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IMPROVING OF TWO-LEVEL CAR HAULER STABILITY

To improve the car hauler lateral stability indicatin optimal cargo location parameters, elastically mounted on a platform, mathematical model of its motion was developed. At the same time fluctuations in cargo and car hauler were considered. Simulation results determined that for «hauler – cargo» system consideration of cargo elastic properties leads to a significant decrease in the frequency and amplitude of the system vertical oscillations. Therefore, the presence of the cargo can be regarded as a dynamic passive damping (in the case of a correct choice and design of layout parameters). It is proposed to reduce the distance between the cargo and the upper platform by determination of maximum values of the cargo oscillations amplitudes. In turn, the reduction of platform height reduces center gravity system height, improves the stability of car hauler.

***Keywords:** car hauler, dynamic processes, fluctuations, platform, stability.*

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ПІДВИЩЕННЯ СТІЙКОСТІ ДВОРІВНЕВОГО АВТОЕВАКУАТОРА

Для підвищення поперечної стійкості автоевакуатора шляхом визначення оптимальних параметрів розташування вантажу, що пружно закріплений на платформі, розроблено математичну модель його руху. При цьому враховано коливання вантажу та автоевакуатора. За результатами моделювання встановлено, що для системи «евакуатор – вантаж» урахування пружних властивостей вантажу приводить до істотного зменшення частоти та амплітуди вертикальних коливань системи. Отже, з'ясовано, що наявність вантажу можна розглядати як засіб динамічного пасивного гасіння коливань (у разі правильного вибору конструктивних і компонувальних параметрів). Запропоновано зменшувати відстань між вантажем і верхньою платформою завдяки визначенню величин максимальних амплітуд коливання вантажів. У свою чергу зниження висоти платформи зменшує висоту центра ваги системи, що підвищує стійкість автоевакуатора.

***Ключові слова:** автоевакуатор, динамічні процеси, коливання, платформа, стійкість.*

Introduction. Stability – is one of the factors which provides driving safety. It also allows to increase speed.

Electric systems are used to control stability of vehicle with a high center of mass, But it impairs vehicle course stability – deviation from chosen trajectory for decreasing lateral acceleration (which leads to rollover) [9]. The mass center's height significantly impacts on transverse stability of vehicle. This feature also concerns to two-level car hauler with elastically fixed weights, which fluctuate while driving.

Vehicles fluctuations are caused by road defects. Vehicle undergoing are low-freq. (15 – 18 Hz) and high-freq. fluctuations. Hard fixed weights fluctuates with high-freqs and elastically fixed weights fluctuates with low-freqs. Load of soft fixed masses is passing by elastic suspension elements [10].

It was established in research [11] that transverse fluctuations impair the vehicle lateral stability and depend on vehicle’s load. When vehicle drives elastically fixed weight, the height of mass center is changing. It leads to deterioration of lateral stability while performing maneuvers and the platform heeling.

Movable mechanical system with elastic fixed weights is quite common in vehicle building.

Car hauler is also movable mechanical system with elastic fixed weight. So it is essential to create a mathematical model of a car hauler with elastic fixed cars which fluctuates while driving objective research and analysis dynamical processes. This model should reproduce layout features and interaction of individual elements or parts of real vibrating system. The fixing method characterizes lateral stability and driving smoothness on the road. The typical fixing method provides hard fixed wheels by fixing straps. The car with hard fixed wheels generates vibration and fluctuations which impairs car hauler stability and driving smoothness. So the dynamic of vertical fluctuations should be researched considering additional spring-loaded weight.

Analysis of the last research sources and publications. The truck train stability improvements were researched by famous scientists, such as D.A. Antonov, P.V. Aksenov, V.P. Volkov, A.S. Litvinov, M.A. Podryhalo, V.P. Sakhno, A.P. Soltus, G.A. Smirnov [10 –14].

