact failure. Also it is noticed that nonlocal damage effects are coupled with temperature history effects (adiabatic effects).

In the work [27] on the base of the finite element approach with regard to elastic-plastic material behavior and large deformations a strike on the side of an adjacent car at reservoir tank vehicle filled with liquid is simulated. The impact on the stress-strain state of the shell thickness and indenter geometry is studied. Similar studies were carried out in [28].

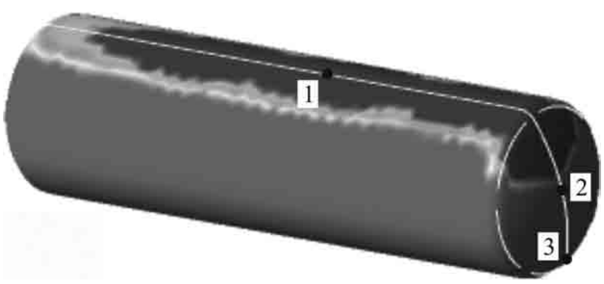


Figure 4 — The position of liquid in the reservoir for t = 0,3 sec after an impact [25]

A number of articles are devoted to the development of new designs of tank vehicles with extended capacity. In the work [29] a new design of two-piece eight-axial tank wagon is proposed. Its features are the presence of two boilers with cone-shaped inserts and backlash-free hitch mechanism. Such technical solution has allowed to increase the capacity of tank vehicle with maintaining steps between the drain and the loading devices in a train set. Furthermore, the reduction of reservoir length has led to lower dynamic loads on the boiler and it allowed to reduce the overall weight of the car.

In the paper [30] a design of four-axial tank vehicle for the sulfuric acid transportation is proposed. The improvement of capacity is also achieved by the use of a boiler with a cone-shaped inserts.

The purpose of the investigation [31] was to estimate such value of a tank head depth wherein the maximum capacity of vehicle is provided and a tank vessel durability meets the requirements. The problem solution was carried out with using the finite element analysis program NASTRAN. The rational tank head depth was received from the tank vessel durability condition. This allowed to increase the tank vessel volume.

A number of investigations are devoted to the design improvement of the restraint elements between different vehicles reservoir and the car frame [32–35]. Furthermore, the researches related to the evaluation of the stress-strain state of tank vehicles bodies to take a decision on the rejection of the wagon or the extension of its use with possible upgrading were conducted [36–38].

3. The works on analysis of dynamics and strength of road tankers. The assessment of the static and dynamic properties of a tank vehicle is crucial and it is related to the three motions: longitudinal (driving and braking), lateral (guidance and steering), and vertical (suspension and damping). In the literature on dynamics of vehicles it was pointed out that liquid cargo motion can have both beneficial and negative aspects in terms of driving stability and braking performance but safest maneuver is braking. Thus the studying of tank vehicles dynamics should be started from their motion on curves.

The most widely used model in the analysis of road tankers lateral dynamics is the quasi-dynamic model of liquid. This model supposed that liquid free surface is flat. Here are some examples of the application of this model.

In the work [39] in order to prevent both yaw instability and jackknifing, an active steering control system is designed on the basis of a simplified three-degree-of-freedom dynamic model of an articulated vehicle carrying a liquid. In the introduced system, the yaw rate of the tractor, the lateral velocity of the tractor and the articulation angle are considered as the three state variables which are targeted in order to track their desired values. The simulation results show that the proposed roll control system which combines backstepping and the sliding-mode control method is more successful in achieving target control and reducing the lateral load transfer ratio than is classical sliding-mode control. A more detailed investigation confirms that the designed active steering system improves both the lateral stability of the vehicle and its handling, in particular during a severe lane-change manoeuvre in which considerable instability occurs.

In the paper [40] a novel tank cross section optimization design algorithm is proposed for enhancing roll stability of fuel tank shape considering the multi-objective genetic algorithm, sum of weighted cost function and Pareto solution. Two conflicting objective functions, fluid c.g. height and overturning moment, are well thought out in the present optimization processing. The optimized results of Pareto solution are compared with sum of weighted cost functions to explore the best method for fuel tank design. The comparison indicates that both solutions are in a good agreement although the Pareto solution indicates a faster convergence. Comparing the genetic algorithm results with conventional method, demonstrates that the optimized tank shape reveals more roll stability while its rollover threshold is approximately 6 % higher than conventional tanks. It should be noted that the resulting cross-section is very close to the Reuleaux triangle.

