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Stiffness characteristics of railway buffers: Requirements, testing and proposal of a new computational model

T. Michálek[a,*], S. Liberová[a], J. Vágner[a], P. Jaroš[a], J. Šlapák[a]

[a] *Faculty of Transport Engineering, University of Pardubice, Studentská 95, 532 10 Pardubice, Czech Republic*

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Abstract

In European railways, the use of UIC draw gear and side buffers to connect individual railway vehicles within a train is still established. The buffers ensure the transmission of longitudinal compressive forces between the adjacent vehicles; longitudinal tensile forces are transmitted by means of the UIC draw gear, a drawbar hook and a screw coupling. Therefore, the stiffness characteristics of the draw and buffing gear are important from the point of view of longitudinal train dynamics, as well as running safety. This paper deals with the stiffness characteristics of railway buffers. The basic requirements for suspension elements used in the buffers are summarised. The solution of tasks in the field of modelling of dynamic phenomena during train running requires knowledge of the dynamic stiffness characteristics of these elements, which, however, are not determined by default. Therefore, experimental measurements of these characteristics were made on the dynamic test stand of the Faculty of Transport Engineering of the University of Pardubice. The experience from the evaluation of these measurements is summarised in the paper. Furthermore, attention is paid to the development of a new computational model of the buffers for use in multibody simulations, considering the results of the physical tests.

Keywords: railway buffer, stiffness characteristics, measurement, multibody simulation

1. Introduction

While the most common technical solution of connecting adjacent railway vehicles within a train is by using a central (automatic) coupler, Europe is practically the last continent that is using, especially in freight transport, a drawbar hook with a screw coupling together with side buffers (i.e., so-called UIC draw and buffing gear). In case of this mechanical interface between the vehicles, the longitudinal force transmission is divided – the drawbar hook and screw coupling transmit tensile forces and the buffers ensure the transmission of compressive forces. Increasing length, weight and speed of freight trains, which are necessary for the competitiveness of railway freight transport, lead to higher requirements on the running safety. The traditional UIC draw and buffing gear hits its limits: The limited strength of the screw coupling limits the transmitted tractive forces and therefore the hauling capability of locomotives, especially on slope-challenging railway lines. In addition to that, the effects of longitudinal train dynamics have to be solved. Especially during train braking, undesirable longitudinal dynamic forces can act in the trainset, in the draw and buffing gear (see, e.g., [1]). In an extreme case, the longitudinal tensile forces can cause a rupture of the screw coupling. The third area of problems is related to the operation in conditions of small-radius curves. The lateral forces, occurring in the contact of buffer heads as a consequence of the existence of the longitudinal forces between

*Corresponding author. Tel.: +420 466 037 415, e-mail: tomas.michalek@upce.cz.
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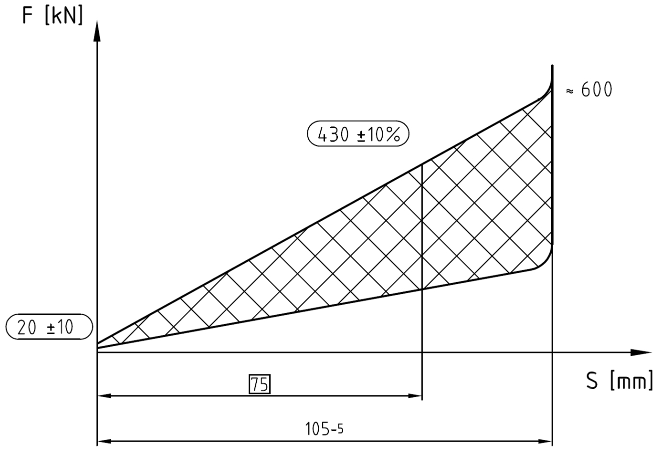
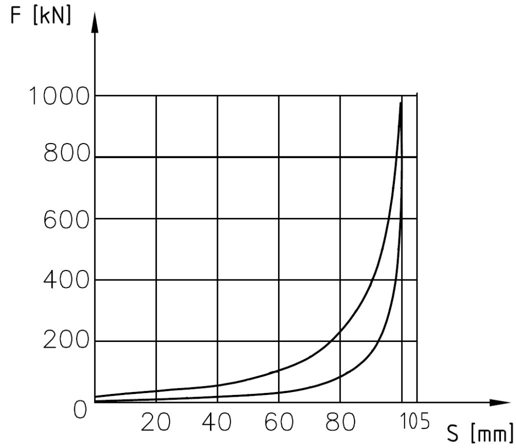


(a)



(b)

Fig. 1. Examples of different types of (quasi)static characteristics of AXTONE railway buffers of category A with 105 mm stroke: (a) buffer with steel ring spring (Keystone RF 32 kJ), (b) buffer with rubber-steel spring (Keystone 30 kJ)

the adjacent vehicles, can significantly influence the safety against derailment and the damaging effects of the vehicles on the track (i.e., the wheel/rail wear level).

2. Requirements on stiffness characteristics of railway buffers

The railway buffers are mounted on both ends of a railway vehicle, on both sides, on a defined position, to ensure force transmission between neighbouring vehicles. The standard side buffer consists of a buffer housing (plunger and base of buffer including anti-rotation device) and an elastic system. The elastic system may be made up of a rubber (elastomer) spring or a steel ring spring. Especially the longitudinal train dynamic effects (but also the running safety) are strongly influenced by the stiffness characteristics of the suspension elements of the buffers as well as the drawbar hook. Knowledge of these characteristics (force-displacement curves) is also important in order to obtain credible results from multibody train dynamic simulations (see, e.g., [7]). The shape of these characteristics is affected by the suspension component type used in the draw and buffing gear – older friction-type elements (especially ring springs) show significantly different force-displacement curves than the newer elastomer suspension components. This difference is demonstrated in Fig. 1 on the comparison of the force-displacement curves of two different AXTONE buffers of the same category and with the same stroke. It is evident that the buffer with a rubber spring element (see Fig. 1b) shows a significantly more progressive characteristic as well as a higher end force than the buffer equipped with a ring spring (see Fig. 1a).

