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DETERMINATION OF BUFFERS FORCES DURING WAGONS IMPACT

Dragan Petrović
petrovic.d@mfkv.kg.ac.rs

University of Kragujevac, Faculty of Mechanical and Civil Engineering in Kraljevo, Dositejeva 19, 36000 Kraljevo, SERBIA

Key words: *Dynamic parameters, Wagons impact, Buffer forces*

Abstract: *When two wagons collide or when the wagons change the tempo of moving (starting, stopping, braking) there are longitudinal forces and accelerations that affect the stress-strain state of the supporting structures of the wagon. These loads can cause stress and strain of such magnitude to constitute a risk to the support structure of the wagons, and therefore for passengers and cargo. This paper is a continuation of research that has been implemented in the Wagon Factory of Kraljevo and the Faculty of Mechanical Engineering & Construction in Kraljevo, and it is focused on an accurate analysis of the collision of two vehicles. Additionally, the theoretical equations of wagon collision are numerically solved and the results are compared with experimental ones. Comparative analysis of analytical, numerical and experimental results of wagons collision has shown satisfactory agreement. In that way, the adopted analytical model can be used for determining the dynamic parameters of the collision in the design of new wagons structures.*

1. INTRODUCTION

Generally, the construction of wagon consists of body, underframe, bogies, buffers, braking system, and various additional parts and equipment. Impact causes the dynamic parameters such as forces and accelerations, whose changes and maximum values depend on the speed of the impact and the characteristics of the mentioned sub-assemblies, as well as the type of cargo and its fixing for the supporting structure of wagon [1]. Such a complex system with many degrees of freedom is replaced with the simpler theoretical models with a limited number of degrees of freedom. In the formation of mathematical models the following restrictions are usually introduced: the construction of wagons and bogies, as well as cargo, are considered to be absolutely rigid bodies, the railway track is horizontal, centres of masses of cargo and wagons move in parallel, i.e. there is no relative movement between the cargo and wagons. Experimental testing has shown that these simplifications lead to the insufficiently accurate results in analysis of wagons impact. The most frequently used models of wagons impact do not take into account the influence of cargo movement during the impact, gaps in assemblies of wagons, influence of the loss of energy during the impact, etc [2, 3]. In order to determine the above-mentioned influences on the values of forces on the buffers during the impact of two wagons, more accurately and somewhat more complex model has been formed [4].

2. THEORETICAL ANALYSIS OF IMPACT OF TWO WAGONS

Consider the case of two wagons impact with buffers stiffness c_1 and c_2, and stiffness of underframes c_{ns1} and c_{ns2}. Wagon whose mass is m_1 is moving with the speed $\vec{v}_1$ and collides with wagon of mass m_2 which moves with the speed $\vec{v}_2$. Wagons are loaded with cargoes whose masses are m_3 and m_4. This is resulted with the relative movement of masses over the wagons for values $\vec{x}_3$ and $\vec{x}_4$. In addition, between the wagons and cargoes there are elastic connections with stiffness c_3 and c_4. Apart from that, the relative movements of cargoes with masses m_3 and m_4 are opposed by forces of dry friction and forces of viscous friction. These forces are proportional to the first degree of speeds of relative movements of cargoes $\vec{\dot{x}}_3$ and $\vec{\dot{x}}_4$. Also, the movements of the first and the second wagon are opposed by forces of rolling friction $\mu_1 \cdot g \cdot (m_1 + m_3)$ and $\mu_2 \cdot g \cdot (m_2 + m_4)$. The process of impact is observed from the moment when buffers of two wagons touch each other. All buffers have the same elastic properties, so that the total buffers movement is $2\Delta\ell$. Since the impact of wagons can be considered as event in an isolated system where the forces, speeds, accelerations or other dynamic sizes of the wagons and cargoes are in the same direction before and after the impact, they can be written without vector label.

