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STUDY OF STABILITY OF A TANK-CONTAINER WITH A FILLED LIQUID AT LONGITUDINAL OSCILLATIONS

Abstract. The effect of the oscillating fluid on the dynamic stability of the tank-container is studied at different filling capacities. The main method for studying the dynamic stability of a railway platform with a tank-container in theoretical calculations is the method of full integration, i.e. all the solutions of the system of differential equations describing the movement of the tank-container with liquid are found, and from them a conclusion is made on the stability of the movement. The study of the longitudinal vibrations of the liquid and the tank-container is considered at various impact speeds and without taking into account the galloping angle. The solution of the system of differential equations reduces to the solution of the hydrodynamic problem.

Key words: dynamic stability, tank-container, spring kit, acceleration, hydrodynamic force, collision speed.

The problem of determining the effect of an oscillating fluid on the dynamic stability of a partially filled tank-container is solved by comparing the dynamic stability areas of a full and partially filled tank-container obtained with the same parameters of the tank-container and the railway platform, types of disturbances and driving conditions. The longitudinal vibrations of the container with the liquid have a significant effect on their stability during movement. Consider the longitudinal vibrations of the tank-container, similar to transverse vibrations. To do this, we introduce the inertial coordinate system (fixed) OXZ, and the tank-container located in the plane of the unperturbed surface (movable) O₁X₁Z₁, connected to the tank's surface (see figure 1).

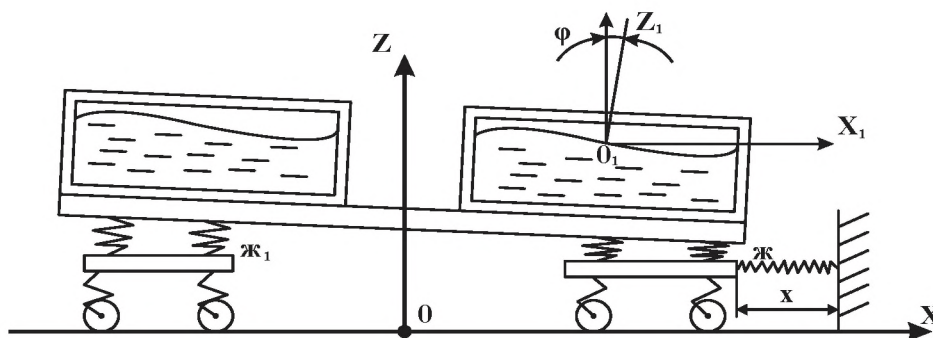


Figure 1 – Design diagram of a platform with a tank-container

The fluid motion relative to the moving system O₁X₁Z₁ will be determined by the function $q_n(t)$, and the longitudinal motion of the «container-liquid» system will be determined by the coordinate function- $X(t)$. Then the problem of hydrodynamics is formulated as follows, it is necessary to find the potential of

the absolute velocities $\varphi_a(x, z, t)$ - particles of a liquid in a container moving with a speed - $\dot{X}(t)$. Since the progressive movement of the tank-container is investigated, the potential velocity of the absolute movement will be [1]:

$$\varphi_a = \varphi + \dot{X}(t)x_1, \quad (1)$$

where \dot{X} - the speed of the tank-container in the longitudinal direction. The function $\varphi(x_1, z_1, t)$ satisfies the Laplace equation and the boundary conditions:

$$\frac{\partial^2 \varphi}{\partial x_1^2} + \frac{\partial^2 \varphi}{\partial z_1^2} = 0, \quad (2)$$

$$\frac{\partial \varphi}{\partial n} = 0 \text{ - on a wettable surface and } \frac{\partial^2 \varphi}{\partial t^2} + g \frac{\partial \varphi}{\partial z_1} = 0 \text{ - on a free surface.} \quad (3)$$