Many scientific works deal with researches of vertical fluctuations dynamic [1–10]. The most part of researches is about cars and trains for general purpose. There are no fundamental investigations of vehicle moving processes with elastically fixed weights, except semi trailer auto transporter [11], where cars are regarded as separate discrete mass points, elastically fixed on a platform.

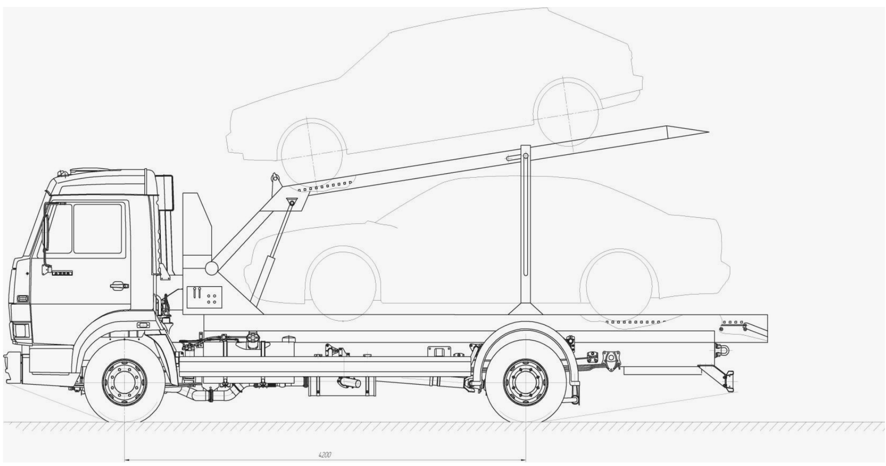

Figure 1 – Doubled car hauler

Car hauler is a complex mechanical system with lots of freedom degree. That's why it is difficult to calculate some parameters of system.

The main problem is optimizing and damping of fluctuations considering the standards ICO 2631-74 and GOST 12.1.012-78, which standardize fluctuations and vibrations and other parameters which provide stability and driving softness.

Specifing unsolved aspects of the problem. Source analisys proves that influence of elastic weight on vertical fluctuations dynamic and two level car hauler stability is not researched.

Objectives setting. The article target is researching of two level car hauler's vertical dynamic (fig. 1); mathematical description of its simplified circuit (fig. 2) for minimizing the amplitude of weight fluctuations by its rational positioning on a platform; improving a lateral stability of vehicle by mass center height decreasing.

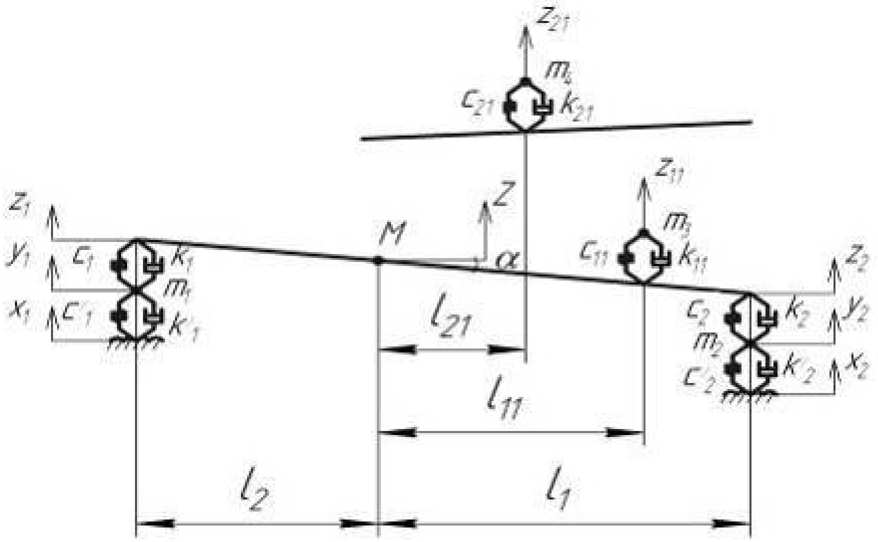

Figure 2 – Calculating circuit of car hauler

The mains and researches. Mathematical model of the fluctuations is described by differential equations based on Lagrange 2[nd] kind equations. It is based on kinematic and dynamic analysis of car hauler structures:

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i}=\frac{\partial L}{\partial q_i}-\frac{\partial R}{\partial \dot{q}_i}, \qquad (1)$$

where $L = T - U$ – Lagrange function;

T, U, R – in accordance kinematic, potential energy and dissipative function;

q_j – generalized coordinate.