In the work [41] a simulation platform is developed for analysis of directional dynamics of partly filled tank vehicle combinations by integrating a steady-state fluid slosh model of the partly filled tank to TruckSim software. A modified Reuleux-triangle tank cross-section with a curved bottom is further proposed to achieve reduction in mass centre height and to adapt to current designs of saddle mounts. The roll performances, evaluated in terms of steady rollover threshold, lateral load transfer and peak directional responses, are further compared with those of currently used tank cross-sections. The comparisons suggested that the modified Reuleux-triangle tank can yield improve roll performance.

In the paper [42] the application of General Regression Neural Network generalized neural network to transport tanks safety prediction is studied. The rollover simulation data by dynamics analysis software ADAMS was used to verify the validity of neural network method. The results show that the maximum relative error of the predicted output is 5 % with a higher accuracy.

In the works [43—46] quasi-dynamic model of liquid is used for theoretical analysis of stability of the partially filled road tanks under different conditions. In paper [47] an experimental methodology is proposed to measure the rollover tendency of road tankers when subjected to lateral perturbations derived from steering manoeuvers. The use of this methodology to analyze the effect of fill level, initial acceleration and tank shape on the rollover tendency of a sprung tank suggests that for high fill levels an oval tank is up to three times more prone to rollover than the circular tank.

Mathematical models based on different approaches, as quasi static modelling of the cargo and equivalent rigid cargo have been compared experimentally in work [48]. In double lane change, dynamical model is the one which estimates the peak value of the side force with minimum error, while quasi static and rigid model give an underestimation. Situation is different for the roll moment: the estimations given by dynamical and quasi static model are good both, but as the former overestimates the peak value, the latter under estimates it; rigid model fails in general. In the round about no meaningful difference can be seen between the three models in the estimation of the forces. Limitations of each model depend on the maneuver type.

A novel idea of an elliptical trammel pendulum for elliptical tank geometries is proposed in [49]. The bases of selecting the parameters of this pendulum such as pendulum mass, length of arms, and location of fixed mass are derived and verified using a finite element approach. Further some applications of this model are described.

In the work [50] the oscillation movement of the trammel pendulum in the tank was described under the tank-fixed coordinate system and its motion equation under the noninertia coordinate system was derived using a Lagrangian function. Tank truck dynamic model was established using Newton's first law and the angular momentum. The study on tankers driving stability was performed.

In the study [51] a compact roll dynamics model for a partly filled tank truck is formulated based on Lagrange's approach. The nonlinear stiffness property of the suspension is also taken into account. The analysis results reveal that the lateral fluid sloshing in a partly filled tank generally couples with the body roll dynamics of the vehicle, and the rollover stability threshold can be enhanced by increasing the vehicle suspension stiffness.

In the paper [52] a new anti-rollover system for tanker trucks that directly acts on the lateral distribution of the transported liquid cargo has been proposed. The system consists of a main tank and two smaller lateral tanks, which can change their fill levels thanks to the employment of a set of electropumps suitable for flammable liquids pumping. Liquid transfer from one lateral tank to the other is controlle d by a set of feedback regulators. Several simulations have been performed and examined. Thanks to the simultaneous action of active and passive stabilising contributions, the system provides significant improvements in terms of lateral load transfer while cornering. In all performed simulations, active tanker trucks' lateral stability was better than those obtained by standard tanker trucks.

A more complicated model of fluid motion is studied in the work [53]. The transient fluid slosh in a horizontal cylindrical tank is analytically modeled considering simultaneous lateral, vertical and roll excitations and assuming potential flows and a linearized free surface boundary condition. For this purpose, the fluid domain in the Cartesian coordinate system is transformed to the bipolar coordinates, where the Laplace equation could be solved using separation of variables. The resulting hydrodynamic pressure, free surface elevation and slosh force and roll moment are formulated in the tank-fixed coordinate system. The transient fluid slosh model is subsequently integrated to a dynamic roll plane model of a tank vehicle combination to investigate the effect of transient liquid slosh on the roll stability of the vehicle during steady-turning as well as path-change maneuvers. The results suggest that the roll stability of tank vehicles can be efficiently analyzed using the coupled linear slosh and multibody vehicle models with significantly lower computational effort than the methods employing computational fluid dynamic fluid slosh models.

