RESEARCH INTO THE LOADING OF THE TANK CAR FRAME CONCEPT WITH FILLER IN THE COMPOSITE CENTER SILL

Oleksij Fomin [1], Juraj Gerlici [2], Alyona Lovska [3], Kateryna Kravchenko [2,*]

[1]State University of Infrastructure and Technology, Kiev, Ukraine
[2]University of Zilina, Zilina, Slovak Republic
[3]Ukrainian State University of Railway Transport, Kharkiv, Ukraine

*E-mail of corresponding author: kateryna.kravchenko@fstroj.uniza.sk

Resume

The study deals with determination of the dynamic loading on the frame of a tank car with closed composite center sill filled with elastic-viscous filler. It has been found that the measures for improvements can decrease the dynamic loading of the frame by 3.5% in comparison to that of the structure without a filler. The strength calculation of the frame of a tank car is also presented. It was found that the maximum equivalent stresses occurred in the contact area between the center sill and the body bolster; they amounted to about 284.7 MPa and did not exceed the allowable values. The computer modelling of the dynamic loading of the tank car frame was also conducted. The numerical values of accelerations and the distribution fields of accelerations in the frame of a tank car were determined. The results of the calculation showed that the hypothesis on the adequacy was not rejected. The natural frequencies and oscillation modes of the tank car frame were also determined.

Available online: https://doi.org/10.26552/com.C.2022.3.B219-B227

Article info

Received 13 January 2022
Accepted 20 April 2022
Online 20 May 2022

Keywords:

tank car
frame
center sill
dynamic loading
strength
modal analysis

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Integration of the railway transport into the system of international corridors requires development and putting into operation of new generation rail cars with improved technical and economical characteristics [1-3].

A great amount of freight transported along international corridors is liquids. Traditionally, they are transported in tank cars.

It should be noted that these cars carry considerable loads on the bearing structure due to the yielding state of liquid freight in the tank and due to operational loading of the tank. One of the components to bear these loads is the frame, in particular, the center sill. It bears constant sign-alternating loads. One of the great loads on the center sill is the longitudinal loading. The cyclical longitudinal loading results in failures of the center sill and can lead to crack development. This can be hazardous for both the train operation and environmental safety during the freight transportation.

Therefore, improvements in the bearing structure can decrease the dynamic loading on the frame of a tank car in operation, improve the strength characteristics of the frame and provide the safe rail transportation of liquid freight.

2 Analysis of recent research and publications

Study [1] presents an analysis of the longitudinal displacements of the liquid freight in tank cars and their impact on the stability. The article also presents the experimental results of the research into the oscillations of the liquid freight and outlines further areas of the research in the field.

Study [2] reveals the impact of the yielding state of liquid freight on the dynamic loading of a tank car. It was found that the displacement of the freight had a considerable effect on the load distribution between the front and rear bogies. However, these studies did not provide any solutions for decreasing the loading on a tank car in operation.

The results of determination of the strength for the bearing structure made of composite materials are presented in [3]. It was revealed that the preloading impacted the strength of the bearing structure. The article presents the main failures of the tank made of composite materials.

The structural analysis of the main units of a Zans car is given in [4]. The results of the strength calculation for the bearing structure of a car and the most loaded units of the bearing structure are given, as well.

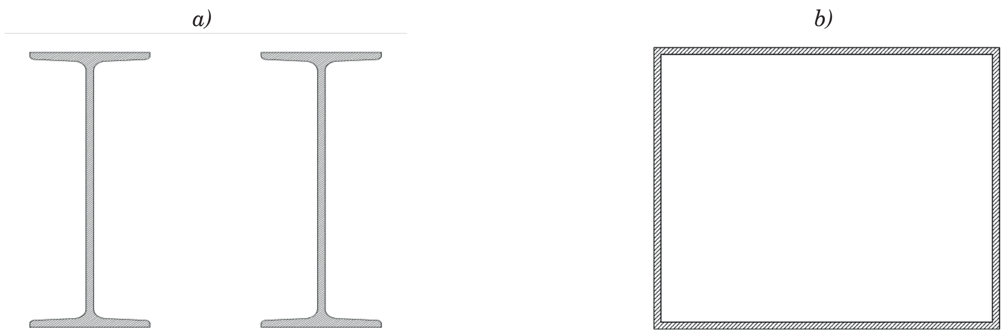

Figure 1 *Section of the center sill of the tank car frame*
a) standard; b) improved

However, this publication does not give any suggestions about improvements in the bearing structure of the tank cars for decreasing the loading.

In [5] authors present determination of the dynamic loading of a tank car moving on the track when the tank is not fully loaded. The effect of the liquid freight displacements on the critical speeds of a tank car was determined.

The experimental determination of the longitudinal loading of a tank for a moving car is given in [6]. The results of experiments were compared to the UIC Standards. Those experiments confirmed the efficiency of structural solutions taken during the designing of a tank car. However, this research does not offer any improvements in the strength characteristics of the tank cars through decreasing their dynamic loading.