The equation of the free surface in the tank-container is written in the form [2]

$$\zeta(x_1, t) = \sum q_n(t) \psi(x_1, 0).$$

Then the solution of equation (2) taking into account the boundary conditions (3) can be represented as

$$\varphi(x_1, z_1, t) = \sum \frac{d}{\pi n} \dot{q}_n(t) \psi_n(x_1, z_1), \quad (4)$$

where $\dot{q}_n(t)$ - time functions characterizing the movement of the liquid, d - length of the tank-container; $\psi_n(x_1, z_1)$ are the eigenvalues obtained by the Fourier method for $\dot{q}_n(t) = \cos(\omega_n t)$, i.e. when studying the natural vibrations of a liquid, the eigenvalues are determined by the formula [3]

$$\psi_n(x_1, z_1) = \frac{2}{\sqrt{d}} \sin \frac{\pi n}{d} x_1 \frac{ch \frac{\pi n}{d} (z_1 + R + h)}{ch \frac{\pi n}{d} (R\pi + h)}. \quad (5)$$

Natural frequencies are defined as follows

$$\mu_n = \frac{\omega_n^2}{g} = \frac{n\pi}{d} th \frac{n\pi}{d} \left(\frac{\pi}{4} R + h \right). \quad (6)$$

We proceed to obtain a system of equations of longitudinal oscillations of the liquid and the tank-container, taking into account the galloping of the platform. In this case, the potential velocity of the absolute motion of the liquid particles, determined by the relation (1), will take the form [4]

$$\varphi_a = \varphi + \dot{\psi} \varphi_1^{(2)} + (\dot{X} + l\dot{\psi})x_1, \quad (7)$$

where $\varphi_1^{(2)}$ - is the Zhukovsky potential, whose approximate value is determined by the relation

$$\varphi_1^{(2)} = x_1 z_1 + x_1^0 z_1 - x_1 z_1^0 - \frac{(-1)^{n+1} 8d^2}{\pi^3} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \frac{sh \frac{(2n-1)\pi}{d} \left(z_1 + \frac{R\sqrt{\pi}}{2} + h \right)}{ch \frac{(2n-1)\pi}{d} \left(\frac{R\sqrt{\pi}}{2} + h \right)} \sin \frac{(2n-1)\pi}{d} x_1, \quad (8)$$

where x_1^0, z_1^0 - are the coordinates of the center of gravity of the fluid.

To compile the Lagrange equation, we represent the kinetic and potential energy in the form [5]

$$T = \frac{1}{2} m_1 \dot{X}^2 + \gamma \rho \dot{X} \sum_{n=1}^{\infty} \dot{q}_n a_n + \frac{1}{2} m_{\mathcal{H}} \gamma \dot{X}^2 + \frac{1}{2} \gamma \sum m_n \dot{q}_n^2,$$

$$\Pi = \frac{1}{2} \mathcal{H} X^2 + \frac{1}{2} \gamma \rho g \sum g_n^2 + \frac{1}{2} \mathcal{H} c_1 \psi(X),$$

and the dispersion function from vibration dampers in spring sets and from the conventional absorbing apparatus of the tank-container will be found by the formula [6]

$$\Phi = \frac{1}{2} \gamma \sum \varepsilon_n \dot{q}_n^2 + \varphi \mathcal{H} |X \dot{X}|.$$

The static characteristic $F(X)$ of the absorbing apparatus, taking into account the rigidity of the tank-container, will take the following values

$$F(X) = \begin{cases} 0, & \text{if } a |X| < \delta; \\ X[1 + \varphi \text{sign}(X\dot{X})], & \delta \leq X \leq \Delta; \\ f(X), & \text{if } a |X| > \Delta; \end{cases} \quad (9)$$

where

$$f(X) = \begin{cases} 0, & \text{at } X < \Delta; \\ N + \kappa_2(X - \Delta) & \text{at } |X| > \Delta; \end{cases}$$

Δ - is the course of the absorbing apparatus, the characteristic of the real absorbing apparatus is shown in figure 2.