Lagrange 2[nd] kind equations can be displayed like:

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{q}_i}-\frac{d}{dt}\frac{\partial U}{\partial \dot{q}_i}=\frac{\partial T}{\partial q_i}-\frac{\partial U}{\partial q_i}-\frac{\partial R}{\partial \dot{q}_i}. \qquad (2)$$

Shifting is calculated considering relative position of static equilibrium. Then equations type stays the same with(out) the weight force which can be unspecified. Lets take function (1) for car hauler movement. For Z axis elastic vertical movements were chosen and for Y axis inelastic vertical movements were chosen in accordance with fig. 2. Disturbing function X selected profile of single inequality as half sine wave [5]. Individual irregularities vibrations caused by the road vary according to a sinusoidal law. The differences are quantitative and insignificant.

Mark: m_1 , m_2 – inelastic masses of appropriate axles of car hauler;

m_3, m_4 – masses of elastic weights;

M, I – elastic mass of car hauler and its inertia moment of the central axis, that is perpendicular to the plane of the figure;

c_1 , c_2 , c'_1, c'_2 ,c_{11}, c_{21}, k_1 , k_2 , k'_1, k'_2, k_{11}, k_{21} – appropriate equivalent stiffness of suspensions and tires and their coefficient of viscous friction;

l_1 , l_2 , l_{11}, l_{12} – appropriate geometrical parameters of car hauler.

Define the kinetic energy of the system:

$$T=\frac{1}{2}M\cdot\dot{z}^2+\frac{1}{2}I\cdot\dot{\alpha}^2+\frac{1}{2}m_1\cdot\dot{y}_1^2+\frac{1}{2}m_2\cdot\dot{y}_2^2+\frac{1}{2}m_3\cdot\dot{z}_{11}^2+\frac{1}{2}m_4\cdot\dot{z}_{21}^2, \tag{3}$$

where is

$$z=\frac{z_1\cdot l_2+z_2\cdot l_1}{l_1+l_2},\quad \alpha=\frac{z_1-z_2}{l_1+l_2}.$$

Define the potential energy of the system:

$$\begin{aligned}U&=\frac{1}{2}c_1\left(z_1-y_1\right)^2+\frac{1}{2}c'_1\left(y_1-x_1\right)^2+\frac{1}{2}c_2\left(z_2-y_2\right)^2+\frac{1}{2}c'_2\left(y_2-x_2\right)^2+\\&+\frac{1}{2}c_{11}\left(z_{11}+\frac{z_1-z_2}{l_1+l_2}\cdot l_{11}\right)^2+\frac{1}{2}c_{21}\left(z_{21}+\frac{z_1-z_2}{l_1+l_2}\cdot l_{21}\right)^2=\\&=\frac{1}{2}c_1\left(z_1^2-2z_1y_1+y_1^2\right)+\frac{1}{2}c'_1\left(y_1^2-2y_1x_1+x_1^2\right)+\frac{1}{2}c_2\left(z_2^2-2z_2y_2+y_2^2\right)+\\&+\frac{1}{2}c'_2\left(y_2^2-2y_2x_2+x_2^2\right)+\frac{1}{2}c_{11}\left(z_{11}^2+2z_{11}\alpha\cdot l_{11}+\alpha^2l_{11}^2\right)+\\&+\frac{1}{2}c_{21}\left(z_{21}^2+2z_{21}\alpha\cdot l_{21}+\alpha^2l_{21}^2\right).\end{aligned} \tag{4}$$