Equations for kinetic energy E_k, potential energy E_p and dissipation function Φ_r of the system on Fig.1 are [5]:

$$E_k = \frac{1}{2} m_1 \dot{x}_1^2 + \frac{1}{2} m_2 \dot{x}_2^2 + \frac{1}{2} m_3 \left(\dot{x}_3 + \dot{x}_1\right)^2 + \frac{1}{2} m_4 \left(\dot{x}_4 + \dot{x}_2\right)^2$$

$$E_p = \frac{1}{2} c_s \left(x_2 - x_1\right)^2 + \frac{1}{2} c_3 x_3^2 + \frac{1}{2} c_4 x_4^2 \tag{1}$$

$$\Phi_r = \mu_1 (m_1 + m_3) g \left|\dot{x}_1\right| + \mu_2 (m_2 + m_4) g \left|\dot{x}_2\right| + \mu_3 m_3 g \left|\dot{x}_3\right| + \mu_4 m_4 g \left|\dot{x}_4\right| + \frac{1}{2} \beta_3 \dot{x}_3^2 + \frac{1}{2} \beta_4 \dot{x}_4^2$$

where: c_s – equivalent stiffness of the system at the moment of impact; μ_1, μ_2, μ_3 and μ_4 – coefficients of dry friction; β_3 and β_4 – dynamic viscosities that define the environment resistance; g – acceleration due to gravity.

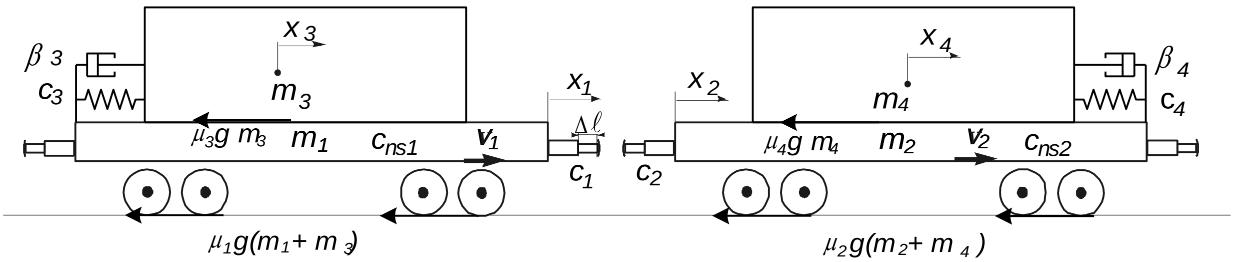

Figure 1: The impact of two wagons when the movement of cargo is present

As the system is influenced by the conservative and dissipative forces, the Lagrange equations of second kind have the following form:

$$\frac{d}{dt}\frac{\partial E_k}{\partial \dot{q}_i} + \frac{\partial \Phi_r}{\partial \dot{q}_i} + \frac{\partial E_p}{\partial q_i} = 0 \tag{2}$$

By changing the equations for kinetic and potential energy into the previous equations, as well as changing the equation for dissipation function, we get the following differential equations:

$$
\begin{aligned}
&(m_1+m_3)\ddot{x}_1+m_3\ddot{x}_3+c_s x_1-c_s x_2+\mu_1(m_1+m_3)g\cdot sign\dot{x}_1=0\\
&(m_2+m_4)\ddot{x}_2+m_4\ddot{x}_4+c_s x_2-c_s x_1+\mu_2(m_2+m_4)g\cdot sign\dot{x}_2=0\\
&m_3\ddot{x}_3+m_3\ddot{x}_1+\beta_3\dot{x}_3+c_3x_3+\mu_3 m_3 g\cdot sign\dot{x}_3=0\\
&m_4\ddot{x}_4+m_4\ddot{x}_2+\beta_4\dot{x}_4+c_4x_4+\mu_4 m_4 g\cdot sign\dot{x}_4=0
\end{aligned}
\tag{3}
$$

The system of differential equations (3) defined in this way takes into account both the movement of cargoes and the influence of friction that occurs between the individual sub-assemblies when two wagons collide, and it is suitable for numerical solution. Also, the function signum (sign) allows the determination of the sign of friction forces that depends on the speeds of the movement of wagons and cargoes. In order to preparation for numerical solution of system of differential equations (3), the changing of the third equation in the first one, and the fourth equation in the second one, is performed:

$$
\begin{aligned}
&\ddot{x}_1=a_1(x_2-x_1)+a_2x_3+a_9\dot{x}_3-a_{10}sign\dot{x}_1+a_{13}sign\dot{x}_3\\
&\ddot{x}_2=a_3(x_1-x_2)+a_4x_4+a_5\dot{x}_4-a_{11}sign\dot{x}_2+a_{14}sign\dot{x}_4
\end{aligned}
\tag{4}
$$

By changing the first equation (4) in the third equation (3) and second equation (4) in the fourth equation (3) we obtain the following equations:

$$
\begin{aligned}
&\ddot{x}_3=a_1(x_1-x_2)-(a_2+a_{12})x_3-(a_9+a_7)\dot{x}_3+a_{10}sign\dot{x}_1-(a_{13}+a_{15})sign\dot{x}_3\\
&\ddot{x}_4=a_3(x_2-x_1)-(a_4+a_8)x_4-(a_5+a_6)\dot{x}_4+a_{11}sign\dot{x}_2-(a_{14}+a_{16})sign\dot{x}_4
\end{aligned}
\tag{5}
$$

The constants $a_1 \div a_{16}$ are given in the following Table 1.

