On the Collision of Railcars as an Interaction of Soliton-like and Shock Wave-like Perturbations

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Abstract: —Several new mathematical issues have been set for the development of high-speed transport, which can be solved in the framework of hydrodynamics to describe the process of hydrodynamics, creating effective rolling stock dampers. which requires the improvement and development of the corresponding mathematical apparatus. In this work, we use a hydrodynamic approach to find the density distributions of matter during railcar collisions at high speeds, which is important in light of the problems of high-speed transport. In our approach, we found an analytical solution to the obtained hydrodynamic equations for the one-dimensional case. The equations under study were obtained taking into account nonequilibrium processes. To find a solution to the hydrodynamic equations, the shock wave approximation is used, similar to the soliton solutions we considered earlier. Taking into account possible deviations from the results of a one-dimensional problem is considered. Such a reduction of solutions of hydrodynamic equations to shock waves has not been considered previously and may be of interest for a wide variety of applied problems. The resulting consideration of railcar collisions is important for solving problems of transport safety and technospheric safety.

Keywords: — High-speed rail transport, hydrodynamics, railcar collision, analytical solution for slab collisions.

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1. Introduction

A large number of different physical and mathematical problems of high-speed rail transport (see, for example, [1-5]) are solved using the apparatus of the equations of hydrodynamics.

In [6–8], we reduced the problem of layer-slabs collision to a description of the interaction of Korteweg–de Vries solitons. Here we have obtained a description of the propagation of shock waves [9-11] for disturbances of arbitrary amplitude, which can be used in the calculations of dampers (see, for example, [5, 12–15]) and construction equipment [16–20].

These are calculations of hydraulic transmissions, which have been developed for a long time, but with the increase in the speed mode of rolling stock and with the consideration of friction received a new continuation [21]. To create effective wheel dampers, vibration dampers, and shock absorbers, hydrodynamics is also used [2-4], which requires improvement by taking into account the nonlinearity and non-equilibrium of the damping process at high speeds. Linear equations are used in [22], and simplified hydrodynamic equations are used in [23]. This can be developed further and refined in detail for a nonlinear compressible medium within our hydrodynamic approach.

The development of the hydrodynamic approach can be applied to describe nonlinear dynamics in the calculations of bridges on high-speed electric transport lines [16], and can also be used in the analysis of the stability of transport structures in extreme conditions [17].

In our works [6-8], nonequilibrium hydrodynamics was proposed. And this can be extended to a wide area of technical applications and used in the design of wheel shock absorbers, pipes, transport structures, bridges and other objects of transport and construction engineering (see, for example, [1-16.23]) in the light of the problems of high-speed transport, since we proposed a rigorous mathematical approach.

The current stage of development of railway transport in Russia and the World is characterized by an increase in the speed of passenger trains while the state of the railway infrastructure remains unchanged, which leads to increased risks to the life and health of passengers in the event of emergency situati0ons. The most dangerous accidents are longitudinal collisions of passenger trains with obstacles on the track, which reflect 99.2% of registered cases of emergency collisions on Russian railways. The adoption of the Strategy for the Development of Railway Transport until 2030, which provides for the production and commissioning of high-speed and high-speed rolling stock, makes the problem of ensuring the safety of railway passenger transportation increasingly urgent . In this regard, the task of increasing the safety of passenger railcars during longitudinal collisions is a priority direction for the development of new generation railway rolling stock . The most effective way to improve the safety of railway transportation is the development and implementation of mechanical safety systems for passenger railcars, based on the use of special destructible elements that absorb the energy of a train colliding with an obstacle Thus, the task of developing a methodology for determining the parameters of security systems passenger railcars and their rationale are relevant [24] .

Consideration of the collision of high-speed railcars is important for problems of transport safety and technospheric safety. The purpose of the work is to develop and theoretically substantiate technical solutions for ensuring mechanical safety of passenger railcars in case of longitudinal collisions

Next, Section 2 examines the model used to describe the collision of rail cars within the framework of the hydrodynamic approach, then in Section 3 a solution to the proposed equations is found using shock waves and the results of the collision of railcars are analyzed in order to determine the degree of impact of the collision of railcars on their condition. In Section 4, the main conclusions of the work are presented.

2. The Model

. In the nonequilibrium case the equations of long-range hydrodynamics [6,7] are obtained, which in the one-dimensional case have the form for finding the density $\rho(x,t)$ and velocity $\upsilon(x,t)$

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho\upsilon)}{\partial x}=0, \qquad (1)$$

$$\frac{\partial(m\rho\upsilon)}{\partial t}+\frac{\partial(m\rho\upsilon^2+P)}{\partial x}=0. \qquad (2)$$

The pressure is [8]:

$$P=-\frac{\partial(e/\rho)}{\partial(1/\rho)}=K(\rho^2-\rho_0^2)-\alpha\left(\frac{\partial\rho}{\partial x}\right)^2, \qquad (3)$$

where ρ_0 is the equilibrium density and $K=9mc_{s0}^2$ is the compression modulus ,$\frac{\alpha}{2mc_{so}^2}\rho_0=$ (m)^2, and the speed of sound is $c_{s0}\approx 3\ 10^3$ m/s.