2.1. Basic requirements of technical standards on railway buffers

The basic requirements on railway buffers for freight wagons are defined in the UIC leaflet No. 526-1 [11] and in the European standard EN 15551 [3]. According to [3], the basic classification of buffers can be done according to their stroke and dynamic energy capacity:

- buffers with 105 mm stroke,
- buffers with 110 mm stroke – they are used for passenger wagons,

Table 1. Classification of buffers with a stroke of 105 mm

Buffer category	Dynamic energy capacity
A	$\geq 30\,\mathrm{kJ}$
B	$\geq 50\,\mathrm{kJ}$
C	$\geq 70\,\mathrm{kJ}$

- buffers with a long stroke of 150 mm – they are used for wagons for the carriage of shock-sensitive goods,
- crashworthy buffers – they allow the absorption of a specified energy due to an exceptional impact.

The present article is dedicated to buffers with 105 mm stroke. These buffers are classified according to the dynamic stored energy (see Table 1). This dynamic stored energy expresses the energy accumulated by the buffers due to impact of two wagons. The relevant test scenarios are defined in the standard [3], Annex E. For these tests, requirements on wagon weight, impact speed (up to 12 km/h) and monitored quantities (i.e., the stored energy, end force, acceleration and absorbed energy – at least 60 % of the stored energy) are defined.

The Standard EN 15551 [3] provides an overview of the tests on buffers (or their parts) which are required for these components, separately for type and piece tests. The tests on the buffer housing and the buffer as a whole are mainly concerned with verifying the mechanical strength and, in the case of type tests, the fatigue resistance. As part of the buffer testing process, the forces imposed on the test specimen are defined. Each type of buffer must be rated not only for loading in the longitudinal direction but also be able to withstand other forces without damage. An overview of the test forces is given in Table 2. Their location and direction are shown in Fig. 2. After each of the tests for forces F1, F2, F3, and F5, the buffer shall be in serviceable condition and the permanent deformation shall be within the tolerance specified at the time of manufacture.

From the point of view of stiffness characteristics of railway buffers, the standard [3] prescribes the verification of (quasi)static characteristics by applying the axial force F1 (see Fig. 2)

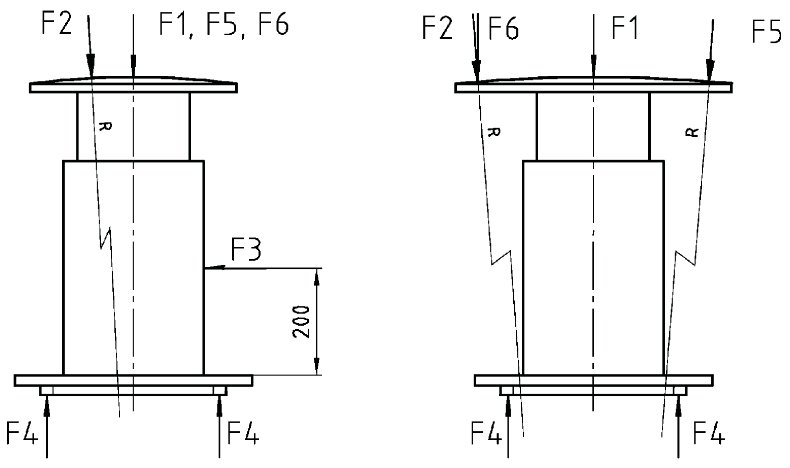


Fig. 2. Points of application of forces during testing of buffers according to EN 15551 [3]: side view (*left*) and top view (*right*)

Table 2. Proof loads for buffers with a stroke of 105 mm

Force (designation)	Type of force	Magnitude of the force
F1	longitudinal axial force affecting the buffer head	$\geq 2\,500\,\mathrm{kN}$
F2	longitudinal off-axis force affecting the buffer head	$\geq 500\,\mathrm{kN}$
F3	vertical force affecting the buffer housing	$\geq 200\,\mathrm{kN}$
F4	total longitudinal force exerted by the buffer plate on the test frame	$\geq 2\,500\,\mathrm{kN}$
F5	longitudinal axial force on the buffer head greater than 450 mm	$\geq 250\,\mathrm{kN}$
F6	force for durability test	$\geq 250\,\mathrm{kN}$

Table 3. Required force values at each stroke level

Stroke	Preload of buffer	25 mm	60 mm	100 mm
Force	$10 \div 50\,\mathrm{kN}$	$30 \div 130\,\mathrm{kN}$	$100 \div 400\,\mathrm{kN}$	$350 \div 1\,000\,\mathrm{kN}$

always on complete buffers. The test conditions are defined as follows:

- the test is carried out 72 hours after installation – this applies to rubber or elastomer springs,
- the test temperature must be between 15 °C and 25 °C,
- the relief phase must follow immediately after the compression phase,
- the stroke speed of the buffer plunger must not exceed 0.05 m/s in both directions,
- the buffer must be in its initial state after full lightening,
- three cycles to maximum stroke are performed,
- the elastic system must not be subjected to unacceptable thermal stress; a break of no more than 10 minutes is permitted between complete cycles.

In the actual test, the following quantities are measured: buffer plunger stroke, force, stroke speed under load and unloading, and temperature during the test. During all three cycles, a graph of stroke versus force is recorded. The limit values for the forces at each stroke level are given in Table 3.

The stored energy W_s and absorbed energy W_a are then determined from the graph. The stored energy for a force not exceeding 1 000 kN shall be greater than or equal to 12.5 kJ. The absorbed energy for the first cycle corresponding to the previous stored energy shall meet the following condition:

$$W_a \geq 0.50\, W_s. \tag{1}$$

The absorbed energy for the second and third cycles corresponding to the previous stored energy shall meet the following:

$$W_a \geq 0.42\, W_s. \tag{2}$$

2.2. Verification of buffer stiffness characteristics within the maintenance process

The monitoring of the technical condition of the buffers is basically carried out in three stages of maintenance. The first stage is carried out during crossing checks and is, therefore, the responsibility of the railway undertaking (RU). The entity in charge of maintenance (ECM) performs two other levels of maintenance: technical inspection and revision. When a train is taken over or handed over to another RU, the train driver performs a technical crossing check according to Appendix 5 of Annex 9 of the General Contract of Use for Wagons [5]. In the case of buffers, this check is focused in particular on

- the appearance of different types of buffers on the front of the wagon,
- buffer height outside the tolerance zone,
- mechanical defects (deformation and completeness of the buffer head, attachment of the plunger and buffer base, deformation and appearance of cracks).