Rayleigh dissipative function:

$$\begin{aligned}R&=\frac{1}{2}k_1\left(\dot{z}_1-\dot{y}_1\right)^2+\frac{1}{2}k'_1\left(\dot{y}_1-\dot{x}_1\right)^2+\frac{1}{2}k_2\left(\dot{z}_2-\dot{y}_2\right)^2+\frac{1}{2}k'_2\left(\dot{y}_2-\dot{x}_2\right)^2+\\&+\frac{1}{2}k_{11}\left(\dot{z}_{11}+\frac{\dot{z}_1-\dot{z}_2}{l_1+l_2}\cdot l_{11}\right)^2+\frac{1}{2}k_{21}\left(\dot{z}_{21}+\frac{\dot{z}_1-\dot{z}_2}{l_1+l_2}\cdot l_{21}\right)^2=\\&=\frac{1}{2}k_1\left(\dot{z}_1^2-2\dot{z}_1\dot{y}_1+\dot{y}_1^2\right)+\frac{1}{2}k'_1\left(\dot{y}_1^2-2\dot{y}_1\dot{x}_1+\dot{x}_1^2\right)+\frac{1}{2}k_2\left(\dot{z}_2^2-2\dot{z}_2\dot{y}_2+\dot{y}_2^2\right)+\\&+\frac{1}{2}k'_2\left(\dot{y}_2^2-2\dot{y}_2\dot{x}_2+\dot{x}_2^2\right)+\frac{1}{2}k_{11}\left(\dot{z}_{11}^2+2\dot{z}_{11}\dot{\alpha}\cdot l_{11}+\dot{\alpha}^2l_{11}^2\right)+\\&+\frac{1}{2}k_{21}\left(\dot{z}_{21}^2+2\dot{z}_{21}\alpha\cdot l_{21}+\dot{\alpha}^2l_{21}^2\right).\end{aligned} \tag{5}$$

Derivatives are needed to prepare for the second kind of Lagrange equation:

$$\begin{aligned}\frac{\partial T}{\partial\dot{z}_1}&=\frac{M}{2\left(l_1+l_2\right)^2}\cdot\left(2\dot{z}_1\cdot l_2^2+2\dot{z}_2\cdot l_2\cdot l_1\right)+\frac{I\left(2\dot{z}_1-2\dot{z}_2\right)}{2\left(l_1+l_2\right)^2}=\\&=\frac{M\cdot l_2^2+I}{\left(l_1+l_2\right)^2}\cdot\dot{z}_1+\frac{M\cdot l_2\cdot l_1-I}{\left(l_1+l_2\right)^2}\cdot\dot{z}_2,\end{aligned} \tag{6}$$

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{z}_1} = a_{11}\ddot{z}_1 + a_{12}\ddot{z}_2 \tag{7}$$

where

$$a_{11} = \frac{M \cdot l_2^2 + I}{\left(l_1 + l_2\right)^2},\; a_{12} = \frac{M \cdot l_2 \cdot l_1 - I}{\left(l_1 + l_2\right)^2},$$

$$\begin{aligned} \frac{\partial T}{\partial \dot{z}_2} &= \frac{M}{2\left(l_1 + l_2\right)^2} \cdot \left(2\dot{z}_1 \cdot l_2 \cdot l_1 + 2\dot{z}_2 \cdot l_1^2\right) + \frac{I\left(-2\dot{z}_1 + 2\dot{z}_2\right)}{2\left(l_1 + l_2\right)^2} = \\ &= \frac{M \cdot l_2 \cdot l_1 - I}{\left(l_1 + l_2\right)^2} \cdot \dot{z}_1 + \frac{M \cdot l_1^2 + I}{\left(l_1 + l_2\right)^2} \cdot \dot{z}_2, \end{aligned} \tag{8}$$