Author of [7] presents the results of improvements in the structure of support elements in tank cars for liquid freight. The author developed the finite-element models of tank cars with various structural solutions to the end supports and evaluated the stress state of the support elements.

The ways of how to increase the strength of devices used for fastening the tank to the tank car frame are described in [8]. The authors obtained the dependencies of change in the stresses on the loading of the tank regardless the friction in the end supports. They also gave some recommendations for decreasing the stresses in the areas where the side supports are fastened to the center sill. However, this study does not describe any measures for decreasing the dynamic loading of the bearing structures of tank cars.

Study [9] presents the results of the strength determination for the tank of a tank car during the cyclic loading. The fatigue strength of the tank was evaluated. The impact of cyclic loading on the fatigue strength of the tank was also evaluated.

Similar research into the strength of the tank of a tank car during the cyclic loading is presented in [10]. The research reveals the time characteristics of the main loads and their impact on the fatigue crack development in the tank, which was observed during the technical observation of the tank cars. However, the authors did not propose any solutions for decreasing the effect of cyclical loading on the bearing structures of the tank cars.

The problems of reducing the dynamic loading of the bearing structures of transport facilities in operational modes are described in [11-12]. The results of the research confirmed the efficiency of the engineering solutions suggested.

The analysis of literature [1-12] demonstrates that the issue of improvements in the strength characteristics of the bearing structures of the tank cars, by reducing the loading in operational modes, is rather urgent and requires further investigation.

3 Objective and main tasks of the article

The objective of the article is to present results of determination of the loading on the tank car frame with the closed composite center sill filled with elastic-viscous material. The following tasks were set to achieve the objective:

- mathematical modelling of the dynamic loading on the frame of a tank car with closed composite center sill with elastic-viscous filler;
- strength calculation of the frame of a tank car;
- computer modeling of the dynamic loading on the tank car frame;
- verification of the dynamic loading model of the tank car frame;
- modal analysis of the tank car frame.

4 Research into the loading of the tank car frame concept with filler in the composite center sill

Authors suggest improvements in the frame of a tank car, in particular the application of the closed composite center sill filled with elastic-viscous material to reduce the loading on the tank car frame in operational modes (Figure 1).

Determination of the optimal profile parameters of the center sill was made in accordance with the strength capacity of the standard frame structure. The center sill

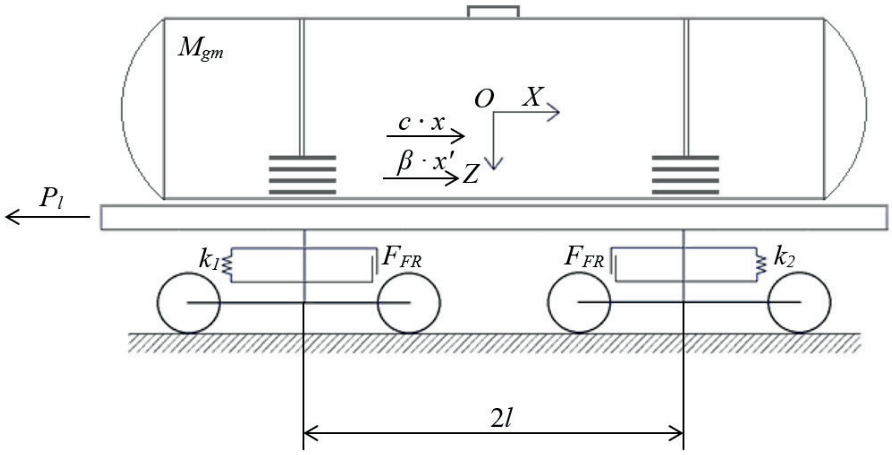

***Figure 2** Design diagram of a tank car*

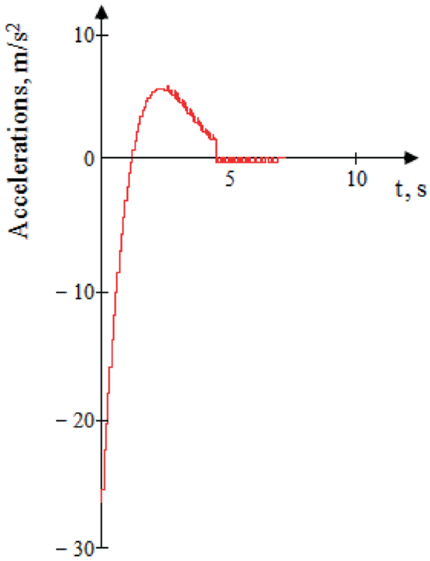

***Figure 3** Accelerations on the bearing structure of a tank car during a jerk*

was made of a composite material. The tare of a tank car was decreased by 2.3% in comparison to that of the standard structure.

The solutions suggested were substantiated through the determination of the dynamic loading of a tank car in the longitudinal plane. Authors used the mathematical model developed by Bogomaz; it describes the dynamic loading on a long-base flat car loaded with four tank containers under the longitudinal force to the rear follower of the coupler [13]. This model was adapted for the research and used for determination of the dynamic loading on a tank car. The design diagram of a tank car is given in Figure 2.