Buffers are also not removed from the vehicle in framework of the technical inspection. Only the technical condition is visually checked, with a focus on the presence of deformations and cracks, welded joints, fastenings and marking. Therefore, the condition of the suspension system, which is a part of the buffers, is not considered in the above inspection processes.

Buffers are removed from the vehicle as part of the inspection, which is carried out on wagons at 6-year intervals. The repair of the buffer is carried out according to Regulation KVs5-B-2010 [8]. However, this regulation only considers buffers that use a ring spring as the elastic system. When checking the ring spring characteristics, the following parameters are controlled:

- preload of buffer,
- length of the assembled spring,
- spring length at nominal load – the spring must have a force load of 320 kN,
- final check of the assembled spring length.

2.3. Summary of the requirements on stiffness characteristics of buffers

For the purpose of describing the dynamic behaviour of the buffer, (quasi)static force-displacement curves are generally available because they are provided by the manufacturers of the relevant components and determined by standardised methodology according to the European standard EN 15551 [3]. In the case of stiffness characteristics of the draw gear (suspension of the drawbar hook), the situation is similar – the European standard EN 15566 [4] requires a measurement of the force-displacement curve with a defined minimum value of the ratio of absorbed and stored energy (also called as damping). However, the stiffness characteristics of buffing and draw gear are usually not investigated under dynamic loading conditions. In terms of the standard [3], the dynamic buffer characteristics are considered in a different way – from the point of view of impact of wagons (e.g., during shunting). The dynamic energy capacity evaluated under these conditions then serves as a criterion for buffer classification (see Table 1). As follows from Section 2.2, the stiffness characteristics are commonly not verified within the vehicle operation or the maintenance process.

3. Experimental testing of railway buffer stiffness characteristics

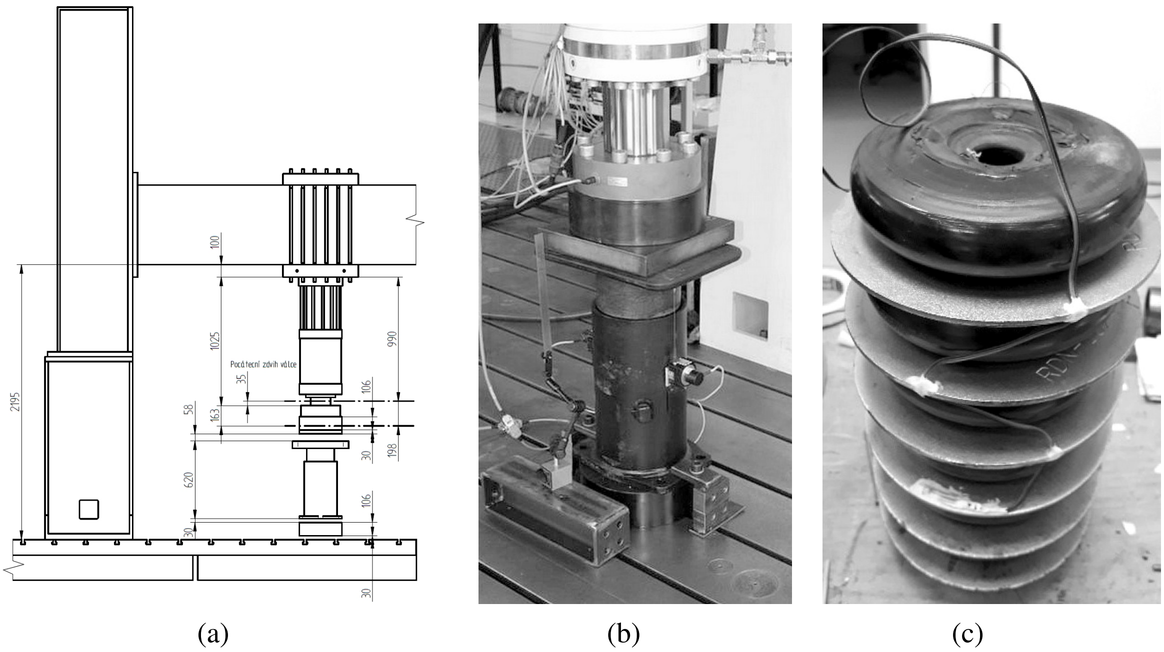
Although the shape of stiffness characteristics of buffers equipped with friction-type suspension elements (the ring springs or the conical belt spring) is influenced by the coefficient of friction value, in principle, their dynamic properties are predictable. However, dynamic characteristics of buffers with rubber-steel or elastomer springs are significantly dependent on the material properties of the applied suspension element. To investigate the dynamic characteristics of railway freight wagon buffers equipped with these elements, relevant experiments on the dynamic test stand were performed.

3.1. Testing device and measurement scenarios

The measurement of the stiffness characteristics of real components was performed in the dynamic test lab of the Educational and Research Centre in Transport (ERCT) at the Faculty of Transport Engineering of the University of Pardubice in 2020. In addition to two different buffers, two different types of drawbar hook suspension were tested. All these tested parts are intended for application on standard railway wagons.

For the measurements, the dynamic test stand INOVA with one electro-hydraulic actuator (maximum force 630 kN, maximum stroke 250 mm) was used. The vertically situated actuator serves for axial compressive loading of the investigated sample. The testing assembly (see Fig. 3a) was designed in such a way that it allows testing of all the investigated samples with respect to their dimensions. The force was measured by the type K GTM force transducer that was attached to the head of the actuator. To eliminate the risk of damage, the contact with the tested sample (buffer plate) was realized through a steel plate bolted to the force transducer. The deformation of the tested sample was measured by means of a couple of draw-wire sensors (Micro-Epsilon type WDS-500-P60-CR-P-SO) mounted directly on the buffer. One of the tested buffers is shown in Fig. 3b during the measurement.