A similar model is used in the work [54]. A computationally efficient transient fluid slosh model is integrated with a multibody dynamics model of a B-train car with 78 degrees of freedom. The effects of transient slosh responses on directional performances of a tanker-train combination are also evaluated under different steering maneuvers and filling conditions. The results showed that transportation of a high density fluid yielded a more critical condition compared to a low density one, when the same axle load was retained. The liquid cargo movements and its resultant forces significantly reduced the yaw stability of the vehicle. Moreover, the critical behavior of the tank vehicle in terms of the rollover at lower velocity was observed compared to the rigid cargo vehicle.

The most complicated model of liquid is a continuum medium model. It is also used in calculations of road tankers dynamics. Thus, in the works [55, 56] a complete dynamic model of a tractor semi-trailer vehicle is modeled and coupled to a 3D full scale tank's fluid dynamics to study the dynamic behaviors of the vehicle subject to liquid slosh loads during steady and transient steering inputs. 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. The coupled tank–vehicle model is subsequently analyzed to determine the roll stability characteristics for different conditions and maneuvers. The results show that the roll angles highly affected by fluid movement but the yaw rate changes would be small. Roll stability of vehicle is also affected by fluid movement inside the tank, describing by dynamic load factor and load transfer ratio. Also the results showed the fluid sloshing model interaction with the vehicle dynamic increases probability of roll over occurrence. Such probability is higher in the lane change maneuver (transient steer); especially in the second half of lane-change maneuver. This means that in a lane-change maneuver, roll over occurs in the time that the driver doesn't expect.

In conclusion there should be noted two experimental results which are of great practical importance. Thus in the paper [57] it is found that while the firetruck is being driven around town the statistical distribution of the angular acceleration is a subject to a normal distribution, the standard deviation is 0.82 sec^{-2}, and the expectation is 0.21 sec^{-2}.

In the study [58] liquid sloshing in cubical and cylindrical containers with similar characteristic length were investigated. The containers with liquid inside were excited sinusoidally by using an electrodynamics shaker while the free liquid surface level change was captured by using high speed camera. Results show that cylindrical containers produce less liquid sloshing and thus more suitable to be used for liquid transportation.

Road tankers lateral dynamics is also important from the point of view of traffic safety. In the work [59] the straight-line braking performance characteristics of a partly filled tank truck with and without transverse baffles are investigated in the presence of transient fluid slosh within the tank. The dynamic interactions of the floating cargo with the vehicle are evaluated by integrating a dynamic fluid slosh model of the partly filled tank with and without transverse baffles with the seven-degrees-of-freedom pitch plane model of a tridem truck. The dynamic fluid slosh within the tank containing equally spaced four curved single-orifice baffles with flow equalizer is modelled using three-dimensional Navier–Stokes equations coupled with the volume-of-fluid equation and analysed using the FLUENT software. The coupled tank–vehicle model is subsequently analysed to determine the straight-line braking properties for different fill volumes, magnitudes of braking treadle pressure, and road surface adhesion coefficients, while the cargo load is considered to be constant. The braking performance is highly dependent upon the fill volume, presence of baffles, and severity of braking input. For a clean-bore tank truck, the stopping distance increases monotonically with decreasing fill volume, while the addition of transverse baffles in general results in considerably shorter stopping distance. The baffled tank truck, however, reveals a relatively shorter stopping distance under an intermediate fill condition, compared with the lower and higher fill volumes.

In the papers [60, 61] the calculations of braking action of partially filled tank vehicles moving on bridges are performed. Calculation results have shown that in the case of tank truck braking the dynamic loads on span increase.