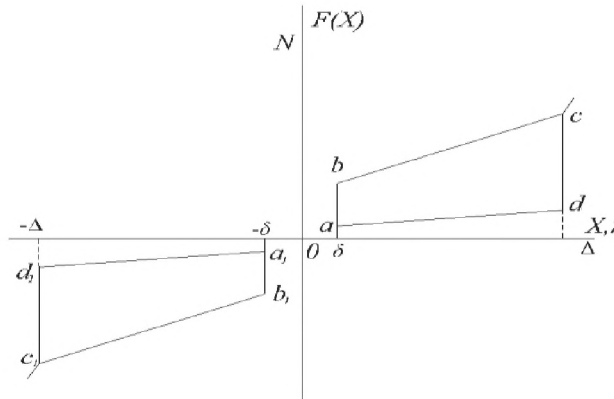


Figure 2 – Static characteristic of an absorbing apparatus

Substituting the potential and kinetic energy ratios, the scattering functions into the Lagrange equation of the second kind and, after performing some transformations, we obtain a system of differential equations describing the longitudinal vibrations of the liquid and the tank-container, taking into account the galloping of the railway platform at various speeds of collisions [7]:

$$\begin{cases} M\ddot{X} + l_2 m^* \ddot{\psi} + \rho \sum a_{2n-1} \ddot{q}_{2n-1} + F(X) = 0, \\ (I_1 + I^*)\ddot{\psi} + l_2 m^* \ddot{X} + \rho \sum \beta_{2n-1} \ddot{q}_{2n-1} + k^2 \psi + 2\beta l_3 \dot{\psi} - \rho g \sum a_{2n-1} \ddot{q}_{2n-1} = 0, \\ \rho \beta_{2n-1} \ddot{\psi} + \frac{\rho}{\mu_{2n-1}} \ddot{q}_{2n-1} + \rho a_{2n-1} \ddot{X} + 2\varepsilon_{2n-1} \frac{\rho}{\mu_{2n-1}} \dot{q}_{2n-1} - \rho g a_{2n-1} \psi + \rho g q_{2n-1} = 0, \end{cases} \quad (10)$$

where l_2 is the distance from the center of gravity of the «tank-container-liquid» system to the center of oscillation O ; $2l_3$ - base of the tank-container; m^* - is the compressed mass of the tank-container and railway platform; I_1 - moment of inertia of the tank-container relative to the transverse axis of rotation; I^* - is the moment of inertia of the equivalent body; $k^2 = 2\kappa l_3^2 - \rho g \tau_0 l_1 - m_1 g l_2$.

The hydrodynamic coefficients a_{2n-1} and β_{2n-1} are the coefficients of series expansion [8]

$$x_1 = \sum_{n=1}^{\infty} a_n \psi_n(x_1, 0) u \varphi_1^2 = \sum_{n=1}^{\infty} \beta_n \psi_n(x_1, 0) dx,$$

moreover

$$a_n = \int_{-\frac{d}{2}}^{\frac{d}{2}} x_1 \psi_n(x_1, 0) dx \quad u \quad \beta_n = \int_{-\frac{d}{2}}^{\frac{d}{2}} (\varphi_1^{(2)})_{z_1=0} \psi_n(x_1, 0) dx.$$

Calculating these integrals, we obtain

$$a_{2n-1} = \frac{2d^{\frac{3}{2}}}{(2n-1)^2 \pi^2}; \quad (11)$$

$$\beta_{2n-1} = \frac{2z^0 d^3}{(2n-1)^2 \pi^2} + \frac{8d^3}{(2n-1)^3 \pi^3} th \frac{(2n-1)\pi}{d} \left(\frac{R\sqrt{\pi}}{2} + \right). \tag{12}$$