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{z}_2} = a_{21}\ddot{z}_1 + a_{22}\ddot{z}_2, \tag{9}$$

where

$$a_{21} = \frac{M \cdot l_2 \cdot l_1 - I}{\left(l_1 + l_2\right)^2},\; a_{22} = \frac{M \cdot l_1^2 + I}{\left(l_1 + l_2\right)^2},$$

$$\frac{\partial T}{\partial \dot{y}_1} = \frac{1}{2} \cdot m_1 \cdot 2\dot{y}_1 = m_1 \dot{y}_1, \tag{10}$$

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{y}_1} = m_1 \ddot{y}_1. \tag{11}$$

Similarly define derivatives:

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{y}_2} = m_2 \ddot{y}_2, \tag{12}$$

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{z}_{11}} = m_3 \ddot{z}_{11}, \tag{13}$$

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{z}_{21}} = m_4 \ddot{z}_{21}. \tag{14}$$

Find the partial derivative of potential energy (4) for the generalized speed dq_i :

$$\frac{\partial U}{\partial \dot{z}_1} = \frac{\partial U}{\partial \dot{z}_2} = \frac{\partial U}{\partial \dot{y}_1} = \frac{\partial U}{\partial \dot{y}_2} = \frac{\partial U}{\partial \dot{z}_{11}} = \frac{\partial U}{\partial \dot{z}_{21}} = 0, \tag{15}$$

then

$$\frac{d}{dt}\frac{\partial U}{\partial \dot{z}_1} = \frac{d}{dt}\frac{\partial U}{\partial \dot{z}_2} = \frac{d}{dt}\frac{\partial U}{\partial \dot{y}_1} = \frac{d}{dt}\frac{\partial U}{\partial \dot{y}_2} = \frac{d}{dt}\frac{\partial U}{\partial \dot{z}_{11}} = \frac{d}{dt}\frac{\partial U}{\partial \dot{z}_{21}} = 0. \tag{16}$$

To compile the right of Lagrange equations of the second kind makes differentiation.

Partial derivatives of kinetic energy T on generalized coordinates q_i equal to:

$$\frac{\partial T}{\partial z_1}=\frac{\partial T}{\partial z_2}=\frac{\partial T}{\partial y_1}=\frac{\partial T}{\partial y_2}=\frac{\partial T}{\partial z_{11}}=\frac{\partial T}{\partial z_{21}}=0\,, \tag{17}$$

Define the partial derivative of potential energy for the generalized coordinates q_i :

$$\frac{\partial U}{\partial z_1}=\frac{1}{2}c_1\left(2z_1-2y_1\right)=c_1\left(z_1-y_1\right), \tag{18}$$

$$\frac{\partial U}{\partial z_2}=\frac{1}{2}c_2\left(2z_2-2y_2\right)=c_2\left(z_2-y_2\right), \tag{19}$$

$$\frac{\partial U}{\partial y_1}=\frac{1}{2}c_1^{/}\left(2y_1-2x_1\right)=c_1^{/}\left(y_1-x_1\right), \tag{20}$$

$$\frac{\partial U}{\partial y_2}=\frac{1}{2}c_2^{/}\left(2y_2-2x_2\right)=c_2^{/}\left(y_2-x_2\right), \tag{21}$$

$$\frac{\partial U}{\partial z_{11}}=\frac{1}{2}c_{11}\left(2z_{11}+2\alpha\cdot l_{11}\right)=c_{11}\left(z_{11}+\alpha\cdot l_{11}\right), \tag{22}$$

$$\frac{\partial U}{\partial z_{21}}=\frac{1}{2}c_{21}\left(2z_{21}+2\alpha\cdot l_{21}\right)=c_{21}\left(z_{21}+\alpha\cdot l_{21}\right). \tag{23}$$