To investigate in detail the dynamic characteristics of the tested buffers, a set of measurement scenarios was defined. Within these measurements, various values of prestress, amplitude and frequency of harmonic loading of the tested sample were considered. The parameters of the



(a) (b) (c)

Fig. 3. Experimental testing of railway buffer stiffness characteristics: (a) scheme of assembly of the INOVA dynamic test stand (dimensional balance), (b) one of the buffers during the measurement, (c) elastomer spring

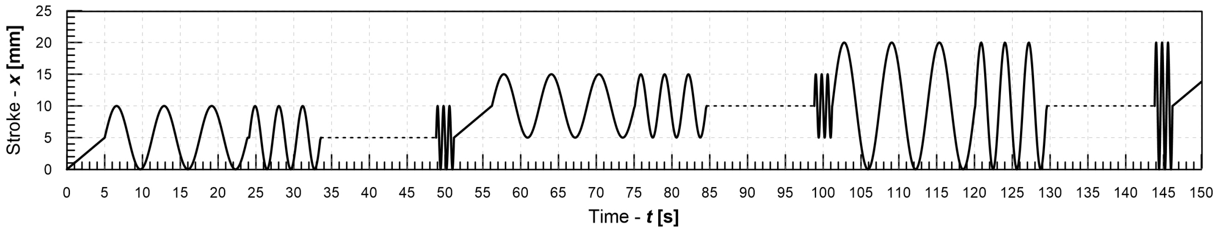


Fig. 4. Example of the time course of loading of tested samples during the experimental determination of their dynamic characteristics on the INOVA dynamic test stand

realized dynamic tests were limited by properties of the used test equipment, i.e., the maximum force of approximately 600 kN and the maximum frequency of up to ca. 2.5 Hz. An example of the loading scenario of a tested sample is shown in the form of required stroke of the buffer in time in Fig. 4. The prestress and amplitude were gradually increased in steps of 5 mm, or 10 mm in such a way that their sum corresponds to the maximum capabilities of the testing assembly used, but simultaneously does not fall into negative values (to avoid force impacts between the actuator and the tested sample). The loading frequency ranged from ca. 0.05 Hz up to approximately 2.5 Hz.

In addition to the dynamic behaviour of the investigated samples, their (quasi)static characteristics were also measured, applying a very low speed of deformation of the relevant buffer. Due to the significant changes in the temperature of the suspension elements used in the tested samples (as a consequence of the energy dissipation during the loading cycles) and their influence on the stiffness characteristics (see below), digital temperature sensors (Dallas type DS18B20) were integrated into the measuring string during testing the buffer equipped with elastomer spring (visible in Fig. 3c, glued on one of the spring metal plates). If the measured spring temperature exceeded a defined limit (40 °C), the measurement was stopped.

3.2. Selected measurement results

In Fig. 5, an example of measured (quasi)static and dynamic stiffness characteristics of the investigated railway freight wagon buffer of category A with a maximum stroke of 105 mm equipped with an elastomer spring is shown. The dotted line represents the (quasi)static stiffness characteristic, determined by means of a simple compression and unloading of the buffer at a constant velocity of 5 mm/s and limited by the maximum force of approximately 600 kN (due to the parameters of the test assembly).

The measured dynamic stiffness characteristics are presented by the set of solid lines in Fig. 5. These results were obtained for three different values of required prestress (20, 50, and 80 mm) during the application of harmonic loading cycles with a maximum loading velocity of 80 mm/s. The individual loading cycles for the selected prestress value differ in their amplitudes and therefore also in the frequency of loading.

From these results, it is evident that the dynamic stiffness characteristics of the buffer with elastomer spring may in some cases fall outside the area defined by the loading and unloading curves of the (quasi)static stiffness characteristic (as, e.g., in Fig. 6) or, by contrast, that they do not even touch these curves (as, e.g., in Fig. 7). To explain the observed effects, it is necessary to perform the evaluation of the results in more detail. From the point of view of dynamics, two examples are presented in the following graphs to demonstrate the influence of loading frequency:

- In Fig. 6, the measured dynamic characteristics for the conditions of a constant prestress

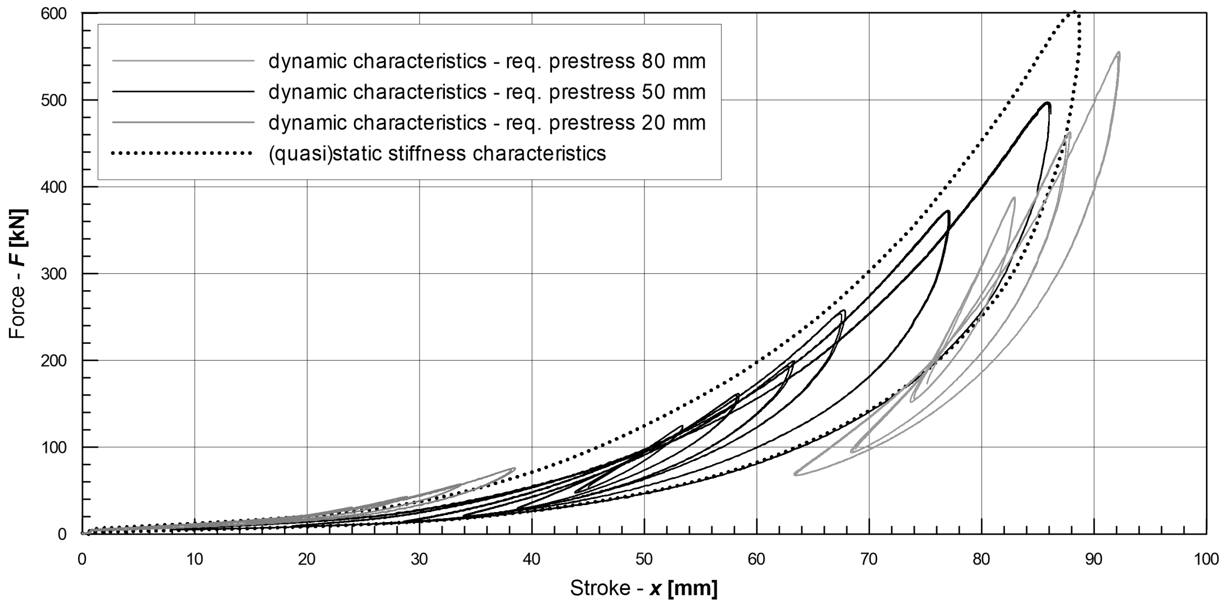


Fig. 5. Measured (quasi)static (*dotted line*) and dynamic (*solid lines*) stiffness characteristics of a railway freight wagon buffer of category A with a maximum stroke of 105 mm equipped with an elastomer spring

(of the required value of 20 mm) and constant amplitude (of approximately 20 mm) are shown. To reach the different values of loading frequency (from 0.08 Hz up to 1.27 Hz), the maximum velocity of harmonic loading varied from 10 mm/s up to 160 mm/s.