Table 1: The values of the constants $a_1 \div a_{16}$

a_1	a_2	a_3	a_4
c/m_1	c_3/m_1	c/m_2	c_4/m_2
a_5	a_6	a_7	a_8
β_4/m_2	β_4/m_4	β_3/m_3	c_4/m_4
a_9	a_{10}	a_{11}	a_{12}
β_3/m_1	$\mu_1\frac{m_1+m_3}{m_1}g$	$\mu_2\frac{m_2+m_4}{m_2}g$	c_3/m_3
a_{13}	a_{14}	a_{15}	a_{16}
$\mu_3\frac{m_3}{m_1}g$	$\mu_4\frac{m_4}{m_2}g$	$\mu_3 g$	$\mu_4 g$

This system, however, does not take into account the reduction of impact forces due to the loss of energy in oscillating structures of wagons during the impact. This effect can be taken into account by using Newton's coefficient of restitution. However, when it comes to the railway vehicles, the coefficient of restitution at impact can be determined only by the experimental testing [4, 6]. By introducing the following sizes:

$$
\begin{aligned}
&y_1=x_1,\quad y_2=\dot{x}_1,\quad y_3=x_2,\quad y_4=\dot{x}_2,\\
&y_5=x_3,\quad y_6=\dot{x}_3,\quad y_7=x_4,\quad y_8=\dot{x}_4
\end{aligned}
\tag{6}
$$

the final form of differential equations of two wagons impact is obtained:

$$
\begin{aligned}
&\ddot{x}_1=a_1(y_3-y_1)+a_2y_5+a_9y_6-a_{10}signy_2+a_{13}signy_6\\
&\ddot{x}_2=a_3(y_1-y_3)+a_4y_7+a_5y_8-a_{11}signy_4+a_{14}signy_8\\
&\ddot{x}_3=a_1(y_1-y_3)-(a_2+a_{12})y_5-(a_7+a_9)y_6+a_{10}signy_2-(a_{13}+a_{15})signy_6\\
&\ddot{x}_4=a_3(y_3-y_1)-(a_4+a_8)y_7-(a_5+a_6)y_8+a_{11}signy_4-(a_{14}+a_{16})signy_8
\end{aligned}
\tag{7}
$$

Such defined system of differential equations takes into account the movement of cargoes during the wagons impact, and is suitable for solution in numerical way.

3. NUMERICAL SIMULATION OF IMPACT OF TWO WAGONS

Based on the formed system of differential equations which describe the dynamic process of the impact of two wagons, a program for their solution is made. It is important to note that method of Runge-Kutta of IV level and programming language Fortran 77 were used [7, 8]. Based on the underlying methodology, the process of two wagons impact is simulated whereby model enables calculations with and without movement of cargo during the impact. Dynamic parameters that were followed during the impact are: t–time, x_1 –movement of the wagon that hits into the other one, $\dot{x}_1$–speed of the wagon that hits into the other one, $\ddot{x}_1$– acceleration of the wagon that hits into the other one, x_2–movement of the wagon that is being hit, $\dot{x}_2$–speed of the wagon that is being hit, $\ddot{x}_2$–acceleration of the wagon that is being hit, x_3–movement of the cargo on the wagon that hits into the other one, $\dot{x}_3$–speed of the cargo on the wagon that hits into the other one, $\ddot{x}_3$–acceleration of the cargo on the wagon that hits into the other one, x_4–movement of the cargo of the wagon that is being hit, $\dot{x}_4$– speed of the cargo of the wagon that is being hit, $\ddot{x}_4$–acceleration of the cargo of the wagon that is being hit, F_u– the total force on the buffers. Total force on the buffers in period until the complete compaction of buffers is:

$$x_1(t)-x_2(t)\le 2\Delta\ell; \qquad F_u(t)=F^o \tag{8}$$

where F^o is the force which occurs when buffers are completely compacted.