By changing variables in the system of equations (10) $q_{2n-1} = x_{2n-1} a_{2n-1} \mu_{2n-1}$ we get [9]

$$\begin{cases} m\ddot{X} + l_2 m^* \ddot{\psi} + \sum \tilde{m}_{2n-1} \ddot{x}_{2n-1} + F(X) = 0, \\ I\ddot{\psi} + l_2 m^* \ddot{X} + \sum \delta_{2n-1} \tilde{m}_{2n-1} x_{2n-1} + k^2 \psi + 2\beta l_3 \dot{\psi} - g \sum \tilde{m}_{2n-1} x_{2n-1} = 0, \\ \delta_{2n-1} \ddot{\psi} + \ddot{X} + \ddot{x}_{2n-1} + 2\varepsilon_{2n-1} \dot{x}_{2n-1} - g\psi + \omega_{2n-1}^2 x_{2n-1} = 0, \text{ где } n = 1, 2, 3, \dots \end{cases} \tag{13}$$

The following notation is introduced in these equations:

$$I = I_1 + I^*; \delta_{2n-1} = z_1^0 + \frac{4d}{\pi} th \frac{(2n-1)\pi}{d} (\sqrt{\pi}R + h); \omega_{2n-1}^2 = g\mu_{2n-1}; \tilde{m}_{2n-1} = \rho a_{2n-1}^2 \mu_{2n-1} \gamma.$$

All coefficients of this system can be calculated and, therefore, it can be integrated. Using standard programs, all unknowns that are part of the system of equations (13), functions and their derivatives were obtained. At the same time, the longitudinal force was calculated according to relations (9) and the coefficient of dynamics k_{dyn} of spring sets according to the formula

$$k_{dyn} = \frac{\kappa\alpha\psi + \beta\alpha\dot{\psi}}{P_{cm}}. \tag{14}$$

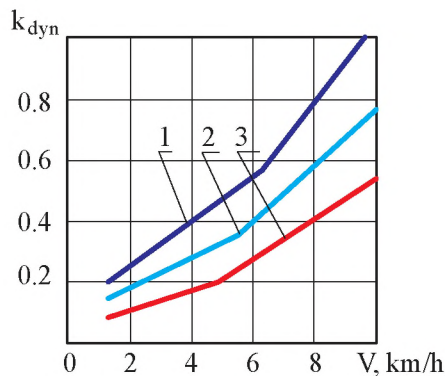
The resulting force of the hydrodynamic pressure of the liquid on the right bottom X_ε^1 and on the left bottom X_ε^2 will be equal to:

$$X_\varepsilon^1 = \rho \iint \left(\frac{\partial \varphi_a}{\partial t} \right)_{x=\frac{d}{2}} ds; X_\varepsilon^2 = -\rho \iint \left(\frac{\partial \varphi_a}{\partial t} \right)_{x=-\frac{d}{2}} ds.$$

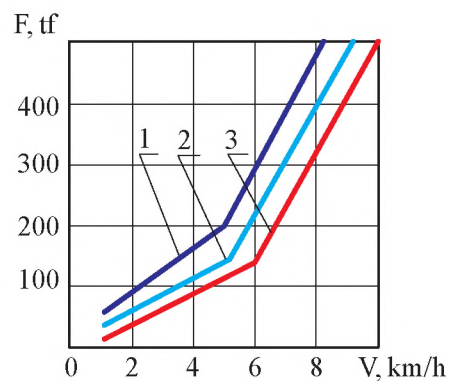
The magnitude of the hydrodynamic force will be equal to: $X_\varepsilon = X_\varepsilon^1 + X_\varepsilon^2$. To calculate the hydrodynamic pressure of the liquid on the bottom during the collision of the tank-container, hydrostatic force should be added to the hydrodynamic force [10]

$$P_\varepsilon = X_\varepsilon + X_\varepsilon^{cm} = X_\varepsilon + \iint_{\Sigma+s} (\rho_0 + \rho g z_1) ds.$$

Below are some results obtained on the basis of the proposed methodology using standard programs. Figures 3 and 4 show graphs of the dependence, respectively, of the coefficient of dynamics and longitudinal force on the speed of collision. The curves correspond to loading cases: 1- one tank-container; 2- two tank-containers; 3- three tank-containers.



