ON THE EFFECTS CAUSED BY THE SHOCK DURING RAILWAY VEHICLE BUFFING

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Abstract. A theory of shock caused by the buffing of railway vehicles is presented. It considers kinematic parameters and forces as response of the mechanical system caused by the vehicles that are effectively taking part in the buffing.

Key words: shock due to buffing, shock absorbers, stored potential deformation energy, forces and accelerations transmitted during buffing.

1. INTRODUCTION

The shock load in railway vehicles is due to the appearance of a relative velocity between neighbouring vehicles, both in travel as well as during the formation of freight trains.

The effect of the shocks, as loads appearing in use, is the transmission of forces through the central coupling of the vehicles and implicitly of accelerations to the masses of the vehicles, particularly to the transported freight and passengers.

In order to diminish the effects caused by the shock, railway vehicles are equipped with shock insulators (dampeners) that have the purpose of reducing the levels of the transmitted forces and accelerations.

The storage capacity for potential deformation energy of the shock insulators is described by the factor $2\beta\left[=\frac{W_e}{E_p}\right]$ (W_e – potential energy due to deformation of the shock insulators; E_p – potential energy due to deformation of the vehicles) that determines the decrease of the level of forces and accelerations transmitted during the collision [1].

In the use of railway vehicles there is a tendency to increase travel speeds, reduce formation times for trains as well as increasing the axle load. Consequently, the forces and accelerations transmitted to the vehicles as a result of the collision, reach relatively high values that need to be considered during the conception design and execution of railway vehicles.

2. ON THE SHOCK CAUSED BY COLLISION

A number of authors (Iosef Friedrichs, Karl Leinz Buttler, B. Richter, Buschmann) have tried to theoretically establish mathematical expressions of the forces and accelerations transmitted to the vehicles during the collision process [5, 6].

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The general case of the collision of two railway cars is considered. The colliding car, with mass m_1 and velocity v_1, impacts a collided car, of mass m_2 and velocity v_2, with $v_1 > v_2$. The cars are equipped with shock insulators (buffers or central coupling dampeners).

In the collision process a part of the kinetic energy of the vehicles is transformed into potential deformation energy which is maximum at time t_{12} when the vehicles travel at the same velocity v_{12}. The expression of the potential deformation energy E_p is:

$$E_\mathrm{p} = \frac{m_1 m_2}{m_1 + m_2} \frac{(v_1 - v_2)^2}{2} = \frac{m_1 m_2}{m_1 + m_2} \frac{v^2}{2}, \tag{1}$$

where m_1 is the mass of the colliding car, m_2 is the mass of the collided car and v is the relative velocity between vehicles that corresponds to collision velocity.

Figure 1 shows the time evolution of the kinematic parameters, i.e., acceleration a, velocity v and displacement x, of the colliding car 1 and the collided car 2 during the shock caused by a collision at 12 km/h. The cars have masses of $m_1 = m_2 = 80$ tonne. On Fig. 1, it is noticed the sum of contractions of the bumpers of the colliding and collided cars $D_1 + D_2 = 196$ mm. Another noticeable element is the moment t_{12} at which the cars have the same velocity and the process of transforming kinetic energy into potential deformation energy stored in the shock insulators (bumpers) ended.

The study of the time variation of the motion parameters of the vehicles, as response functions to the shock caused by collision, leads to the following observations:

1. At each moment t of the collision process which occurs during the time interval $(0 \to t_2)$, the contraction D of the shock insulators that equip the vehicles is:

$$D(t) = x_1(t) - x_2(t) = \int_0^t v_1(t)\mathrm{d}t - \int_0^t v_2(t)\mathrm{d}t. \tag{2}$$

2. At the time t_{12}, when the vehicles have the common velocity v_{12} and the stored potential energy of the vehicles is maximum, the difference between the distances traveled by the vehicles represents the maximum contraction of the shock absorbers $D_{\max}$ and, obviously the surface S, between the curves v_1 and v_2 [2]:

$$D_{\max} = x_1(t_{12}) - x_2(t_{12}) = \int_0^{t_{12}} v_1(t)\mathrm{d}t - \int_0^{t_{12}} v_2(t)\mathrm{d}t = S. \tag{3}$$

3. Experimentally it is observed that, at time $t = t_{12}^*$, the accelerations transmitted to the vehicles cancel out. Consequently, the vehicles move on the time interval $(t_{12}^* \to t_2)$, with constant velocities v_1^* and v_2^* respectively, while remaining in contact on the whole interval, while the space between the vehicles increases $D(t) = x_1(t) - x_2(t)$.