Total force on the buffers in period of solid impact occurs when buffers are completely compacted:

$$x_1(t)-x_2(t)> 2\Delta\ell; \qquad F_u(t)=F_u \tag{9}$$

Consequently, the mathematical model of change of force during the impact is defined by the following equation:

$$F_u(t)=\begin{cases} c_I\left[x_1(t)-x_2(t)\right]^{n_1} & ;x_1(t)-x_2(t)\le 2\Delta l \\ c_I\,2\Delta l^{n_1}+c_{II}\left[x_1(t)-x_2(t)-2\Delta l\right]^{n_2} & ;x_1(t)-x_2(t)>2\Delta l \end{cases} \tag{10}$$

In the above expressions, non-linearity between the force and the displacement is taken into account with coefficients n_1 and n_2. In the case of linear dependence between the force and displacement, these coefficients are equal 1.

4. ANALYSIS OF RESULTS OF NUMERICAL SIMULATION

The numerical calculation of dynamic parameters of impact is carried out for three types of wagons: Tadnss-z, Uacns-z and Hccrrss-z. These wagons are previously experimentally tested. During the first period of impact, the overall stiffness of the system is $c_s=c_I$, while in the second period of rigid impact, the stiffness of the system is $c_s=c_{II}$. Here, a certain approximation is introduced, namely, the characteristics of stiffness can be considered linear only in static and quasi-static loads. However, at the dynamic load, the parameters of stiffness are nonlinear. The experimental determination of the dynamic stiffness c_I and c_{II} could contribute to obtaining more accurate values of the requested parameters of wagons impact. In this paper the results of quasi-static tests [9–12] are used and according to them specific stiffness of buffers c_I and supporting structures of wagon which participating in the impact c_{II}, are determined.

Table 2: The results of impact for wagon Uacns-z

Size	Unit	Exp. results	Num.results
F^o	[kN]	1280	1240
v^o	[m/s]	-	2.1
F_u^{max}	[kN]	2980	3020
a_2^{max}	[m/s^2]	+56/-55	+66/-52

Table 3: The results of impact for wagon Tadnss-z

Size	Unit	Exp. results	Num.results
F^o	[kN]	1502	1480
v^o	[m/s]	-	2,36
F_u^{max}	[kN]	3540	3220
a_2^{max}	[m/s^2]	+55/-45	+58/-43

t	[ms]	245	225

t	[ms]	243	223

Although in the calculation we get change more dynamic parameters of wagons impact, in the following analysis comparison of numerical results of parameters obtained by the experimental tests is performed.

In the Tables 2–3 v^o is the speed which occurs when buffers are completely compacted. When wagon Uah/Ra hits into an empty wagon Hccrrss-z, it should be taken into account that there is a movement of the roof and platform of this wagon. This movement is measured during testing (Fig. 2) and was 11.8 mm [13]. By numerical calculation this value is 10.9 mm.

Table 4: The results of impact for wagon Hccrrss-z

Size	Unit	Exp. results		Num. results	
		Empty	Full	Empty	Full
F_u^{max}	[kN]	1142	748	1161	761
t	[ms]	279	298	271	294

Figure 2: The testing of roof movement (Hccrrss-z)

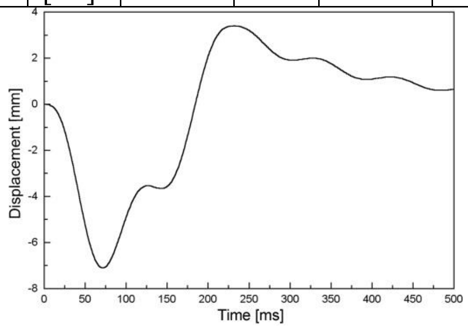

Figure 3: The diagram of roof movement obtained by the numerical simulation (Hccrrss-z)

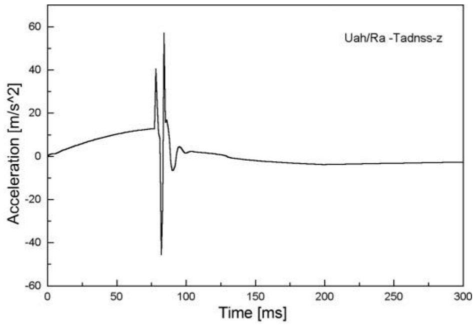

Figure 4: Acceleration change obtained by numerical simulation (wagon Tadnss-z)

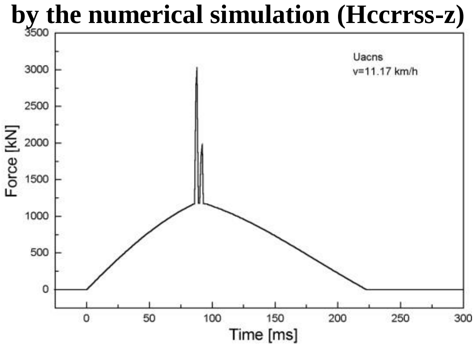

Figure 5: Total force on buffers of Uacns-z wagon obtained by numerical simulation