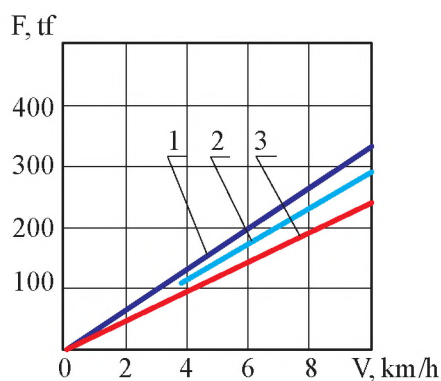
The curves correspond to the load: 1-one tank-container, 2- two tank-containers; 3- three tank-containers
Figure 3 – Graph of the dynamics coefficient versus impact velocity



The curves correspond to the load: 1- one tank-container, 2- two tank-containers; 3- three tank-containers
Figure 4 – Graph of longitudinal force versus impact velocity

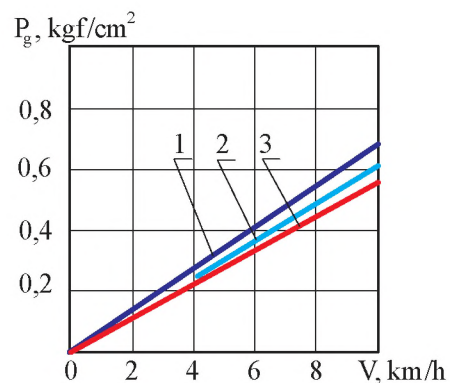
As can be seen from figure 3, the dynamic coefficient in the cases of loading two and three tank-containers is much less for the case of loading one tank-container for all impact speeds. The decrease in the value of the dynamics coefficient in these cases can be explained by the significantly greater inertia of these tank-containers, i.e. an increase in ρ - is the radius of inertia. For the case of loading three tank-containers, the limit value of the dynamics coefficient is reached at approximately a collision speed of 10 km/h.

Figure 4 shows that the longitudinal force increases with an increase in the collision velocity; moreover, the longitudinal force in the case of loading two and three tank-containers is higher than in the case of loading one tank-container. This is explained by the fact that the maximum longitudinal force is proportional to the square root of the platform mass [2,11] and, therefore, for the same stiffness of the inter-car connections, a greater longitudinal force will be manifested when a larger tank-container collides. Figures 5 and 6 show graphs of, respectively, the longitudinal force and hydrodynamic pressure versus the collision speed during underfilling of the tank-container. The curves correspond to the cases: 1- underfilling 0.3m; 2- underfilling 0.6m; 3- underfilling 0.9m.



The curves correspond to: 1 - underfilling 0.3 m;
2- underfilling 0.6m; 3- underfilling 0.9m

Figure 5 – Graph of the longitudinal force versus collision speed during underfilling of the tank-container



The curves correspond to: 1 - underfilling 0.3 m;
2- underfilling 0.6m; 3- underfilling 0.9m

Figure 6 – Graph of hydrodynamic pressure versus collision speed during underfilling of the tank-container

From the analysis of graphs 5 and 6 it is seen that the longitudinal force and hydrodynamic pressure of the liquid on the bottom of the container with an increase in the impact velocity increase at the same level of filling with liquid. With an increase in underfilling at the same collision velocity, the hydrodynamic pressure of the liquid increases. It should be noted that the effect of the oscillating fluid on the maximum longitudinal forces of the tank-container is less affected than the hydrodynamic pressure of the fluid in the bottom.

Conclusions: The dynamic coefficient in cases of loading two and three tank-containers is much less than in comparison with the case of loading one tank-container for all impact speeds. The decrease in the value of the dynamics coefficient in these cases can be explained by the significantly greater inertia of these tank-containers, i.e. an increase in ρ - is the radius of inertia.