- In Fig. 7, the middle part of the graph presented in Fig. 5 is shown in a more transparent form. In this case, the prestress is set to the required value of 50 mm and the maximum velocity of harmonic loading is constant (80 mm/s). To ensure the various loading fre-

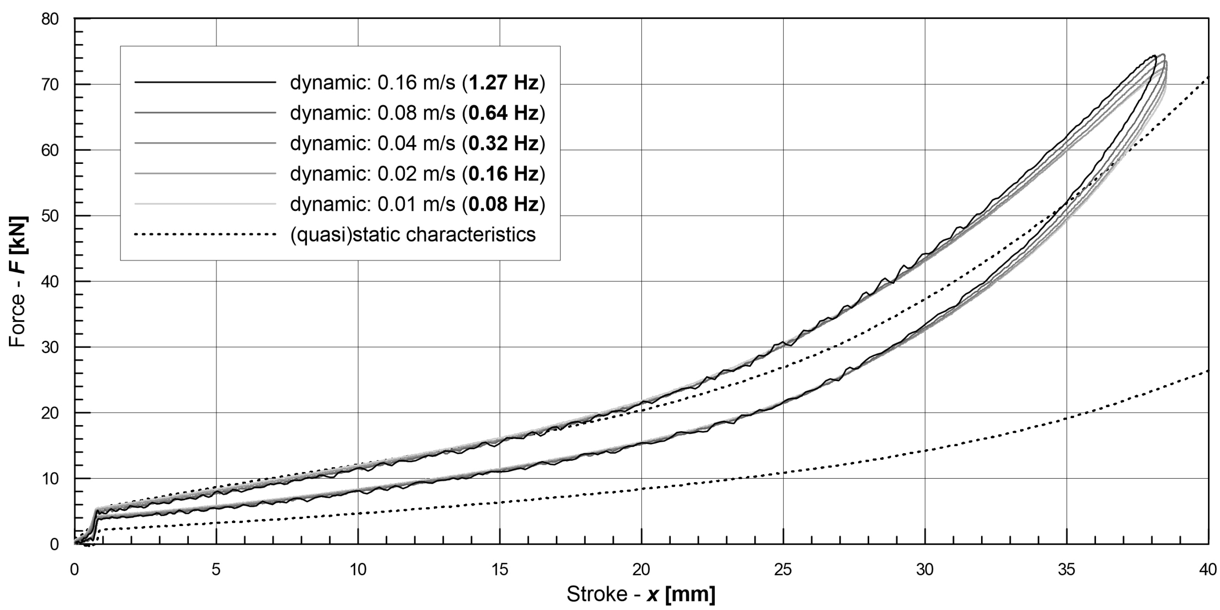


Fig. 6. Comparison of the dynamic stiffness characteristics of a railway freight wagon buffer of category A equipped with an elastomer spring at different frequencies of harmonic loading (constant amplitude)

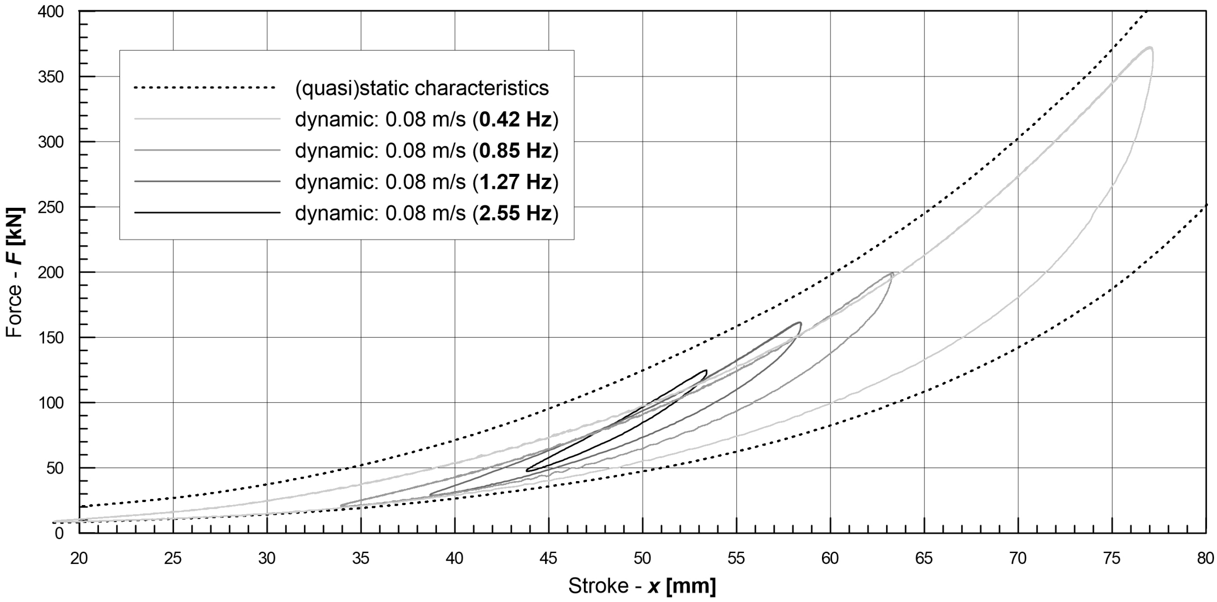
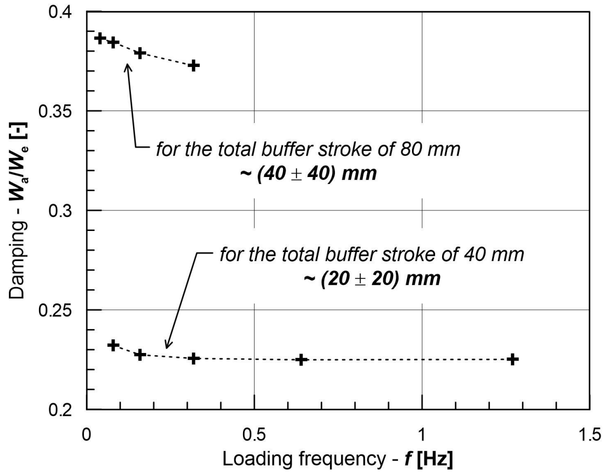