In the work [62] the mathematical model of concrete mixer truck motion is created. The truck was filled with semi-fluid concrete mixture. The vibrations of mixture are designed by a pendulum. Moving-off and rectilineal motion of truck is considered taking into account engine characteristics and road type.

We have also obtained interesting results in the study of the dynamics of lateral road tankers. The paper [63] demonstrates calculation results for the braking process of road tank. These calculations are based on the analysis of a simplified model of a tank with liquid cargo, as a system with two degrees of freedom and unaccounted wheels weight. In this work the interaction force F_{ed} between the liquid cargo and the wall is represented as a sum of the elastic and dissipative component of the interaction force:

$$F_{ed} = cs + \alpha\dot{s}.$$

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

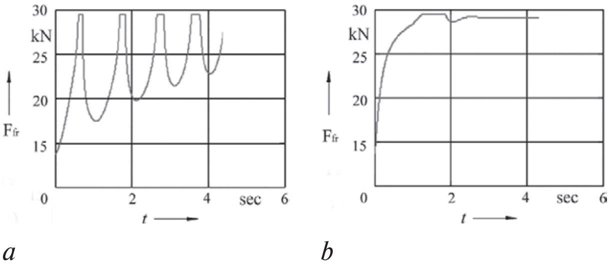
$$c = c_0 \text{ if } s \le s_0; \; c = c_0 e^{\frac{s-s_0}{3(s_{\max}-s)}} \text{ if } s > s_0, \qquad (1)$$

where c_0 — value of coefficient c for the case of liquid small oscillations [64], N/m; s_0 — coordinate s, when liquid reaches the cell, m; $s_{\max}$ — coordinate s, for the case when all liquid cargo is located near one of the sides of the tank body and its free surface is vertical, m; α — coefficient, allowing to take into consideration liquid oscillations damping in the road reservoir, kg/s.

The dot over the variable denotes the derivative calculated by time.

Formulae (1) is obtained by the approximation of the calculation results of liquid cargo oscillations in road tanks [65] and showed good agreement with experiment [66].

Calculations showed that for small values of α (this fact corresponds to tank without baffles), there is an alternation of friction with and without sliding (figure 6 *a*). This can lead to the car overturning and losses of controlability (such effect periodically takes place in the situation when the car moves along slippy road, this case is also observed while simulation in MSC ADAMS [67]). When the coefficient α increases there is a smooth change of friction forces (figure 6 *b*). The increase of α can be achieved by setting the internal baffles.



a *b*

Figure 6 — The dependence of the friction force between the front axle wheels and the road on time for: *a* — α = 2000 kg/sec; *b* — α = 20 000 kg/sec [61]

The aim of the work [68] was to determine the features of the friction forces changes between the wheels and the road for the case of tank braking using on a more complex model and taking into account tank body oscillations on the springs and inertia of wheels. Performed analysis showed that complication of the model describing oscillations of a tank partially filled with liquid doesn't lead to significant changes in the results of motion kinematic parameters and forces in the road–wheel contacts.

Thus, the performed analysis confirms that there is a need of transverse baffles installation to ensure tank controllability at emergency braking. These partitions allow to damp liquid cargo oscillations quickly or to ensure the best possible liquid cargo energy dissipation. For the cases when it is impossible to install perforated baffles in the existing road tank constructions it is recommended for drivers to use partial (smooth) braking to reduce the oscillations amplitudes of liquid cargo in the partially filled reservoir. This will allow to avoid the motion of wheels with slipping.

To finish the preview of investigations on the road tanks dynamics there should be mentioned three papers. They demonstrate models allowing to realize the detailed 3D-modeling of a vehicle carring liquid cargo.

In the work [69] authors propose a new method for the dynamic simulation of tank trucks carrying fluids and silo vehicles carrying granulates. The method couples Lagrangian particle methods, such as smoothed particle hydrodynamics for fluids or the discrete element method for granular media, and multibody systems using co-simulations. A co-simulation approach is realized coupling a multibody system simulation using SIMPACK for the vehicle with a particle-based fluid simulation using the software PASIMODO for the cargo [70]. Comparisons between different tank designs show the significant influence of the cargo movement and the tank design on the driving characteristics of the vehicle. A positive effect of subdivisions in the tank in longitudinal directions in terms of braking stability can be seen, as they reduce the sloshing motion in that direction.