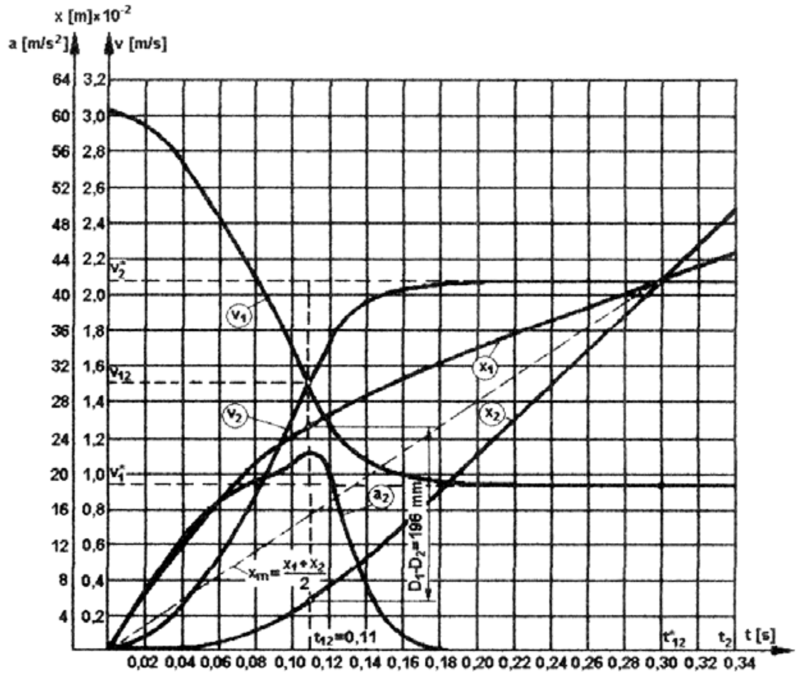

Fig. 1 – Time evolution of acceleration $a_2(t)$ and parameters $v_1(t)$, $v_2(t)$, $x_1(t)$ and $x_2(t)$, of collided car 2, determined experimentally for collision C $\to$ C.

This phenomenon occurs because at time t_{12}^* the shock absorbers of the vehicles show another deformation, remanent contraction, that in the interval ($t_{12}^* \to t_2$)cancels out. Thus, the increase of the space between the vehicles at each moment of the time interval ($t_{12}^* \to t_2$) is compensated by the recovery of the contraction of the shock absorbers. At the moment t_2 , which marks the end of the collision process, the shock absorbers, either bumpers or central coupling dampeners, return to their initial position, corresponding to the time $t = t_1 = 0$ as the starting of the collision process.

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4. The process of transforming stored potential energy into kinetic energy, triggered at $t = t_{12}$, ends at $t = t_{12}^*$, when the vehicles reach velocities v_1^* and v_2^* respectively.

Consequently, the values of the maximum contraction $D_{\max}$ and the surface S which represents the value of the maximum contraction are:

$$D_{\max} = \int_{t_{12}}^{t_{12}^*} v_1(t)\mathrm{d}t - \int_{t_{12}}^{t_{12}^*} v_2(t)\mathrm{d}t = -S\,. \tag{4}$$

The energy coefficient that characterizes the efficiency of shock insulators is 2β, meaning the ratio between the potential deformation energy stored by the shock insulators W_{e} and the total potential energy, which includes the potential energy stored by the elastic elements that represent the bearing structures, the elastic elements that form the suspension of the vehicle, equipment and existing load (freight, passengers):

$$2\beta = \frac{W_{\mathrm{e}}}{E_{\mathrm{p}}}\,. \tag{5}$$

The theoretical expressions of the transmitted force established by various authors [2–3] can be used only under the condition that the vehicles are equipped with shock insulators that show a linear variation between force and contraction.