Next, find the partial derivatives of Rayleigh dissipative function for the generalized speed ∂q_i

$$\frac{\partial R}{\partial \dot{z}_1}=\frac{1}{2}k_1\left(2\dot{z}_1-2\dot{y}_1\right)=k_1\left(\dot{z}_1-\dot{y}_1\right), \tag{24}$$

$$\frac{\partial R}{\partial \dot{z}_2}=\frac{1}{2}k_1\left(2\dot{z}_2-2\dot{y}_2\right)=k_1\left(\dot{z}_2-\dot{y}_2\right), \tag{25}$$

$$\frac{\partial R}{\partial \dot{y}_1}=\frac{1}{2}k_1^{/}\left(2\dot{y}_1-2\dot{x}_1\right)=k_1^{/}\left(\dot{y}_1-\dot{x}_1\right), \tag{26}$$

$$\frac{\partial R}{\partial \dot{y}_2}=\frac{1}{2}k_2^{/}\left(2\dot{y}_2-2\dot{x}_2\right)=k_2^{/}\left(\dot{y}_2-\dot{x}_2\right), \tag{27}$$

$$\frac{\partial R}{\partial \dot{z}_{11}}=\frac{1}{2}k_{11}\left(2\dot{z}_{11}+2\dot{\alpha}\cdot l_{11}\right)=k_{11}\left(\dot{z}_{11}+\dot{\alpha}\cdot l_{11}\right), \tag{28}$$

$$\frac{\partial R}{\partial \dot{z}_{21}}=\frac{1}{2}k_{21}\left(2\dot{z}_{21}+2\dot{\alpha}\cdot l_{21}\right)=k_{21}\left(\dot{z}_{21}+\dot{\alpha}\cdot l_{21}\right). \tag{29}$$

Substituting fragments (3) – (29) into Lagrange equation (2) to get a system of six second order differential equations (30), that describes the vertical oscillations towing considering the elastic weight properties.

$$\begin{cases} a_{11}\ddot{z}_1 + a_{12}\ddot{z}_2 + k_1(\dot{z}_1 - \dot{y}_1) + c_1(z_1 - y_1) = 0 \\ a_{21}\ddot{z}_1 + a_{22}\ddot{z}_2 + k_2(\dot{z}_2 - \dot{y}_2) + c_2(z_2 - y_2) = 0 \\ m_1\ddot{y}_1 + k_1'(\dot{z}_1 - \dot{x}_1) + c_1'(z_1 - x_1) = 0 \\ m_2\ddot{y}_2 + k_2'(\dot{z}_2 - \dot{x}_2) + c_2'(z_2 - x_2) = 0 \\ m_3\ddot{z}_{11} + k_{11}(\dot{z}_{11} + \dot{\alpha}\cdot l_{11}) + c_{11}(z_{11} + \alpha\cdot l_{11}) = 0 \\ m_4\ddot{z}_{21} + k_{21}(\dot{z}_{21} + \dot{\alpha}\cdot l_{21}) + c_{21}(z_{21} + \alpha\cdot l_{21}) = 0. \end{cases} \qquad (30)$$

On the basis of rational equations it is possible to determine optimal coordinates for weight placing on vehicles provided minimum fluctuations on its platform. Set next:

$$\omega_1 = \sqrt{\frac{c_{11}\cdot\alpha\cdot l_{11}}{m_3}}\ ; \qquad \omega_2 = \sqrt{\frac{c_{21}\cdot\alpha\cdot l_{21}}{m_4}}\ , \qquad (31)$$

where ω_1 and ω_2 is a weight fluctuation freqs.

To reduce the mutual influence of fluctuations and avoid resonance it is essential toprovide the maximum frequency differentiation.

$$\max\left[\sqrt{\frac{c_{11}\cdot\alpha\cdot l_{11}}{m_3} - \sqrt{\frac{c_{21}\cdot\alpha\cdot l_{21}}{m_4}}}\right]. \qquad (32)$$

In cause, that

$$\frac{m_3\cdot l_{11} + m_4 l_{21}}{l_{11} + l_{21}} = a\,.$$

Chosing l_{11}, l_{21} by method of finding the conditional Lagrange extremum

$$\hat{o}(l_{11}, l_{21}) = \left(\sqrt{\frac{c_{11}\cdot\alpha\cdot l_{11}}{m_3} - \sqrt{\frac{c_{21}\cdot\alpha\cdot l_{21}}{m_4}}}\right) + \lambda\left(\frac{m_3\cdot l_{11} + m_4 l_{21}}{l_{11} + l_{21}}\right), \qquad (33)$$

where λ – Lagrange multiplier.