The calculation was made for a jerk. It included the case when the tank car was fully loaded with conditional freight. The restrictions of the mathematical model were zero displacements of the liquid freight in the tank.

$$M_{gm} \cdot \ddot{x} + (M_B \cdot h) \cdot \ddot{\varphi} = P_l - 2P_{fr} - \beta \cdot \dot{x} - c \cdot x, \quad (1)$$

$$\begin{aligned} &I_B \cdot \ddot{\varphi} + (M_B \cdot h) \cdot \ddot{x} - g \cdot \varphi \cdot (M_B \cdot h) = \\ &l \cdot F_{FR}(sign\dot{\Delta}_1 - sign\dot{\Delta}_2) + l(k_1 \cdot \Delta_1 - k_2 \cdot \Delta_2), \end{aligned} \quad (2)$$

$$M_B \cdot \ddot{z} = k_1 \cdot \Delta_1 + k_2 \cdot \Delta_2 - F_{FR}(sign\dot{\Delta}_1 - sign\dot{\Delta}_2), \quad (3)$$

where

$$\Delta_1 = z - l \cdot \varphi; \ \Delta_2 = z + l \cdot \varphi,$$

M_{gm} - gross mass of a tank car; M_B - mass of the bearing structure of a tank car; I_B - inertia moment of a tank car; P_l - longitudinal force to the front followers of the coupler (P_n = 2.5 MH [14-15]); P_{fr} - friction forces emerging between the center bowls and the body center plates; c - rigidity of the material in the center sill; β - viscous resistance coefficient of the material in the center sill; l - half base of a tank car; F_{FR} - absolute value of the dry friction in a spring group; k_1, k_2 - rigidity of the springs in the spring suspension of the bogies of a tank car; x, φ, z - coordinates describing longitudinal, angular (around the transverse axle) and vertical displacements of a tank car, respectively.

The calculation included the bearing structure of a tank car on the 18-100 bogies. The differential

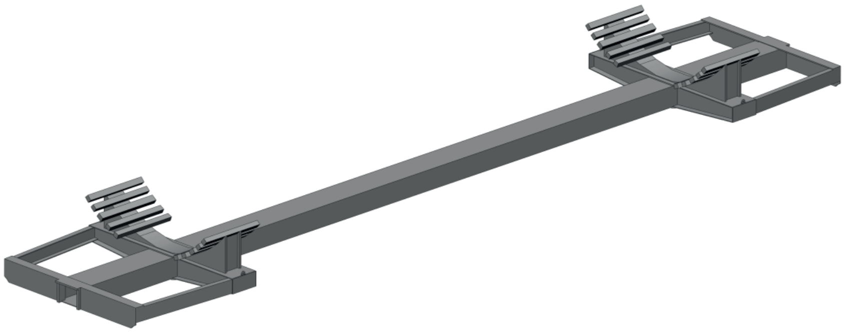

Figure 4 *Spatial model of the tank car frame*

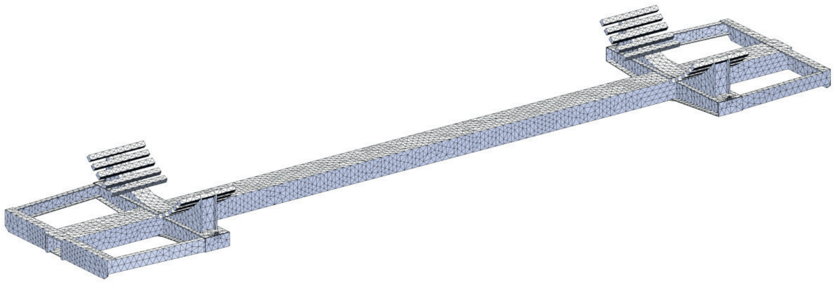

Figure 5 *Finite element model of the tank car frame*

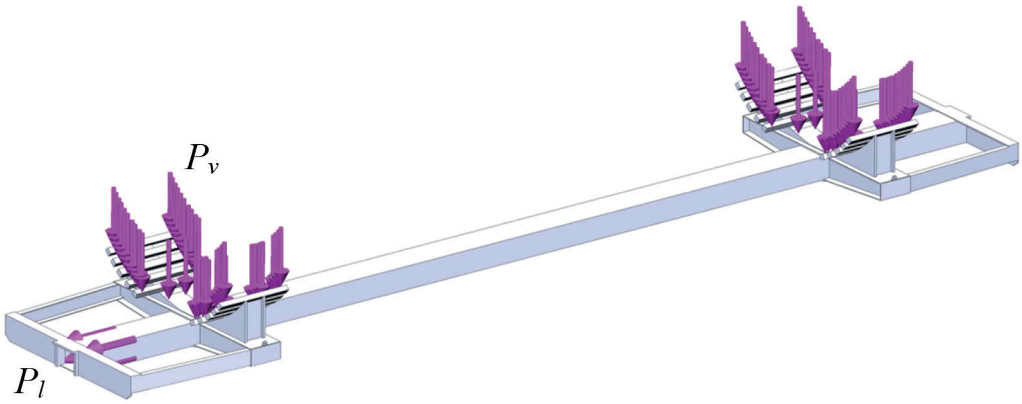

Figure 6 *Design diagram of the tank car frame*

equations of motion were solved with the Runge-Kutta method in MathCad [16-17]. The initial displacements and speeds were taken equal to zero [18-20]. It included a rigidity of the material in the center sill of 82 kN/m and the coefficient of viscous resistance 120 kN·s/m.