Longitudinal force increases with an increase in collision velocity; moreover, the longitudinal force in cases of loading two and three tank-containers is higher than in comparison with the case of loading one tank-container. The longitudinal force and hydrodynamic pressure of the liquid on the bottom of the container with increasing collision velocity increase at the same level of filling with liquid. With an increase in underfilling at the same collision velocity, the hydrodynamic pressure of the liquid increases.

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БОЙЛЫҚ ТЕРБЕЛІС БАРЫСЫНДА СҰЙЫҚПЕН ТОЛТЫРЫЛҒАН ТАНК-КОНТЕЙНЕРДІҢ ТҰРАҚТЫЛЫҒЫН ЗЕРТТЕУ

Аннотация. Тербелмелі сұйықтықтың танк-контейнердің динамикалық тұрақтылығына түрлі деңгейде толтыру барысындағы әсері зерттеледі. Теориялық есептеуде танк-контейнері бар теміржол платформасының динамикалық тұрақтылығын зерттеудің негізгі әдісі – толық интеграциялау әдісі, яғни ішінде сұйықтық бар танк-контейнер қозғалысын сипаттайтын дифференциалдық теңдеулер жүйесінің барлық шешімі анықталды және сол бойынша қозғалыс тұрақтылығы туралы қорытынды жасалды. Сұйықтық пен танк-контейнердің бойлық тербелістерін зерттеу түрлі соқтығысу жылдамдығында қарастырылады.

Қозғалмаған бос беттің $O_1x_1z_1$ жазықтығында орналасқан, инерциялық OXZ және танк-контейнерге байланысты екі координаталық жүйені енгіземіз. Сұйықтық пен танк-контейнердің бойлық тербелістері серпіліс бұрышты ескерусіз қарастырады, яғни қозғалатын координаталар жүйесіне қатысты сұйықтық қозғалысы $q(t)$ функциясымен, ал бойлық тербеліс «контейнер-сұйықтық» жүйесінің қозғалысы $X(t)$ координат функциясы түрінде қарастырылады. Шешім гидродинамикалық есепті шешуге септігін тигізеді, яғни $\dot{X}(t)$ жылдамдықпен қозғалатын контейнердегі сұйықтықтың абсолютті жылдамдығын табуымыз қажет.

Теміржол платформасының серпілуін ескере отырып, сұйықтық пен танк-контейнердің бойлық тербелістерінің дифференциалдық теңдеулер жүйесі соқтығысу жылдамдығын ескере отырып, 2-ші ретті Лагранж теңдеуі негізінде алынды. 2-ші ретті Лагранж теңдеуін құру үшін кинетикалық және потенциалдық энергия, серіппелі дірілдеткіш қондырғылардан және танк-контейнерінің әдеттегі сіңіру аппараттарынан шашырау функциясы есептелді.

Стандартты бағдарламаларды қолдана отырып, дифференциалдық теңдеулер жүйесіне кіретін барлық белгісіз мәлімет, функция және олардың туындылары алынды. Сонымен қатар серіппелі жиынтықтардың бойлық күші мен динамика коэффициенті есептелді.

Сандық тәжірибелер ұсынылған әдіс негізінде стандартты бағдарламаларды қолдану негізінде жүргізілді. Сандық тәжірибе нәтижелері соқтығысу жылдамдықтарынан динамика коэффициенті, бойлық және гидродинамикалық күштер тәуелділік графигі түрінде келтірілген.

Екі және үш танк-контейнерін тиеу кезінде динамика коэффициенті барлық соқтығысу жылдамдығы үшін бір танк-контейнерін тиеумен салыстырғанда, едәуір аз. Бұл жағдайда динамик коэффициентінің төмендеу жағдайын осы танк-контейнер инерциясы, яғни ρ -инерция радиусының едәуір жоғарылау сипатымен түсіндіруге болады.