To find l_{11}, l_{21} write the Lagrange equation in cause, that:

$$\hat{o}'_{11} = 0\ ; \qquad \hat{o}'_{21} = 0\ ;$$

$$\begin{cases} \frac{1}{2}\sqrt{c_{11}\cdot\alpha}\cdot\sqrt{\frac{1}{m_3\cdot l_{11}}} + \lambda\left(\frac{m_3\cdot l_{11}}{l_{11}+l_{21}}\right)_{l_{11}} = 0 \\ \frac{1}{2}\sqrt{\frac{c_{21}\cdot\alpha}{m_4\cdot l_{21}}} + \lambda\left(\frac{m_3\cdot l_{21}}{l_{11}+l_{21}}\right)_{l_{21}} = 0 \\ \frac{m_3\cdot l_{11} + m_4 l_{21}}{l_{11}+l_{21}} = a. \end{cases} \qquad (34)$$

Find the original

$$\lambda\left(\frac{m_3\cdot l_{11}}{l_{11}+l_{21}}\right)'_{l_{11}} = \lambda m_3\left(\frac{(l_{11}+l_{21}) - l_{11}}{(l_{11}+l_{21})^2}\right) = \frac{\lambda\cdot m_3\cdot l_{21}}{l_{11}+l_{21}}. \qquad (35)$$

In cause, that

$$\left[a = \frac{l}{2}\right],$$

$$\begin{cases} \frac{1}{2}\sqrt{\frac{c_{11}\cdot\alpha}{m_3\cdot l_{11}}} + \frac{\lambda\cdot m_3\cdot l_{21}}{(l_{11}+l_{21})^2} = 0 \\ \frac{1}{2}\sqrt{\frac{c_{21}\cdot\alpha}{m_4\cdot l_{21}}} + \frac{\lambda\cdot m_4\cdot l_{11}}{(l_{11}+l_{21})^2} = 0 \\ \frac{m_3\cdot l_{11}+m_4\cdot l_{21}}{l_{11}+l_{21}} = a. \end{cases} \quad (36)$$

The result of the decision system – rational coordinates for placing weights on a platform l_{11} and l_{12}.

As a result of calculation adopted by the initial data received schedules fluctuations of car hauler and cars-weights on it. (fig. 3 – 6).

Fluctuations in the rear and front axles of car hauler represent sinusoid that are exponented as damping. The maximum displacement is 0.0045 m in the first seconds of motion when hitting an obstacle.

Moving of weights at both loading platform (Fig. 5, 6) is also sinusoids that is exponented as damping. For the car, placed on top platform the maximum amplitude is 0.0035 m. The smallest displacement from equilibrium gets the car, placed on the bottom platform. It is 0.0025 m. Thus it is possible to reduce the gap to acceptable level between the car roof and upper platform to lower the center of gravity of the system.