The maximum accelerations were 26.4 m/s^2 and occurred at a jerk (Figure 3). After that the acceleration went up and after a gentle jerk it faded. This acceleration value was 3.5% lower than that obtained for the bearing structure without filler [21].

The accelerations obtained were included in the strength calculation of the frame of a tank car. The calculation was made with the finite element method in SolidWorks Simulation [22-23]. It was based on the spatial model of a tank car (Figure 4).

The finite-element model of the frame was built with isoparametric tetrahedrons [24-26] (Figure 5). The optimal number of the tetrahedrons was calculated by the graphic analytical method [27-28]. The number of the elements in the mesh was 33193 and nodes - 11118. The maximum element size of the mesh was 100 mm, the minimum size - 20 mm, the maximum element side ratio - 109.25; the percentage of elements with the side ratio less than three - 18.1 and more than ten - 25.3. The number of elements in the circle was 9. The element size gain ratio was 1.7.

The design model included the following forces to the frame: vertical static loading in the areas of support of the tank on the frame P_v and longitudinal loading P_l on the front followers of the coupler (Figure 6). The center sill was made of a composite with the titanium matrix reinforced with boron, borsic, silicon carbide, beryllium and molybdenum fabrics. The endurance strength of the composite is: along the fabrics - 1100 -

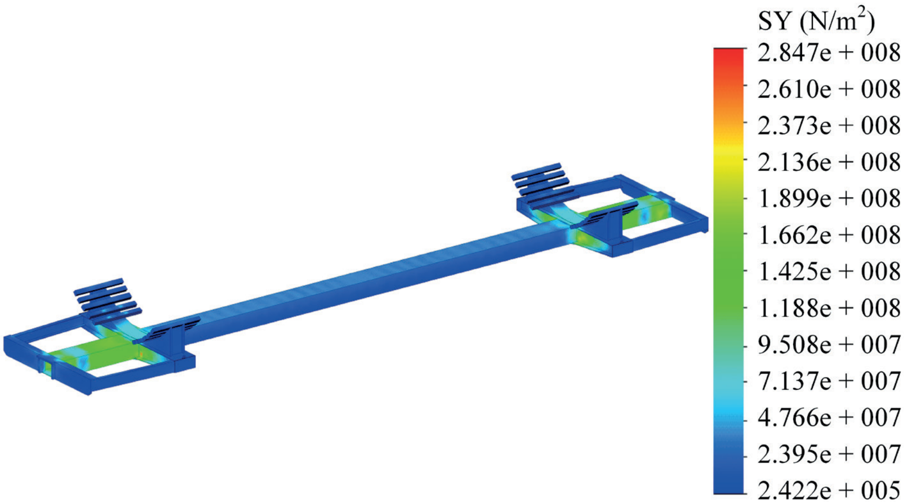

Figure 7 *Stress state of the tank car frame*

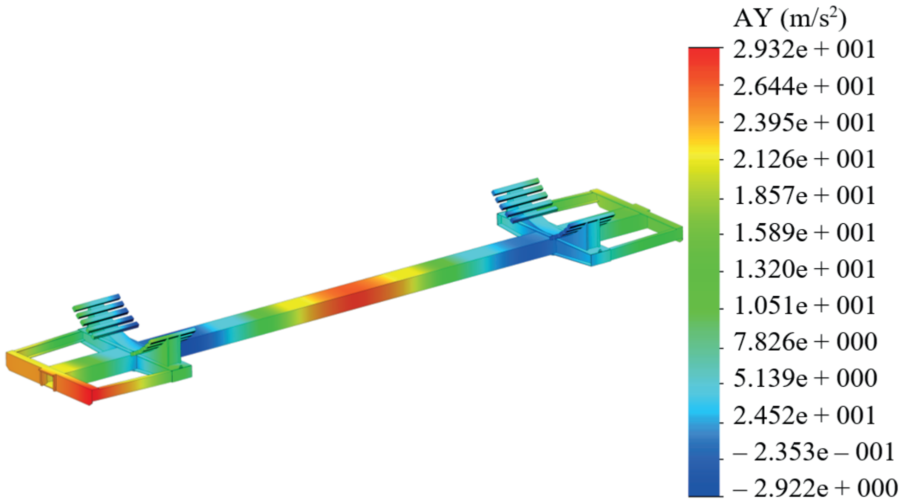

Figure 8 *Accelerations in the tank car frame*

Table 1 *Results of modeling the dynamic loading of the tank car frame*

Longitudinal force, MN	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5
Mathematical model	20.1	20.9	21.8	22.7	23.8	24.7	25.6	26.4
Computer model	22.6	23.5	24.3	25.5	26.7	27.5	28.4	29.3

1300 MPa, across the fabrics - 650 MPa. The fixing of the model was carried out in the areas of support on the chassis [29-30].