Railway vehicles can be equipped with shock insulators whose elastic elements show a nonlinear variation between force and contraction [4].

For shock insulators of any type of variation of force as a function of contraction, the plenitude coefficient p is defined, which represents the ratio of the stored potential deformation energy and the product between the maximum transmitted force and the maximum contraction of the shock insulator.

In the case of a collision between two vehicles equipped with different types of shock insulators, the plenitude coefficient is:

– for the shock insulators of the colliding car:

$$p_1 = \frac{W_{\mathrm{e1}}^*}{F_{\max} f_1}\,; \tag{6}$$

– for the shock absorbers of the collided car:

$$p_2 = \frac{W_{\mathrm{e2}}^*}{F_{\max} f_2}\,, \tag{7}$$

where: W_{e1}^*, W_{e2}^* are respectively the potential deformation energy of the shock isolators of the colliding and collided cars; f_1, f_2 are respectively the maximum contraction of the shock absorbers of the colliding and collided cars.

Further on, the conventional rigidity K_T of the buffer and K_C of the central coupling dampener, are defined as the ratio of the maximum transmitted force and the maximum contraction of the shock insulator for a collision velocity v:

– for the shock absorber of the colliding vehicle:

$$K_{T1} = \frac{F_{max}/2}{f_1}, \quad K_{C1} = \frac{F_{max}}{f_1}; \tag{8}$$

– for the shock isolators of the collided vehicle:

$$K_{T2} = \frac{F_{max}/2}{f_2}, \quad K_{C2} = \frac{F_{max}}{f_2}. \tag{9}$$

Replacing f_1 and f_2 from (8) and (9), into equations (6) and (7) respectively, leads to the expressions for the potential deformation energies stored by the buffers:

– of the colliding vehicle:

$$W_{e1}^{*} = \frac{F_{max}^2}{2K_{T1}} \mathrm{p}_1 = \frac{F_{max}^2}{K_{C1}} p_1; \tag{10}$$

– of the collided vehicle:

$$W_{e2}^{*} = \frac{F_{max}^2}{2K_{T2}} p_2 = \frac{F_{max}^2}{K_{C2}} p_2. \tag{11}$$

The specific energy factors β1 and β2, of the colliding and collided cars respectively, are:

$$\beta_1 = \frac{W_{e1}^{*}}{E_p}; \quad \beta_2 = \frac{W_{e2}^{*}}{E_p}. \tag{12}$$

Using equations (12), (10) and (11), the following equation is obtained:

$$(\beta_1 + \beta_2) E_p = \frac{F_{max}^2}{2} \left(\frac{p_1}{K_{T1}} + \frac{p_2}{K_{T2}} \right) = F_{max}^2 \left(\frac{p_1}{K_{C1}} + \frac{p_2}{K_{C2}} \right). \tag{13}$$

Replacing the expression of potential energy E_p (eq. 1), the expression of the maximum transmitted force during the collision process is obtained for the case of vehicles equipped with buffers:

$$F_{max} = (v_1 - v_2) \sqrt{\frac{m_1 m_2}{m_1 + m_2} (\beta_1 + \beta_2) \frac{K_{T1} K_{T2}}{p_1 K_{T2} + p_2 K_{T1}}}. \tag{14}$$

In the case of the collision of two vehicles of the same type, with $m_1 = m_2 = m$, $K_{T1} = K_{T2} = K_T$, $p_1 = p_2 = p$, and $\beta_1 = \beta_2 = \beta$, the expression of the transmitted force becomes:

$$F_{\max} = (v_1 - v_2)\sqrt{\frac{m}{4} 2\beta \frac{K_T}{p}} . \tag{15}$$

In the case of vehicles equipped with central couplings, the expression of the transmitted force results from equation (13) can be expressed as:

$$F_{\max} = (v_1 - v_2)\sqrt{\frac{1}{2}\frac{m_1 m_2}{m_1 + m_2}(\beta_1 + \beta_2)\frac{K_{C1}K_{C2}}{p_1 K_{C2} + p_2 K_{C1}}} . \tag{16}$$