In the paper [71], a methodology for evaluating the interaction between fluid sloshing and vehicle dynamics is proposed. The fluid and the tank are modelled 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. The motion of the tank is determined based on the response of a 14 degrees of freedom vehicle model subjected to the forces due to the fluid sloshing. Straight line braking manoeuvres and lane change manoeuvres have been carried out to evaluate the effects of fill level, baffles and tank shape.

In the work [72] a time-accurate finite element model for predicting the coupled dynamic response of tanker trucks and their liquid payloads is presented along with an experimental validation of the model. The tanker truck components are modeled using rigid bodies, flexible bodies, joints and actuators. The model is validated using a full-scale army heavy class tactical trailer carrying a water tank. The trailer is placed on an *n*-post motion base simulator which was used to perform harmonic/ramp pitch, roll and stir excitations of the trailer in order to simulate typical road maneuvers. Experiments were carried out with an empty tank and a 65%-filled tank. The experiment's measurements are compared with the results predicted using the computational model. The comparison shows that the model can predict with reasonably good accuracy the test tanker-trailer's dynamic response.

Unfortunately, a disadvantage of the recent works is the long duration of the calculations which complicates their active practical application.

Most of works related to the analysis of the structural strength of road tankers considers the possibilities of optimizing the design in accordance with existing regulations.

In the study [73] the structural integrity of a wedge-shaped tank vehicle with a cyclical cross-section and three compartments designed to have maximum payload, has been investigated using the software ANSYS. Different finite element models of the tank vehicle have been set up to investigate the influence of the diameters of the front and the rear shell end, the angle of the wedge shaped compartment and the overall length, in the structural integrity of the tank vehicle. The outcomes of this study provide, among others, the structural integrity of such a tank vehicle with marginal geometrical values, offering a useful insight for tank manufacturers.

Static structural analysis of the water tank as part of the truck body was performed in the work [74]. The finite analysis was performed by commercial computer program. The pressure is applied as nonuniform loading (i.e. hydrostatic pressure) with minimal value on the top and maximal value in the bottom. Displacements and stresses were very high in basic design so seven modified structures were proposed in order to find the best one.

In the work [75] a systematic design approach applied to road tankers for transportation of dangerous goods is developed. The method ensures payload maximization, a sensible load distribution among axle bogies, and furthermore, provides an estimation of the road tanker's handling and rollover characteristics from an early design stage.

A method for automating the construction of FEM models hull road tanker with ability to change its geometrical characteristics is suggested in the article [76].

The results of studies [77] showed that the strength characteristics of tank vehicles made of aluminum-magnesium alloy are more preferable from the standpoint of the optimal design. Low tank weight and, as a consequence, the ability to carry a larger volume of cargo for one way allow to get a significantly greater economic benefit than the difference in price between the steel and the aluminum tank during tank vehicle's lifecycle.

A general approach to strength checking of elements which fasten flying vehicle fueler's tank to automobile chassis on which the tank is mounted is described in [78]. The approach is based on the experience of designing and exploitation of fuelers of such purpose. The article is timely because neither state nor branch normative documents concerning the stress analysis of fuelers bearing elements have been developed yet.

The peculiarities of design of reservoirs' restraint elements design of various tank vehicles to the frame are studied in the works [79, 80].

In the papers [81, 82] by the method of finite elements in ABAQUS/CAE system a model of an emergency situation was developed. This situation is possible at the contact of road tanker with moving transport. It is proved that in a road traffic incident with a road tanker, a clashing in the back head with the maximum permitted urban velocity of 60 km/h leads to breaking strains with the depressurization of the tank vehicle. Analysis of the results showed that when a tanker vehicle is on impact with a tractor moving at a velocity higher than 15 km/h, the stresses values exceed the limits of the strength of the reservoir material.

The analysis carried out in the work [83] has showed that the calculations of quasi-static load, regulated by GOST 50913-96, do not allow to provide the operational reliability of a predetermined period of operation of the tank vehicle. Dynamic calculations provide to reveal the stress concentration zone using FEM. To perform these calculations "ISPA" Russian software package was chosen by the author. Then, fatigue life prediction was calculated.