The elastic viscous material in the frame was modeled through linkages with similar characteristics by choosing appropriate options in the SolidWorks Simulation.

Results of the calculation are presented in Figure 7.

The maximum equivalent stresses were recorded in the contact area between the center sill and the body bolster; they amounted to about 284.7 MPa. These stresses did not exceed the allowable values [14-15, 31].

The distribution fields of accelerations in the tank car frame were determined in accordance with the design diagram given in Figure 6. Results of the calculation are given in Figure 8. The maximum accelerations were recorded in the middle part of the center sill; they amounted to 29.3 m/s². In the end parts of the frame the accelerations were about 26 m/s². The lowest value of accelerations was recorded in the areas of support of the tank on the frame. It is explained by the securing of the model by the body center plates [32-33].

The mathematical model in Equations (1) - (3) was verified with an F-test [34-35]. The variation parameter was the longitudinal force on the front followers of the coupler. As a result of the calculations, the acceleration acting on the car frame was obtained. The calculation of accelerations was carried out using the mathematical model in Equations (1) - (3) and the computer model is shown in Figure 6. Results of the calculation are given in Table 1. The needed number of static data was found with a Student's t-test.

Results of the calculation demonstrated that at the error mean square S_{sq} = 5.1 and the dispersion of

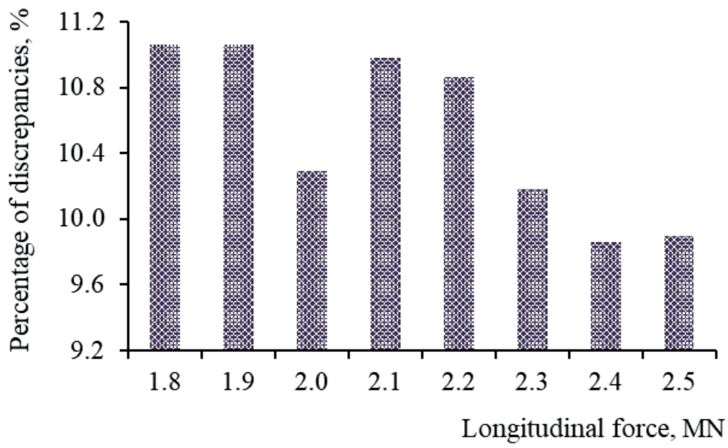

Figure 9 Difference between the results of the mathematical and computer modeling

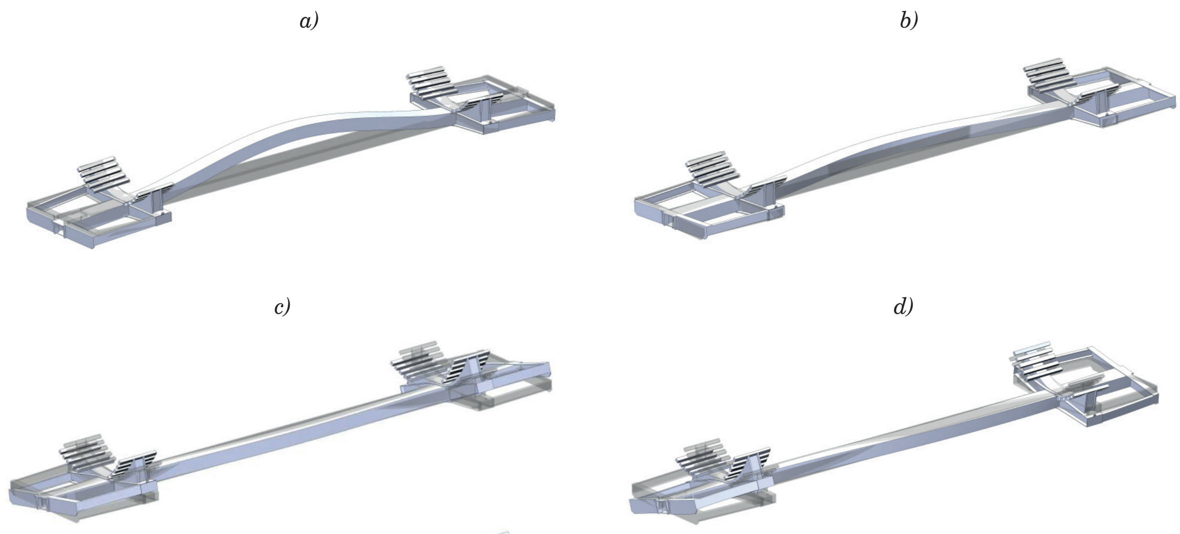

Figure 10 *Some oscillation modes of the tank car frame (scale of deformations 15:1)*
a) Mode 1; b) Mode 2; c) Mode 3; d) Mode 4

Table 2 *Values of the natural oscillation frequencies of the tank car frame*

Mode	Frequency, *Hz*	Mode	Frequency, *Hz*
1	28.0	6	54.1
2	38.9	7	64.4
3	45.1	8	67.0
4	46.3	9	81.9
5	49.2	10	97.9

adequacy S_{ad}^2 = 5.76, the actual value of an F-test was F_a = 1.13, which is lower than the tabular criterion value F_t = 3.07. Thus, the hypothesis on adequacy of the model designed was not rejected.