Fig. 7. Comparison of the dynamic stiffness characteristics of a railway freight wagon buffer of category A equipped with an elastomer spring at different frequencies of harmonic loading (changing amplitude)

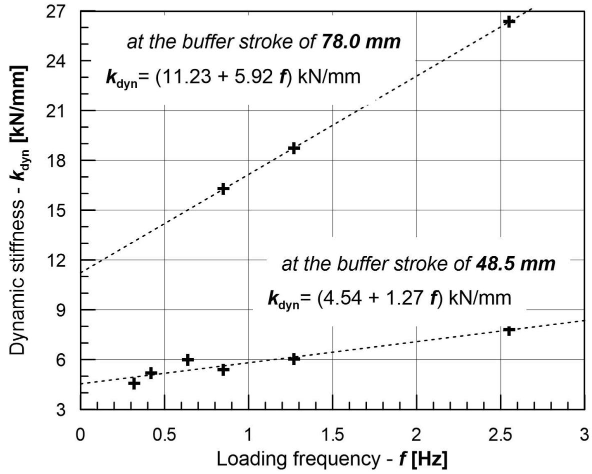
quencies, the individual measured dynamic characteristics differ in the amplitude (ranging from 5 mm up to 30 mm). Therefore, the presented characteristics correspond to the loading frequency ranging from 0.42 to 2.55 Hz.

On the basis of the results in Fig. 6, it is possible to state that the dynamic characteristics become more progressive with increasing frequency of loading and their loading (as well as unloading) curves show higher stiffness than the measured (quasi)static characteristics. In this case, an important attribute of the observed dynamic characteristics is the fact that the loading curve exceeds the envelope curve given by the (quasi)static curve at higher values of buffer stroke and, by contrast, the unloading curve does not touch the relevant (quasi)static curve in the whole observed range of deformation. The shape of the dynamic characteristics is closely related to the stored and absorbed energy of the buffer. The measurement results show a slight decrease in damping (defined according to EN 15551 [3] as a ratio between the absorbed and stored energy) with increasing loading frequency. In this specific case, the damping decreases from 0.232 at 0.08 Hz to 0.225 at 1.27 Hz. Compared to the generally required damping value, see (1) or (2), these values for the partial buffer stroke are very low. However, it should be noted that for a higher buffer stroke (and analogous scenarios of loading), the damping will be higher – e.g., for the buffer stroke of 80 mm (consisted of a prestress of 40 mm and an amplitude of 40 mm), the observed damping ranges between 0.386 at 0.04 Hz and 0.373 at 0.32 Hz. Of course, the absolute values of the stored and absorbed energy are also higher. For these two mentioned loading scenarios, the results and their trends are shown in the graph in Fig. 8a.

The results in Fig. 7 confirm the fact that a higher frequency of loading leads to a higher dynamic stiffness of the spring. Because of the different amplitudes of harmonic loading, it makes no sense to compare the absorbed and stored energy in this case. To quantify the influence of the loading frequency on the dynamic stiffness, the stiffness of the loading curve was calculated for the mean value of buffer stroke within the loading cycles (i.e., at a stroke of 48.5 mm). The observed results and their linear approximation are presented in the graph in Fig. 8b. In com-



(a)



(b)

Fig. 8. Selected properties of the measured dynamic stiffness characteristics of the buffer with an elastomer spring: (a) dependency of damping on loading frequency for two different types of loading cycles, (b) dependency of dynamic stiffness of the loading curve at the stroke of approximately 50 mm and 80 mm on loading frequency

parison with the dynamic characteristics presented in Fig. 6, the curves in Fig. 7 practically do not exceed the limits given by the (quasi)static stiffness characteristics.

In Fig. 5, very interesting results were obtained for the set of loading cycles with the required prestress of 80 mm (see the grey curves in the right part of the graph). Compared to the (quasi)static stiffness characteristics, the relevant curves correspond to a significantly lower level of force. As follows from further measurements, this phenomenon can be explained as an influence of the temperature of the suspension element on the shape of its stiffness characteristics, which is distinctive for the elastomer springs. As mentioned in Section 2.1, one of the required properties of suspension elements for application in the draw and buffing gear is a relatively high damping value (given by the ratio of absorbed and stored energy). Therefore, the dissipation of energy from a part of the stored energy occurs during the harmonic loading of the tested sample as a consequence of internal friction in the spring material and friction between the spring material and the inserted steel rings. The energy dissipated in the form of heat is warming up the spring element, which leads to a change in its mechanical properties. This effect is demonstrated in Fig. 9, where two (quasi)static stiffness characteristics of an elastomeric drawbar hook suspension are shown. The black curve corresponds to the surface temperature of the spring of ca. 25 °C and the grey curve was measured at a surface temperature of approximately 75 °C. The increase in the elastomer spring temperature was reached by the previous dynamic loading and its influence on the (quasi)static stiffness characteristic is very significant. The maximum stroke required during the measurement was set to 45 mm and the increase in the surface temperature by 50 °C is related to a decrease in the end force from 593 kN (at a stroke of 42.5 mm) to 374 kN (at a stroke of 44.5 mm). Together with this softening of the stiffness characteristic, a slight decrease in damping was observed (from 39 % to 37 %). However, the total amount of energy dissipated (under the condition of a similar stroke value) decreased by approximately 45 %.