Here we consider the propagation of perturbations of arbitrary amplitude using the equations of hydrodynamics (1)-(3). Integrating these equations over the density jump, assuming the speed of shock wave is equal to the speed of sound and taking into account the expression for pressure (3), we obtain an equation for the density. Also, as before with Korteweg–de Vries solitons, we can integrate over the length of the layer and take into account the propagation of the shock wave front and its reflection from boundaries. Since for the maximum, a wave equation is obtained from the equations of hydrodynamics that admits the d'Alembert solution [8].

As a result of integration we obtain

$$\rho=\frac{1}{L}\int_{l_1}^{l_2}\rho'dx=\rho_0+4\frac{(\rho_1-\rho_0)}{\lambda L}\left[\frac{1}{1+\exp(\lambda(x-l_2-Dt))}-\frac{1}{1+\exp(\lambda(x-l_1-Dt))}\right], \qquad (4)$$

where ρ_1 is formula (5), $\lambda=\sqrt{K/\alpha}$, l_1 and l_2 is the boundaries of the railcar, and L is its size,

$$D^2=2K\rho_1/m=\frac{(\rho_0\upsilon_0)^2}{(\rho_1-\rho_0)^2}. \qquad (5)$$

An approximate solution of one-dimensional hydrodynamic equations using shock waves can be used in calculations of dampers for railcars and construction equipment. In our works, nonequilibrium hydrodynamics was proposed. And this can be extended to a wide range of technical applications

3. Results

Modern technologies of computer modeling and numerical calculation of the stress-strain state of structures under the influence of excess shock loads make it possible to predict with acceptable accuracy the consequences of frontal collisions and judge the impact resistance and damageability of locomotives. When designing new generation locomotives, it is expected that computer technologies will be widely introduced, which, unlike setting up full-scale experiments (crash tests), turn out to be less costly economically, are able to take into account important features of the behavior of the structure and its material under shock loading, and make it possible to judge the effectiveness of the adopted technical solutions already in the early stages of design. As a result, deadlines are reduced and its quality increases. Consequently, improving methods for modeling and calculating the impact resistance of locomotives, taking into account large deformations of the structural material, impact application of loads and contact interaction of colliding objects, is an urgent task and is of scientific and practical interest.

Figure 1 shows profiles of the relative density (ρ/ρ_0) for the interaction of two rod cars in a system of equal speeds, when the train begins to move off at an initial velocity of $\upsilon_0=100$ m/s at times $t=1;2;3;4;5;6;7;8;9$ ms.. Figure 2 shows profiles of the relative density (ρ/ρ_0) for the interaction of two rod cars in a system of equal speeds, when the train begins to move off at an initial velocity of $\upsilon_0=300$ m/s at times $t=1;2;3;4;5;6$ ms.

Figure 3 shows profiles of the relative density (ρ/ρ_0) for the interaction of two rod cars in a system of equal speeds, when the train begins to move off at an initial velocity of $\upsilon_0=500$ m/s at times $t=1;2;3;4;5$ ms. After the initial compression and formation of a hot spot, followed by expansion, at the expansion stage a rarefaction is observed in the center

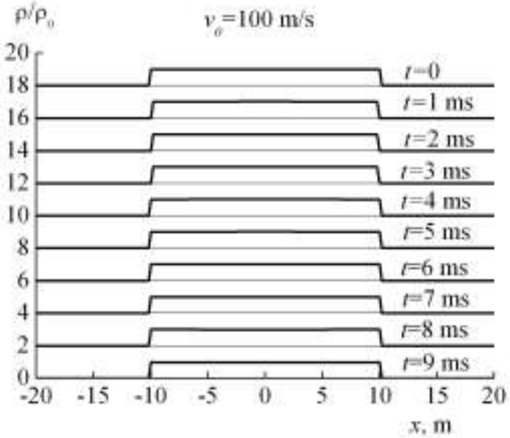

Fig. 1. Density profiles of the collision of rod cars at an initial velocity of $\upsilon_0 = 100$ m/s at times $t = 1; 2; 3; 4; 5; 6; 7; 8; 9$ ms

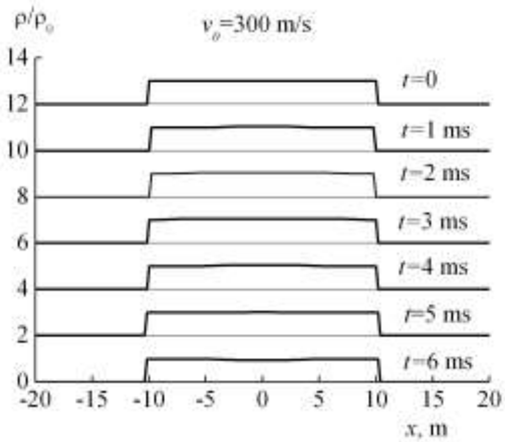

Fig. 2. Density profiles of the collision of rod cars at an initial velocity of $\upsilon_0 = 300$ m/s at times $t = 1; 2; 3; 4; 5; 6$ ms