In the case of the collision of two vehicles of the same type, with $m_1 = m_2 = m$, $K_{T1} = K_{T2} = K_T$, $p_1 = p_2 = p$, and $\beta_1 = \beta_2 = \beta$, the expression of the transmitted force becomes:

$$F_{\max} = \frac{(v_1 - v_2)}{2}\sqrt{\frac{m}{2} 2\beta \frac{K_C}{p}} . \tag{17}$$

The established formulation can be used for determining the force transmitted during the collision of vehicles equipped with shock absorbers, either linear or non linear.

In order to theoretically determine the force transmitted during the collision (with vehicles of masses $m_1 = m_2 = 80$ ton) the variation of the energy factor, 2β, and the ratio between conventional stiffness K_T for the buffers and the plenitude coefficient were experimentally determined, taking five collision cases of two railway cars were considered:

1. Both cars equipped with 75 mm buffers.
2. Both cars equipped with category A buffers, according to UIC526-1, with elastic elements composed of RINGFEDER rings.
3. Both cars equipped with category A buffers, according to UIC526-1 with rubber elastic elements (new buffers).
4. The colliding car was equipped with category A buffers, and C buffers (according to UIC526-1) in the collided car.
5. Both cars equipped with category C buffers.

The results for each case are presented in figures 2 to 7. The variation of the energy factor, 2β, and the ratio between conventional stiffness K_T are presented separately for the first case in Fig. 2, while for the rest of the cases they are presented jointly in a single chart.

Fig. 2 – The diagram of the variation of the 2β factor as a function of velocity, for the collision of two vehicles equipped with 75 mm buffers (case 1).

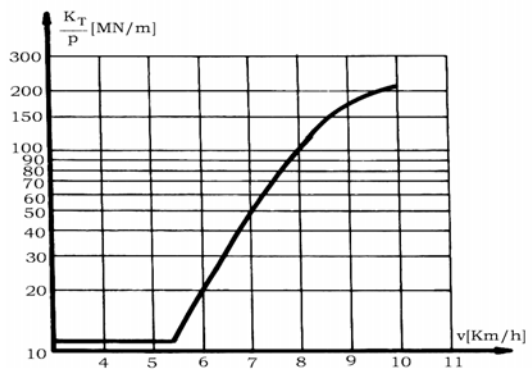

Fig. 3 – Diagram of the variation of the K_T / p parameter as a function of velocity, for the collision of two vehicles equipped with 75 mm buffers (case 1).

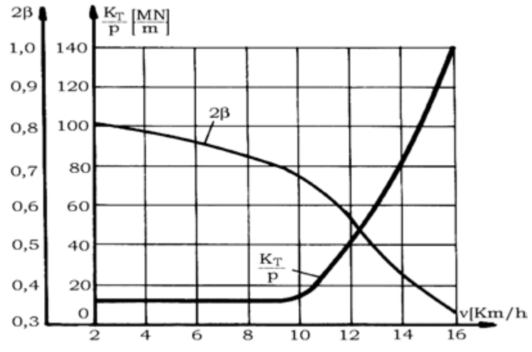

Fig. 4 – The diagram of the variation of the 2β factor and the parameter K_T / p, for the collision of two railway cars equipped with category A buffers, according to UIC526-1, with elastic elements composed of RINGFEDER rings (case 2).

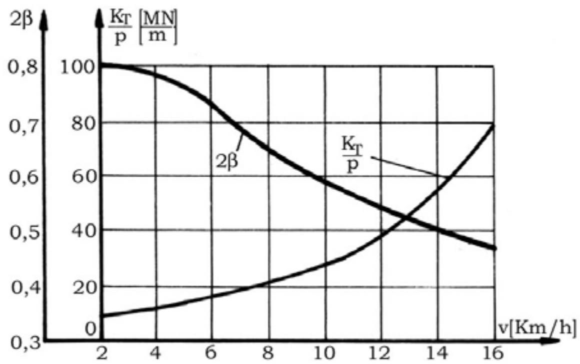

Fig. 5 – The diagram of the variation of the 2β factor and the parameter K_T / p, for the collision of two railway cars equipped with category A buffers, according to UIC526-1 with rubber elastic elements (new buffers) (case 3).