The difference between the results of the mathematical and computer modeling of the dynamic loading of the frame of a tank car is presented in Figure 9.

The maximum value of this difference was 11.0%; at the longitudinal force on the frame of a tank car it amounted to 1.8 MN and 1.9 MN and the lowest value was about 9.8%, at 2.4 MN.

Besides that, the design diagram of a tank car (Figure 6) was used for determination of the natural frequencies and oscillation modes of the tank car frame.

Some oscillation modes of the tank car frame are given in Figure 10. Transparent color in Figure 10 indicates the stationary position of the frame and matte - the form of vibrations, taking into account the enlarged scale. In this case, each mode shown in Figure 10 corresponds to the numerical value of the frequency indicated in Table 2.

From the results given in Table 2 it can be concluded that the natural frequencies were in a range of the allowable values, as the first frequency exceeded 8 Hz [14-15].

5 Conclusions

1. Authors conducted the mathematic modeling of the dynamic loading of a frame of the tank car with the closed composite center sill filled with elastic-viscous material. It was found that the maximum accelerations were 26.4 m/s^2 and occurred at a jerk. The acceleration value was 3.5% lower than that obtained for the bearing structure without filler.
2. The research included the strength calculation of the frame of a tank car. The maximum equivalent stresses were recorded in the contact area between the center sill and the body bolster; they amounted to about 284.7 MPa. The stresses obtained did not exceed the allowable values.
3. The research also included the computer modelling of the dynamic loading of the frame of a tank car. The maximum accelerations were recorded in the middle part of the center sill and amounted to 29.3 m/s^2. In the end parts of the frame the accelerations were about 26 m/s^2. The lowest accelerations were recorded in the areas of support of the tank on the frame.
4. The designed model of the dynamic loading of the tank car frame was verified. It was found that at the error mean square S_{sq}=5.1 and the dispersion of adequacy S_{ad}^2 = 5.76, the actual value of an F-test was F_a=1.13, which is lower than the tabular criterion value F_t =3 .07. Thus, the hypothesis on adequacy of the model designed was not rejected.
5. The modal analysis was performed for the frame of a tank car. The natural oscillations frequencies of the frame of a tank car were in the range of allowable values. The first natural oscillation frequency exceeded 8 Hz.

The research conducted can be used by those concerned about the development of innovative freight car structures and enhanced efficiency of the railway transport.

References

[1] DIZO, J., HARUSINEC, J., BLATNICKY, M. Computation of modal properties of two types of freight wagon bogie frames using the finite element method. *Manufacturing Technology* [online]. 2018, **18**(2), p. 208-214. ISSN 1213-2489. Available from: https://doi.org/10.21062/ujep/79.2018/a/1213-2489/MT/18/2/208

[2] STASTNIAK, P., MORAVCIK, M., SMETANKA, L., BARAN, P. Strength investigation of main frame in new track friendly railway bogie. *Manufacturing Technology* [online]. 2018, **18**(2), p. 315-320. ISSN 1213-2489. Available from: https://doi.org/10.21062/ujep/98.2018/a/1213-2489/MT/18/2/315

[3] DIZO, J., HARUSINEC, J., BLATNICKY, M. Structural analysis of a modified freight wagon bogie frame. *MATEC Web of Conferences* [online]. 2017, **134**, 00010. ISSN 2261-236X. Available from: https://doi.org/10.1051/matecconf/201713400010

[4] YOUSEFI, S., TAHERI, M. N., SHAHRAVI, M. Analysis of longitudinal fluid sloshing in tank wagon. *International Journal of Heavy Vehicle Systems* [online]. 2019, **26**(2), p. 225-238. ISSN 1744-232X. Available from: https://doi.org/10.1504/IJHVS.2019.098280

[2] SHI, H., WANG, L., NICOLSEN, B., SHABANA, A. A. Integration of geometry and analysis for the study of liquid sloshing in railroad vehicle dynamics. *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics* [online]. 2017, **231**, p. 608-629. ISSN 1464-4193. Available from: https://doi.org/10.1177/1464419317696418

[3] STREET, G. E., MISTRY, P. J., JOHNSON, M. S. Impact resistance of fibre reinforced composite railway freight tank wagons. *Journal of Composites Science* [online]. 2021, **5**(6), 152. ISSN 2504-477X. Available from: https://doi.org/10.3390/jcs5060152