Бойлық күш соқтығысу жылдамдығының жоғарылауы негізінде артады, дегенмен екі және үш танк-контейнерін тиеу кезінде бойлық күштің мәні, бір танк-контейнерін тиеумен салыстырғанда үлкен келеді. Соқтығысу жылдамдығының жоғарылауы арқылы контейнер түбіндегі сұйықтың бойлық күші мен гидродинамикалық қысымы сұйықтықпен толтыру бір деңгейге жеткенде артады. Бірдей соқтығысу жылдамдығымен құйылып, аз толтырылғанда сұйықтықтың гидродинамикалық қысымы артады.

Түйін сөздер: динамикалық орнықтылық, танк-контейнер, рессорлық жинақ, үдеу, гидродинамикалық күш, соқтығысу жылдамдығы.

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ИССЛЕДОВАНИЕ УСТОЙЧИВОСТИ ТАНКА-КОНТЕЙНЕРА ЗАПОЛНЕННОЙ ЖИДКОСТЬЮ ПРИ ПРОДОЛЬНЫХ КОЛЕБАНИЯХ

Аннотация. Изучается влияние колеблющейся жидкости на динамическую устойчивость танка-контейнера при различной заполняемости емкости. Основным методом исследования динамической устойчивости железнодорожной платформы с танком-контейнером при теоретических расчетах является метод полной интеграции, т.е. находятся все решения системы дифференциальных уравнений, описывающих движение

танка-контейнера с жидкостью, и по ним выдается заключение об устойчивости движения. Исследование продольных колебаний жидкости и танка-контейнера рассматривается при различных скоростях соударения.

Введем две системы координат: инерционную OXZ и связанную с танком-контейнером, находящуюся в плоскости невозмущенной свободной поверхности $O_1x_1z_1$. Рассматриваются продольные колебания жидкости и танка-контейнера без учета угла галлопирования, т.е. движение жидкости относительно подвижной системы координат рассматривается функцией $q(t)$, а продольное колебание движение системы «контейнер-жидкость» в виде функции координаты $X(t)$. Решение сводится к решению задачи гидродинамики, т.е. нахождению абсолютной скорости жидкости в емкости контейнера, движущейся со скоростью $\dot{X}(t)$.

Система дифференциальных уравнений продольных колебаний жидкости и танка-контейнера с учетом галлопирования железнодорожной платформы получена на основе уравнения Лагранжа 2-го рода с учетом скорости соударения. Для составления уравнения Лагранжа 2-го рода были вычислены кинетическая и потенциальная энергия, функция рассеивания от гасителей колебаний в рессорных комплектах и от условного поглощающего аппарата танка-контейнера.

С использованием стандартных программ были получены все неизвестные, входящие в систему дифференциальных уравнений, функции и их производные. Одновременно были вычислены продольная сила и коэффициент динамической перегрузки рессорных комплектов.

Были проведены численные эксперименты на основе предложенной методики с использованием стандартных программ. Результаты численных экспериментов представлены в виде графиков зависимостей, соответственно, коэффициента динамики, продольной и гидродинамической силы от скорости соударения.

Коэффициент динамики в случаях загрузки двух и трех танков-контейнеров значительно меньше, чем по сравнению случаем загрузки одного танка-контейнера для всех скоростей соударения. Уменьшение значения коэффициента динамики в данных случаях можно объяснить значительно большей инерционностью этих танков-контейнеров, т.е. увеличением ρ - радиуса инерции.

Продольная сила растет с увеличением скорости соударения; причем значение продольной силы в случаях загрузки двух и трех танков-контейнеров больше, чем по сравнению случаем загрузки одного танка-контейнера. Продольная сила и гидродинамическое давление жидкости на днище контейнера с увеличением скорости соударения увеличиваются при одном и том же уровне заполнения жидкостью. При увеличении недолива при одной и той же скорости соударения гидродинамическое давление жидкости увеличивается.

Ключевые слова: динамическая устойчивость, танк-контейнер, рессорный комплект, ускорение, гидродинамическая сила, скорость соударения.

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