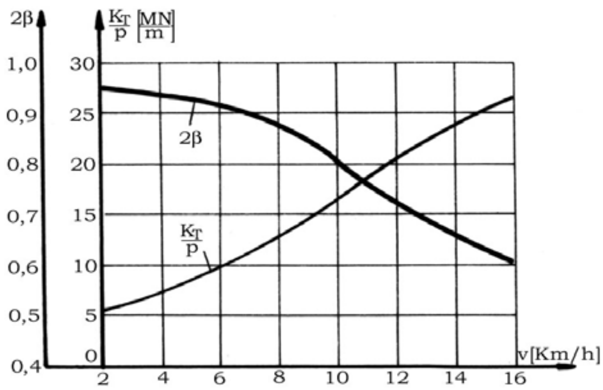

Fig. 6 – The diagram of the variation of the 2β factor and the parameter K_T / p, for the collision of two railway cars equipped with category A buffers on the colliding car and category C buffers (according to UIC 526-1) on the collided car (case 4).

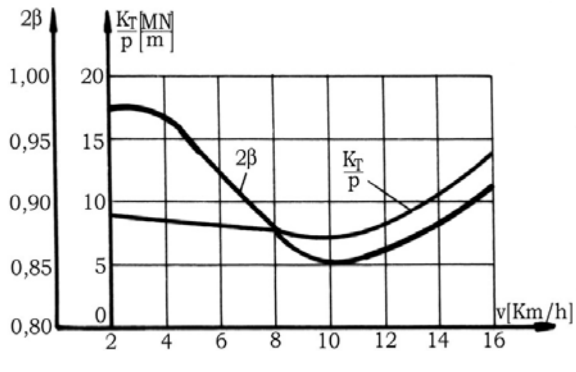

Fig. 7 – The diagram of the variation of the 2β factor and the parameter K_T / p, for the collision of two railway cars equipped with category C buffers (case 5).

3. EXPERIMENTAL DETERMINATION OF THE 2β, K_T, P PARAMETERS AND THE FORCE F TRANSMITTED DURING THE COLLISION PROCESS

In order to experimentally determine the parameters 2β, K_T, P and the force transmitted to the cars during the collision, over 2 500 collisions were conducted, in a specialized stand for the shock testing of railway vehicles. The stand is equipped with appropriate mechanical installations, railway cars, transducers, experimental data acquisition, storage and analysis equipment [7].

During the testing, the colliding car, launched from the inclined plane of the testing stand, collided at various velocities the standing, unbraked, collided car sitting on the level part of the stand. The used cars, colliding and collided, were 4 axle freight cars, loaded with uniform materials (sand, gravel, broken rock, etc.) up to a total mass of 80 tonne/car.

For each shock caused by the collision of the cars, during the collision process the following parameters were experimentally determined:

– collision velocity v;
– forces transmitted through the bumpers $F(t)$;
– contractions of the buffers of the collided car $D(t)$;
– acceleration transmitted to the collided car $a(t)$.

The forces transmitted through the buffers were measured with force transducers affixed to the frontal beam of the car with specially designed devices.

The time evolution of the force transmitted during the considered collision cases (F_1 at V = 9.15 km/h; F_2 at V = 13.0 km/h; F_3 at V = 13.2 km/h; F_4 at V = 14.11 km/h; F_5 at V = 13.80 km/h), is shown in Fig. 8.

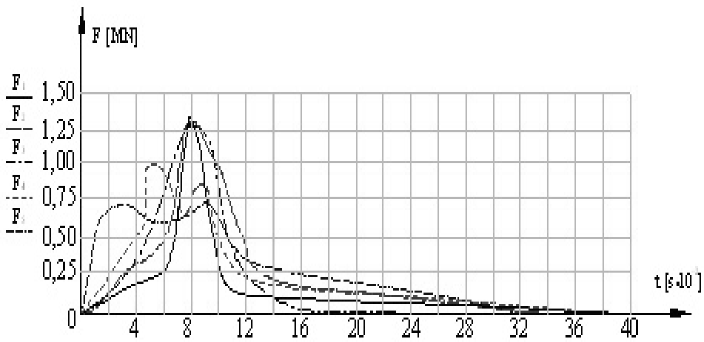

Fig. 8 – The diagram of the variation of the forces transmitted during the collision process through a buffer, as a function of time.