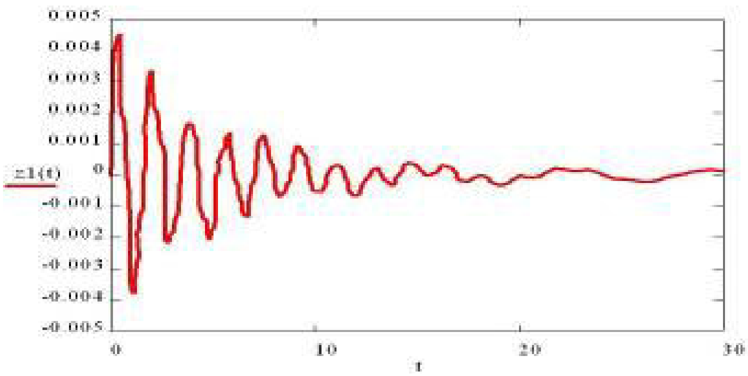

Figure 3 – Car hauler front axle shiftings

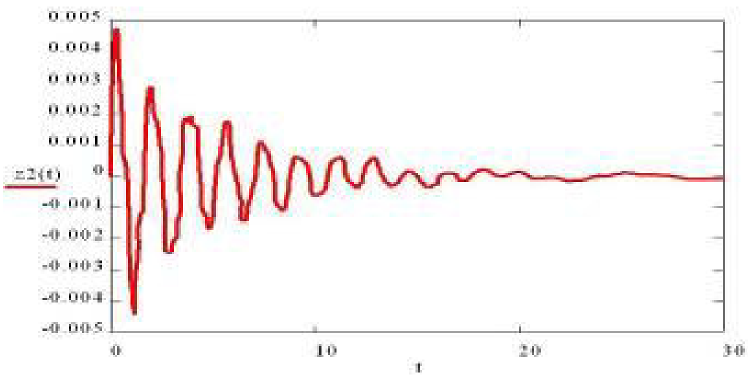

Figure 4 – Car hauler rear axle shiftings

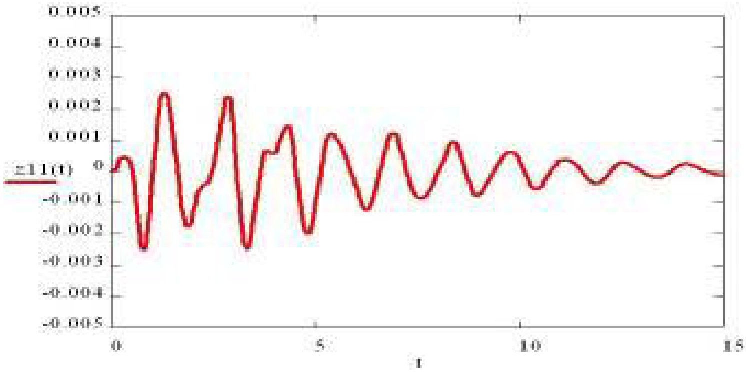

Figure 5 – Car-weight shifting on bottom platform

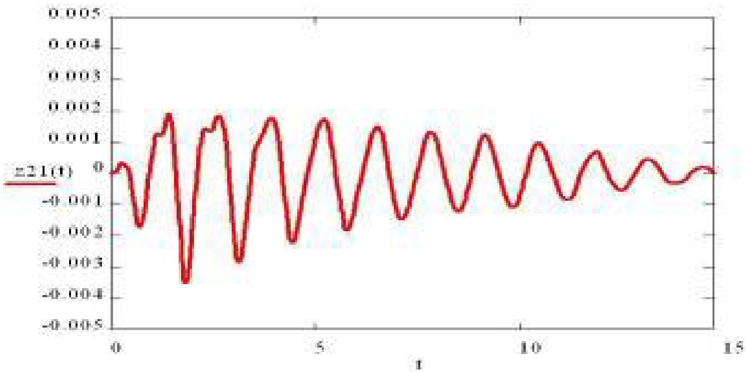

Figure 6 – Car-weight shifting on top platform

Conclusions. The simulation results indicate that considering of weight elastic properties in system «car hauler – car» leads to significant decreasing of the frequency and amplitude of the vertical fluctuations of the system. Thus, the availability of cargo can be viewed as a mean of passive dynamic vibration reduction (in case of correct choice of constructional and layout options). In this case there will be certain resonance speed of the system, which will show this effect as much as possible.

Determination of the maximum amplitude of cargo's fluctuations enables to reduce the distance between the cargo and the upper platform. In its turn lowering the platform reduces the height of gravity center system, which improves stability car hauler.

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