The same issue was studied in the works [84, 85]. The mathematical model random impacts vector with lag time effect on axis of vehicle was considered. Finite-element model of the boiler semi-trailer tanker was developed. The next step was obtained probabilistic behaviors of the system, such as spectral density and standard deviation of stresses, the influence of the lag effect of external forces using the methods of statistical dynamics. In paper has been determined that the distribution of the standard deviation. The largest amplitude was in the middle of the tank. When analyzing the standard deviation at stresses determined that there are dangerous zone near the supports and hatches. The approach to assessing the reliability of construction was offered by criteria for the accumulation of fatigue.

The paper [86] compares the stress and displacement distributions of different head-shell junction configurations in LPG road tankers during vehicle maneuvers, such as braking, cornering, and vertical bumps. Various combinations of heads (e. g., spherical and toroidal) and shell cross sections (circular and elliptical) are considered. The ABAQUS finite element software is used to model and analyze the fluid-filled tankers. The results show that the most critical maneuver affecting the fluid-filled tankers is cornering and the safest maneuver is braking. Moreover, the results reveal that the outer surface of the tanker generally behaves the most critically in all maneuvers, and cylindrical tankers with smaller cross-sections behave more acceptably compared to those with larger cross-sections. Among fluid-filled vehicle tankers with identical platform areas, tankers with elliptical cross-sections behave the most acceptably.

4. Conclusions. Certainly the described above materials do not contain all the conducting research of tank vehicles. Thus, in the review the issues related to updating of baffles constructions in tank vehicles reservoirs have not been almost touched upon. Here we'll mention some of our works devoted to the titled subject. The review [87] describes a significant number of modern constructive designs for decreasing amplitudes of liquid cargo oscillations. In the work [88] we have proposed the method allowing to estimate the efficiency of the liquid cargo damping on the base of calculatons of liquid energy dissipation. In this regard, the studies [89-91] were performed to analyze the influence of various factors on the parameters characterizing liquid oscillations in tank vehicles reservoirs. Finite element modeling of the Newtonian and non-Newtonian liquids oscillations in the cylindrical transport reservoirs at their braking was performed. In the works [92, 93] the issues related to the definition of a rational configuration of solid and perforated baffles were studied. In these papers there is some information about other research in baffles constructions.

In general, the presented materials allow to make a number of conclusions:

1. Under current conditions the share of analytic and experimental research is gradually reducing due to a virtual computer simulation of tank vehicles. However, analytical studies, despite their relatively simplified type, allow us to establish new effects that can not be often revealed under computer simulation as a result of abundance of output parameters. Experimental studies are still the main criterion for the adequacy of the developed models.

2. Researchers actively use a variety of specialized software systems designed to solve problems of fluid dynamics, multibody dynamics and analysis of the stress-strain state of structures. It is difficult to single out any specific software tools, which have obvious advantages. Particular software tools are traditionally most commonly used by crew separate scientific group to solve the above mentioned problems.

3. The present analysis suggests that further research in the field of dynamics and strength of tank vehicles will be connected with a broader application of computer programs which enables to simulate fluid dynamics as a continuous medium. This is due to the steady increase in performance of computer hardware and software development. Besides, there is a tendency in increase in specification of these objects during the analysis of their strength.

4. 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 stability and controllability of the vehicle. Besides, liquid sloshing in the tank vehicle's reservoir leads to redistribution of stresses and strains in the structure of the vehicle which is necessary to take into account in the process of its design.

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СОВРЕМЕННЫЕ ИССЛЕДОВАНИЯ ДИНАМИКИ И ПРОЧНОСТИ ЦИСТЕРН

Выполнен обзор исследований динамики и прочности автомобильных и железнодорожных цистерн, которые проведены в мире за последние десять лет. Приведены наиболее интересные результаты таких работ. Рассматриваются перспективы развития исследований, основная цель которых — обеспечение безопасности транспортирования жидких грузов.

Ключевые слова: *автоцистерна, железнодорожная цистерна, компьютерное моделирование, колебания жидкости, эквивалентные модели, перегородки*