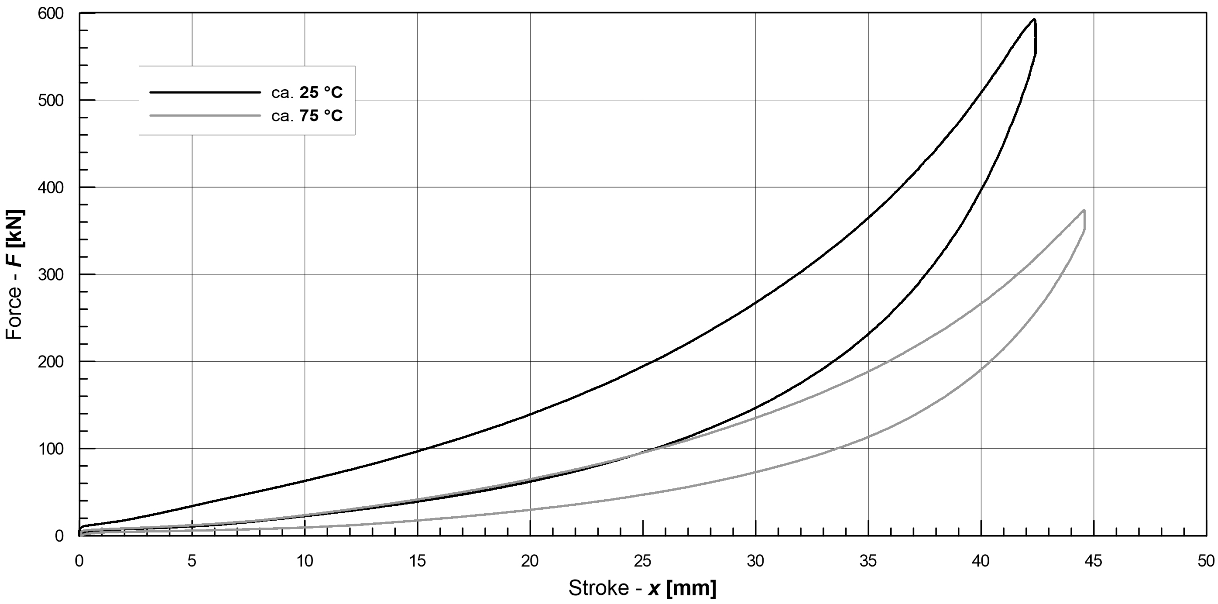


Fig. 9. Comparison of (quasi)static stiffness characteristics of an elastomer suspension element of a drawbar hook at the surface temperature of the spring of ca. 25 °C (*black line*) and ca. 75 °C (*grey line*)

4. Computational modelling of dynamic characteristics of railway buffers

As mentioned above, knowledge of the dynamic behaviour of the draw and buffing gear of railway vehicles is essential especially for plausible modelling of longitudinal train dynamics effects (see, e.g., [2, 7, 9]). According to the relevant standards [3, 4], manufacturers of relevant components define only the (quasi)static stiffness characteristics or these characteristics can be measured (verified) in the framework of maintenance actions (repairs of buffers). In case of application of the components (buffers and suspension elements of drawbar hooks or central couplers) with friction-type suspension (especially the ring springs), the mathematical model containing a description of the loading and unloading curve of the (quasi)static stiffness characteristic and the transition between them seems to be sufficient. This type of mathematical model, which is also suitable for the modelling of leaf springs in multibody simulations of freight wagons (see, e.g., [12]), can be defined as

$$\frac{dF}{dx} = \begin{cases} \dfrac{F_l(x) - F}{F_l(x) - F_u(x)}\,(k_t - k_l) + k_l & \Leftrightarrow \quad \Delta x > 0, \\[2ex] \dfrac{F - F_u(x)}{F_l(x) - F_u(x)}\,(k_t - k_u) + k_u & \Leftrightarrow \quad \Delta x < 0, \end{cases} \tag{3}$$

where

- $F_l(x)$ defines the (linear) loading curve of (quasi)static stiffness characteristic,
- $F_u(x)$ defines the (linear) unloading curve of (quasi)static stiffness characteristic,
- F is the current value of force acting in the suspension element,
- k_l is the stiffness of the loading curve of (quasi)static stiffness characteristic,
- k_u is the stiffness of the unloading curve of (quasi)static stiffness characteristic,
- k_t is the initial stiffness of the transition curve between the loading and unloading curve,
- x is the current value of deformation of the suspension element; the positive sign of its

change ($\Delta x > 0$) indicates loading, the negative sign ($\Delta x < 0$) indicates unloading.

For components equipped with elastomer suspension elements, the aforementioned model is also applicable. To do this, the above defined stiffness values k_l, k_u, and k_t have to be considered as functions of the deformation x instead of constant values, because of nonlinearity of the loading and unloading curve of the relevant (quasi)static stiffness characteristics, i.e.,

$$\frac{dF}{dx} = \begin{cases} \dfrac{F_l(x) - F}{F_l(x) - F_u(x)} \left(k_t(x) - k_l(x)\right) + k_l(x) & \Leftrightarrow \quad \Delta x > 0, \\ \dfrac{F - F_u(x)}{F_l(x) - F_u(x)} \left(k_t(x) - k_u(x)\right) + k_u(x) & \Leftrightarrow \quad \Delta x < 0. \end{cases} \tag{4}$$

Such a model was used, for example, within the longitudinal train dynamics simulations presented in [7]. However, this approach neglects effects of the dynamics of loading as well as the temperature, which were observed during the experimental investigation of the dynamic characteristics of real samples of side buffers and suspension of drawbar hooks (see the results presented in Section 3). To correct this imperfection, a new computational model of a railway buffer for multibody simulations (MBS) is being developed.

4.1. Integration of the effect of dissipated energy into the MBS model of the buffer

At this stage of research, the effect of the elastomeric spring temperature was integrated into the model, which is based on the modified equation (4). For these purposes, the loading and unloading curves of the (quasi)static stiffness characteristics must be defined as a function of the temperature. With respect to the measured (quasi)static characteristics of an elastomer spring of a drawbar hook at different values of the surface temperature (see Fig. 9), a general shape of dependency of the force on the loading and unloading curve on the temperature was proposed as

$$F\left(x, T_s\right) = F\left(x, T_{s0}\right)\left[1 - c_{ts}\left(T_s - T_{s0}\right)\left(1 - e^{-\frac{x}{\alpha}}\right)\right], \tag{5}$$

where

- $F\left(x, T_s\right)$ defines the loading or unloading curve of (quasi)static stiffness characteristic at the current spring temperature T_s,
- $F\left(x, T_{s0}\right)$ represents the loading or unloading curve of (quasi)static stiffness characteristic at the reference spring temperature T_{s0},
- c_{ts} is the coefficient of temperature sensitivity, reflecting a relative decrease of the force at a certain change in temperature,
- α is a constant characterising the investigated temperature effect in dependency on the spring deformation (buffer stroke).