[4] STASTNIAK, P., SMETANKA, L., MORAVCIK, M. Structural analysis of a main construction assemblies of the new wagon prototype type zans. *Manufacturing technology* [online]. 2018, **18**(3), p. 510-517. ISSN 1213-2489. Available from: https://doi.org/10.21062/ujep/130.2018/a/1213-2489/MT/18/3/510

[5] RAHMATI-ALAEI, A., SHARAVI, M., SAMADIAN ZAKARIA, M. Hunting stability analysis of partially filled tank wagon on curved track using coupled CFD-MBD method. *Multibody System Dynamics* [online]. 2020, **50**, p. 45-69. ISSN 1384-5640. Available from: https://doi.org/10.1007/s11044-019-09715-y

[6] KUBA, E., MORAVCIK, M., PAVELCIK, V. Experimental verification of tank wagon's ability to transmit longitudinal forces in opposite track curves. *Transportation Research Procedia* [online]. 2021, **55**, p. 774-781. ISSN 2352-1457. Available from: https://doi.org/10.1016/j.trpro.2021.07.045

[7] PAVLYUCHENKOV, M. V. Structure rationalization of tank cars support devices for fluids (in Ukrainian). *Science and Transport Progress Bulletin of Dnipropetrovsk National University of Railway Transport* [online]. 2014, **1**(49), p. 151-159. ISSN 2307-3489. Available from: https://doi.org/10.15802/stp2014/22681

[8] SENKO, V. I., SHIMANOVSKIJ, A. O., PUTYATO, A. V. Investigation of ways to increase the strength of

the parts of fastening the boiler to the frame of the railway tank car (in Russian). *Bulletin of Brest State Technical University* [online]. 2004, **4**, p. 54 - 57. eISSN 2706-5812. Available from: https://rep.bstu.by/handle/data/12269

[9] BOYKO, A., KONONOVA, O. Strength calculation for a tank of the tank-car under repeated loading (in Russian). In: XIII International Colloquium Mechanical Fatigue of Metals: proceedings [online]. 2006. ISBN 966-305-027-6, p. 484-490. Available from: http://elartu.tntu.edu.ua/handle/123456789/16833

[10] ZARIPOV, R. Y., VASILEVSKY, V. P. Strength calculation for a tankof the tank-car under repeated loading (in Russian). *The Bulletin of Kazakh Academy of Transport and Communications named after M. Tynyshpaev* [online]. 2017, **1**(100), p. 53-59. ISSN 1609-1817. Available from: https://docplayer.com/58604073-K'azkka-habarshysy-1-100-2017-issn-the-bulletin-of-kazatc-vestnik-kazatk-1-100-vol-100-no.html

[11] LOVSKA, A., FOMIN, O., PISTEK, V., KUCERA, P. Dynamic load and strength determination of carrying structure of wagons transported by ferries. *Journal of Marine Science and Engineering* [online]. 2020, **8**, 902. ISSN 2077-1312. Available from: https://doi.org/10.3390/jmse8110902

[12] LOVSKA, A., FOMIN, O., PISTEK, V., KUCERA, P. Calculation of loads on carrying structures of articulated circular-tube wagons equipped with new draft gear concepts. *Applied Sciences* [online]. 2020, **10,** 7441. ISSN 2076-3417. Available from: https://doi.org/10.3390/app10217441

[13] BOGOMAZ, G. I., MEKHOV, D. D., PILIPCHENKO, O. P., CHERNOMASHENTSEVA, Y. G. Loading of tank containers located on a railway flat wagon when impact into an automatic coupler (in Russian). *Dynamics and Motion Control of Mechanical Systems*. 1992, **1**, p. 87-95.

[14] DSTU 7598:2014. Freight wagons. General requirements for calculations and design of new and modernized wagons of 1520 mm track (non-self-propelled). Kiev: UkrNDNTS:, 2015.

[15] GOST 33211-2014. Freight wagons. Requirements for strength and dynamic properties. Moscow: FGUP "Standartinform": 2016.

[16] KIRYANOV, D. V. *Mathcad 13* (in Russian). Saint Petersburg: BHV Petersburg, 2006. ISBN 5-94157-850-4.

[17] DYAKONOV, V. *Mathcad 8/2000: a special reference book* (in Russian). Saint Petersburg: Piter, 2000. ISBN 5-272-00069-2.