In Fig. 9, we have presented the variation according to velocity of the transmitted force for all 5 collision cases.

In the diagrams from Figs. 8 and 9, the meaning of the annotations is: F_1 – buffer with displacement of 75 mm type RINGFEDER, 75→75; F_2 – category A buffer type RINGFEDER, A→A; F_3 – Category A buffer, rubber A→A; F_4 –

Category A buffer, rubber, A→C; F_5 – Category C buffer, type RINGFEDER+hidraulic, C→C and they represent the collision cases.

The forces transmitted on a central coupling were determined using an original solution represented by the force transducer and the arrangement in Fig. 10.

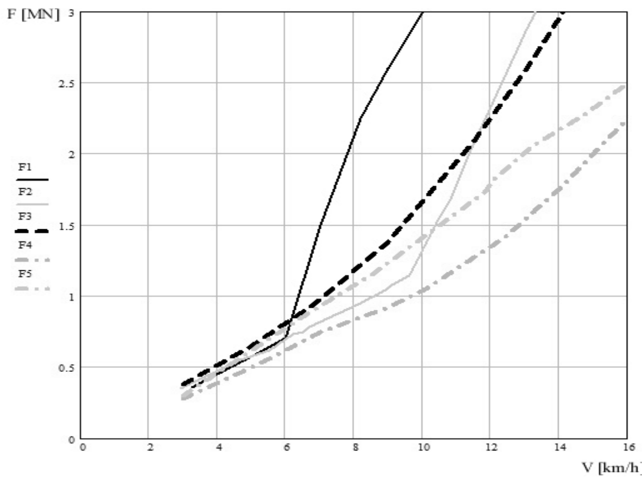

Fig. 9 – Diagram of the variation of the total force $F=F_1+F_2$ transmitted during the collision as a function of collision velocity V.

Collision testing in this case was conducted with two vehicles, the colliding vehicle with mass $m_1 = 92\,\mathrm{t}$ and the collided vehicle with mass $m_2 = 94$ tonne. The cars were equipped with shock insulators with friction elastic elements, in two situations:

– elastic element with maximum displacement 90 mm;

– elastic element with maximum displacement 120 mm.

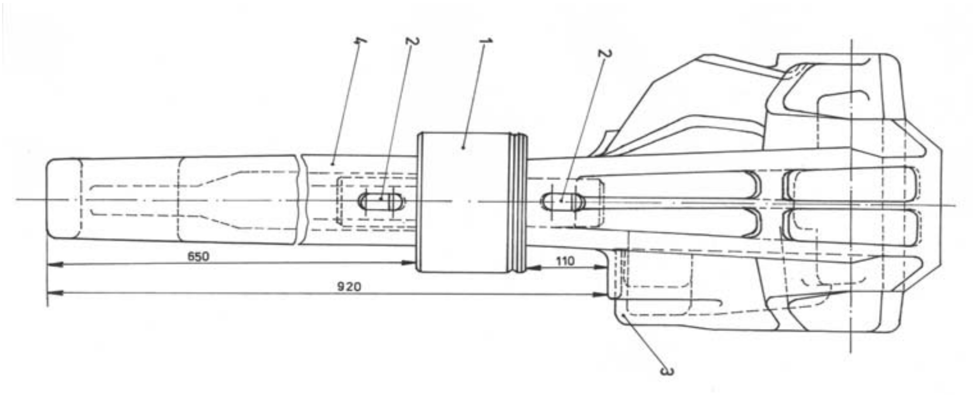

Fig. 10 – Own concept arrangement
(1 – force transducer, 2 – affixing device, 3 – coupling head, 4 – coupling end).