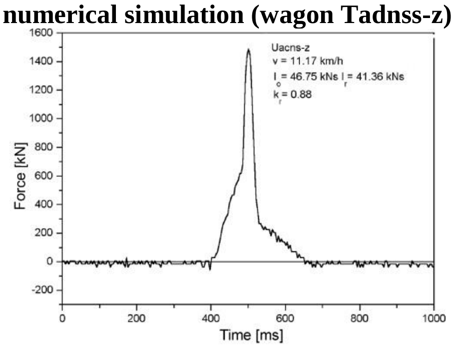

Figure 6: Force change on the first buffer of Uacns-z wagon obtained experimentally

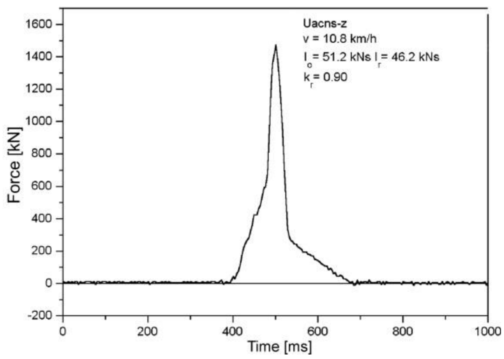

Figure 7: Force change on the second buffer of Uacns-z wagon obtained experimentally

5. COMPARATIVE ANALYSIS OF EXPERIMENTAL AND NUMERICAL RESULTS

By summarizing the presented research and obtained results, it can be said that proposed methodology enables determination of behaviour and stability of the wagons supporting structure at the action of impulse loads. The way of determination of dynamic parameters and the stress-strain state of main parts of the wagon supporting structure at impact is presented, by using the principles of non-linear dynamics and the theory of elasticity. By analysing the duration time of impact, the large similarity of the numerical and experimental results is noticed. The other dynamic parameters are also very similar. This is primarily related to the values of acceleration, maximal values of total forces, as well as values of forces at completely compacted buffers. Some of diagrams obtained by numerical simulation and experimental tests are given in the following figures.

6. CONCLUSION

In this paper, experimental research was done at three different wagons: the wagon for transportation of powdered materials Uacns-z, the wagon for transportation of grain material Tadnss-z, and the wagon Hccrrss-z which is used for transportation of cars. Beside the results of experimental testing of mentioned wagons, the analytical model of impact of two wagons is developed. The model takes into account the movement of cargo during the impact. The established differential equations are solved by numerical way. By analysing the obtained results of numerical simulation of impact of wagons, it can be concluded that they are consistent with the results obtained experimentally. The developed model can be used for determination of dynamic parameters of the impact in the design phases of new wagons. The improvements of the proposed model can be achieved by further exploring of dynamic stiffness of the wagon supporting structure, as well as determination of energy that is lost on oscillation during impact.

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ОПРЕДЕЛЯНЕ НА БУФЕРНИТЕ СИЛИ ПРИ УДАР МЕЖДУ ВАГОНИ

Драган Петрович,
petrovic.d@mfkv.kg.ac.rs

Факултет за машинни и строителни инжинери в гр. Кралево,
ул. Доситева 19, 36000, към университета в Крагуевац,
СЪРБИЯ

Ключови думи: *динамични параметри, удар между вагони, буферни сили.*

Резюме: *Когато два вагона се удрят или когато вагоните сменят темпото на движение (теглене, задържане, спиране), съществуват надлъжни сили и ускорения, които влияят на якостно-деформационното състоянието на носещите конструкции на вагона. Тези сили могат да причинят напрежение и деформации с такива величини, които представляват риск за носещата конструкция на вагоните и следователно за пътниците и товарите. Настоящата статия е продължение на изследванията, които са реализирани във фабриката за вагони в Кралево и Факултета по машиностроене и строителство в Кралево и е фокусиран върху точен анализ на удар между две превозни средства. Освен това теоретичните уравнения на удар между вагоните се решават числено и резултатите се сравняват с експериментално получени. Сравнителният анализ на аналитичните, числените и експерименталните резултати на удар между вагоните показа задоволително съгласие. По този начин възприетият аналитичен модел може да се използва за определяне на динамичните параметри на удар при проектирането на нови конструкции вагони.*