[18] TURPAK, S. M., TARAN, I. O., FOMIN, O. V., TRETIAK, O. O. Logistic technology to deliver raw material for metallurgical production. *Scientific Bulletin of National Mining University* [online]. 2018, **1**, p. 162-169. ISSN 2071-2227. Available fromhttps://doi.org/10.29202/nvngu/2018-1/3

[19] KALANTAIEVSKA, S., PIEVTSOV, H., KUVSHYNOV, O., SHYSHATSKYI, A., YAROSH, S., GATSENKO, S., ZUBRYTSKYI, H., ZHYVOTOVSKYI, R., PETRUK S., ZUIKO, V. Method of integral estimation of channel state in the multiantenna radio communication systems. *Eastern-European Journal of Enterprise Technologies* [online]. 2018, **5/9**(95), p. 60-76. ISSN 1729-3774 Available from: https://doi.org/10.15587/1729-4061.2018.144085

[20] KUCHUK, N., MOHAMMED, A. S., SHYSHATSKYI, A., NALAPKO, O. The method of improving the efficiency of routes selection in networks of connection with the possibility of self-organization. *International Journal of Advanced Trends in Computer Science and Engineering* [online]. 2019, **8**(1), p. 1-6. ISSN 2278-3091. Available from: https://doi.org/10.30534/ijatcse/2019/0181.22019

[21] FOMIN, O., GERLICI, J., GORBUNOV, M., VATULIA, G., LOVSKA, A., KRAVCHENKO, K. Research into the strength of an open wagon with double sidewalls filled with aluminium foam. *Materials* [online]. 2021, **14**(12), 3420. eISSN 1996-1944. Available from: https://doi.org/10.3390/ma14123420

[22] LOVSKA, A. O. Computer simulation of wagon body bearing structure dynamics during transportation by train ferry. *Eastern-European Journal of Enterprise Technologies* [online]. 2015, **3/7**(75), p. 9-14. ISSN 1729-3774. Available from: https://doi.org/10.15587/1729-4061.2015.43749

[23] LOVSKA, A. A. Peculiarities of computer modeling of strength of body bearing construction of gondola car during transportation by ferry-bridge. *Metallurgical and Mining Industry*. 2015, **1**, p. 49-54. ISSN 2076-0507.

[24] FOMIN, O. Modern requirements to carrying systems of railway general-purpose gondola cars. *Metallurgical and Mining Industry*. 2014, **5**, p. 31-43. ISSN 2076-0507.

[25] LOVSKA, A., FOMIN, O., PISTEK, P., KUCERA, P. Dynamic load modelling within combined transport trains during transportation on a railway ferry. *Applied Sciences* [online]. 2020, **10**(16), 5710. eISSN 2076-3417. Available from: https://doi.org/10.3390/app10165710

[26] FOMIN, O., LOVSKA, A. Determination of dynamic loading of bearing structures of freight wagons with actual dimensions. *Eastern-European Journal of Enterprise Technologies* [online]. 2021, **2/7** (110), p. 6-15. ISSN 1729-3774. Available from: https://doi.org/10.15587/1729-4061.2021.220534

[27] VATULIA, G. L., PETRENKO, D. H., NOVIKOVA, M. A. Experimental estimation of load-carrying capacity of circular, square and rectangular CFTS columns. Scientific Bulletin of the National Mining University. 2017, **6**. p. 97- 02. ISSN 2071-2227.

[28] VATULIA, G., KOMAGOROVA, S., PAVLIUCHENKOV, M. Optimization of the truss beam. Verification of the calculation results. *MATEC Web of Conferences* [online]. 2018, **230**, 02037. ISSN 2261-236X. Available from: https://doi.org/10.1051/matecconf/201823002037
[29] FOMIN, O. V., LOVSKA, A. O., PLAKHTII, O. A., NERUBATSKYI, V. P. The influence of implementation of circular pipes in load-bearing structures of bodies of freight cars on their physico-mechanical properties. *Scientific Bulletin of National Mining University*. 2017, **6**, p. 89-96. ISSN 2071-2227.
[30] LOVSKAYA, A., RYIBIN, A. The study of dynamic load on a wagon-platform at a shunting collision. *Eastern-European Journal of Enterprise Technologies* [online]. 2016, **3**, p. 4-8. ISSN 1729-3774. Available from: https://doi.org/10.15587/1729-4061.2016.72054
[31] EN 12663-2. Railway applications - structural requirements of railway vehicle bodies. Part 2: Freight wagons. Bulgaria, 2010.
[32] FOMIN, O. V., BURLUTSKY, O. V., FOMINA, Y. V. Development and application of cataloging in structural design of freight car building. *Metallurgical and Mining Industry* [online]. 2015, **2**, p. 250-256. ISSN 2076-0507.
[33] LOVSKA, A. Simulation of loads on the carrying structure of an articulated flat car in combined transportation. *International Journal of Engineering and Technology (UAE)* [online]. 2018, **7**(4.3), p. 140-146. ISSN 2227-524X. Available from: https://doi.org/10.14419/ijet.v7i4.3.19724
[34] PISTEK, V., KUCERA, P., FOMIN, O., LOVSKA, A. Effective mistuning identification method of integrated bladed discs of marine engine turbochargers. *Journal of Marine Science and Engineering* [online]. 2020, **8**, 379. eISSN 2077-1312. Available from: https://doi.org 10.3390/jmse8050379
[35] BYCHKOV, A. S., KONDRATIEV, A. V. Criterion-based assessment of performance improvement for aircraft structural parts with thermal spray coatings. *Journal of Superhard Materials* [online]. 2019, **41**(1), p. 53-59. ISSN 1063-4576. Available from: https://doi.org/10.3103/S1063457619010088