Figures 11 and 12 show the variation of the transmitted forces and accelerations as a function of velocity, for the collisions at various speeds (F_1, a_1 – dampener with displacement of 90 mm; F_2, a_2 – dampener with displacement of 120 mm).

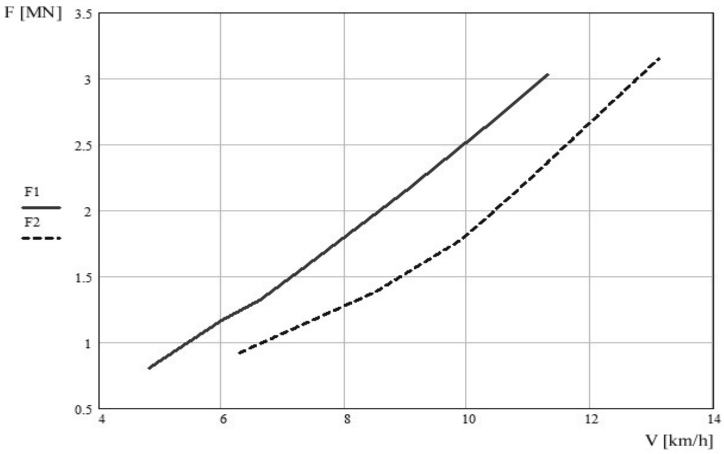

Fig. 11 – Diagram of the force F transmitted during the collision as a function of collision velocity.

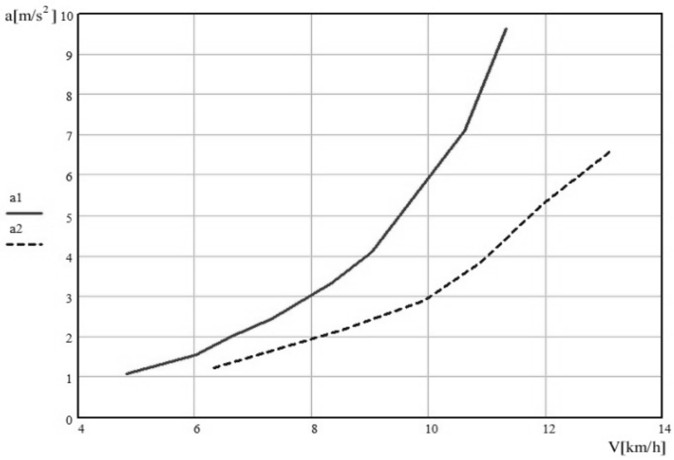

Fig. 12 – Diagram of the accelerations transmitted during the collision process as a function of the collision velocity.

4. CONCLUSIONS

The paper presents a confirmation of a theoretical concept through the analysis of experimental results on the shock process caused by the buffing of railway vehicles. Benefiting from especially precise and correctly chosen experimental means of determining the kinematic parameters – acceleration of the buffed car a_2 and velocity of the buffing car, we have experimentally proven the validity of proposed theory of our own conception, on the kinematics of shock due to railway car buffing and we underline:

a) The kinematic parameters are the most eloquent in the buffing process equation. They simply exist and are influenced by the energy stored by the elastic elements, such as:

– shock insulators;
– bearing structures of railway vehicles;
– elastic elements of the suspension and railway vehicle equipment;
– freight.

b) Thus, according to the elements described, we can experimentally observe the certainty that the displacement (contraction) of the shock insulators represents, up to the time t_{12} (storing of potential deformation energy) as well as the relaxation (t_{12}–t_{12}^*), the same value S.

We propose an analytical expression for the design phase related to „force transmitted during shock". The proposed expression admits the nonlinear dependence between force and contraction for shock insulators. It can be used by designers in order to take into account for calculations the effects of shock for any vehicle.

The dynamic characteristics of the shock insulators cannot be established merely by the proposed method "buffing test".

It is necessary for a researcher to design his own methods and specific measurements transducers for the desired parameters (for example the force transducers in Fig. 10).

The capacity for storing potential deformation energy of the shock insulators is decisive on the consequences of shock as an unwanted event (Figs. 11 and 12).

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