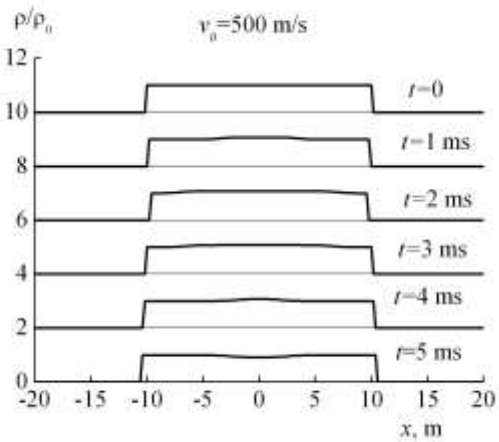

Fig. 3. Density profiles of the collision of rod cars at an initial velocity of $\upsilon_0 = 500$ m/s at times $t = 1; 2; 3; 4; 5$ ms

We also can be found a simplified solution to the issue in the two-dimensional case. The equations are obtained from the hydrodynamic equations by integrating the hydrodynamic equations over the transverse coordinate, assuming that the density ρ (x, t) does not depend on the coordinate y.

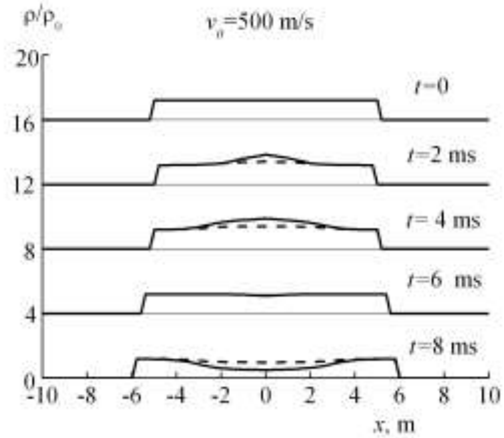

Fig.4. Instantaneous collision profiles of identical slabs (solid lines) at velocity $\upsilon_0 = 500$ m/s various points $t = 0; 2; 4; 6; 8$ ms for the two-dimensional case, the dashed lines are density profiles for one-dimensional layers.

Thus, Figure 4 shows the density profiles for collisions of identical railcars with a longitudinal dimension of $L = 6$ m with velocity $\upsilon_0 = 500$ m/s at time moments $t = 0; 2; 4; 6; 8$ ms. In this case, the results are indicated by solid lines The dashed lines correspond to the one-dimensional case. It can be seen that in the two-dimensional case, the oscillations of compression and rarefaction are stronger. As for the size, the region of rarefaction turns out to be of the order of the railcar length (6 m) and, therefore, in accordance with the estimates of shock absorber parameters [5], does not result in destruction.

When considering the behavior of railcars over a longer time interval, the propagation of the shock wave from the head of the train to its end, the reflection of the wave and its reverse movement to the head railcar can be traced. The process of wave movement is accompanied by a gradual decrease in the amplitudes of accelerations and forces in the intercar connections, which is due to the dissipation of energy in the absorbing devices of the coupling devices and the structural material. Consequently, to assess the maximum load of the load-bearing elements of the train, it is sufficient to perform calculation studies only for the initial phase of the collision, when the largest longitudinal dynamic loads are experienced by the head railcar and the railcar following it

The developed method for calculating longitudinal vibrations of a train allows simulate dynamic processes in the composition, estimate speeds, accelerations its units, internal forces in inter-car nonlinear connections. Methodology used in refined calculations of the longitudinal dynamics of the train at collision with an obstacle. It is possible to take into account real diagrams deformation of energy absorption devices measured experimentally during destructive tests. Rigidity characteristics can be specified inter-car connections for other types of inter-car connections. Methodology allows you to analyze the parameters of dynamic processes as part of destructible energy absorption devices placed between railcars.

4. Conclusions

Thus, in the present work, the nonequilibrium hydrodynamic approach has been further developed to describe complex systems on the example of slab collision. The non-equilibrium approach to the hydrodynamic equations allows describing the experimental data better than the equation of state corresponding to traditional hydrodynamics, assuming the establishment of local thermodynamic equilibrium. In this description, the isolation of the hot spot was essential. In this paper, we show that the introduction of dispersion terms does not violate this representation. During the expansion stage, a rarefied region is formed in the center of the system. This consideration was carried out in one-dimensional case and may be carried in two-dimensional case too.

The reduction of the hydrodynamic equations to the solution of two Korteweg-de Vries equations in the form of solitons makes it possible to find an analytical solution to the issue.

As a result of our assessment of the modeling results, a refined hydrodynamic computer model of railcar collisions can be selected for further research. In the third part of the work, we proposed an approach for selecting the parameters of energy absorption devices [24]. Thus, on the basis of the "Universal Mechanism" program complex, as a result of calculations and numerical experiments, for example, the development of a energy absorption devices design can be carried out. Prospects for further development of the topic of structural protection of railway transport may be associated with the improvement of test scenarios of emergency situations and technologies for their modeling.

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This approach can be extended to a wide range of technical applications and used in the design of wheel dampers, pipes, transport structures, bridges and other transport and construction equipment in the light of high-speed transport problems.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article

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