Because the spring temperature is determined by the absorbed (dissipated) energy and emitted heat, an equation of heat equilibrium has to be introduced into the multibody simulation model. This equation is based on the simple idea that the absorbed energy W_a has to be partially changed into an increase of the spring temperature and, simultaneously, a part of the heat is emitted into the environment. Therefore, the equation is proposed as follows:

$$dW_a = C dT + \lambda\left(T_s - T_0\right) dt, \tag{6}$$

where

- $C\,[\mathrm{J\,K^{-1}}]$ is the thermal capacity of the spring,

- λ [W K^{-1}] is the coefficient of thermal losses of the buffer,
- T_s [°C] is the spring temperature,
- T_0 [°C] is the temperature of the environment,
- t [s] is the time.

Then, a change in the spring temperature ΔT_s can be expressed as

$$\Delta T_s = \left[\frac{Q_a}{\lambda} - (T_s - T_0)\right]\left(1 - e^{-\frac{\lambda}{C}\Delta t}\right), \tag{7}$$

where Q_a [W] is the thermal power of the energy absorbed by the spring, i.e., the absorbed (dissipated) energy in the relevant time step Δt of the multibody simulation. The resulting current temperature T_s creates an input into (5) modifying the loading and unloading curve of the (quasi)static stiffness characteristics.

4.2. Verification of the proposed elastomer spring model

To verify the proposed improvements of the buffer model, including the temperature effect of the elastomer spring, the measurement results presented in Fig. 7 were used. It is evident that the curves corresponding to the loading cycles do not touch the loading curve of the (quasi)static stiffness characteristic. A possible explanation of this effect lies in the fact that the buffer (and its spring) was loaded before the measurement of these specific cycles by a defined sequence of loading cycles and, therefore, the relevant absorbed energy led to an increase in temperature compared to the conditions applied for measurement of the (quasi)static characteristic (i.e., approximately 25 °C).

If the temperature dependence given by (5) is integrated into the elastomer spring model defined generally by (4) and an increased temperature of the spring T_s is considered, it is possible to approximate the measured curves without any other forced modification of the basic (quasi)static stiffness characteristics. For the defined (constant) spring temperature of 35 °C and the same loading scenarios (i.e., for the harmonic loading cycles with a prestress of 48.5 mm, amplitudes of 5, 10, 15, and 30 mm and the maximum loading velocity of 80 mm/s), the simulation results are compared to the measurement results in Fig. 10. It can be stated that the considered change in temperature helps to approximate the simulation results to the measured data (i.e., to reflect the decrease in force at a given value of buffer stroke), which is also connected with a decrease in the amount of the absorbed (dissipated) energy in the elastomer spring within a loading cycle.

Because the example presented above shows only the effect of a defined (constant) spring temperature, the question is how the integration of the energy dissipation process (defined by (7)) into the elastomer spring model affects the dynamic behaviour of the model. To demonstrate this effect, the following simulation scenario was realized: At the beginning, the buffer model was loaded by a slow simple loading to the maximum stroke value, subsequent slow simple unloading and then loaded by harmonic cycles with a prestress of 78 mm, an amplitude of 15 mm and the maximum velocity of loading of 80 mm/s (i.e., by the loading frequency of 0.85 Hz). This simulation scenario is depicted in the upper graph of Fig. 11 as a dependency of the buffer stroke on time. The aim of this attempt was to bring the simulation results close to the selected measurement results, which are presented in the right part of Fig. 5 and which are evidently influenced by the increased spring temperature because of their position out of the envelope curves defined by the (quasi)static stiffness characteristics (see Section 3.2).

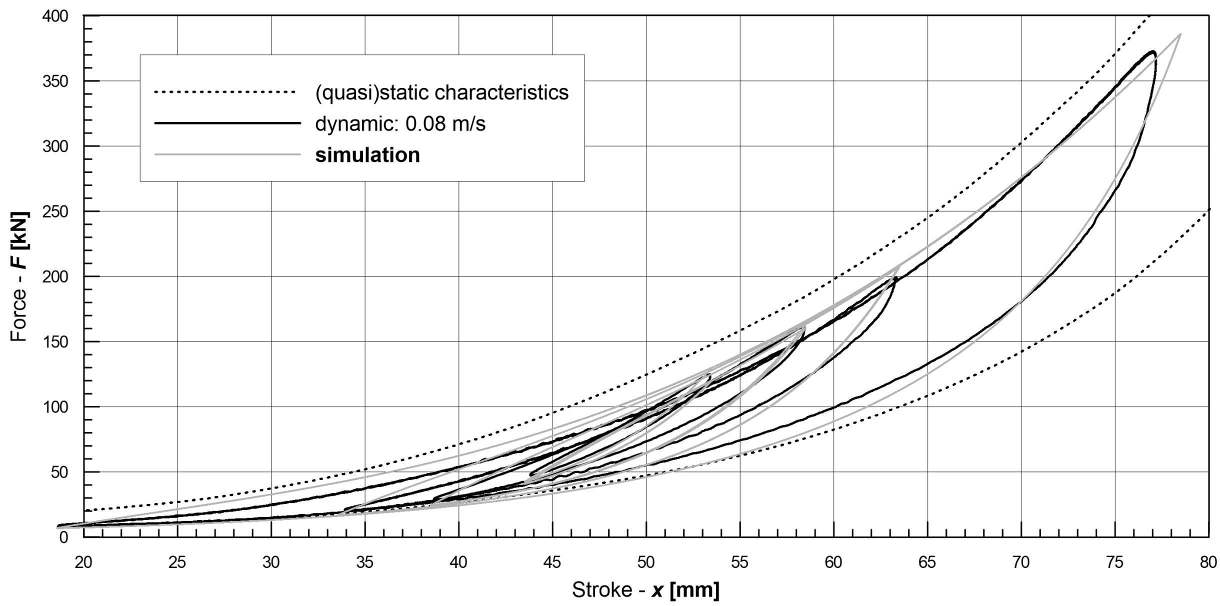


Fig. 10. Comparison of the measured (quasi)static and selected dynamic characteristics of a railway freight wagon buffer of category A equipped with an elastomer spring with the corresponding simulated dynamic characteristics under the condition of an increased spring temperature

The bottom graph of Fig. 11 shows the time behaviour of the total amount of energy absorbed (dissipated) in the elastomer spring (the black line) as well as the time behaviour of the spring temperature (the grey line) during the simulation scenario considered. This graph can be also used for a better explanation of the principle of the newly proposed elastomer spring model. It is evident that the energy dissipation is considered only if the spring is being unloaded (i.e., the buffer stroke value is decreasing). In this situation, the thermal power of the absorbed

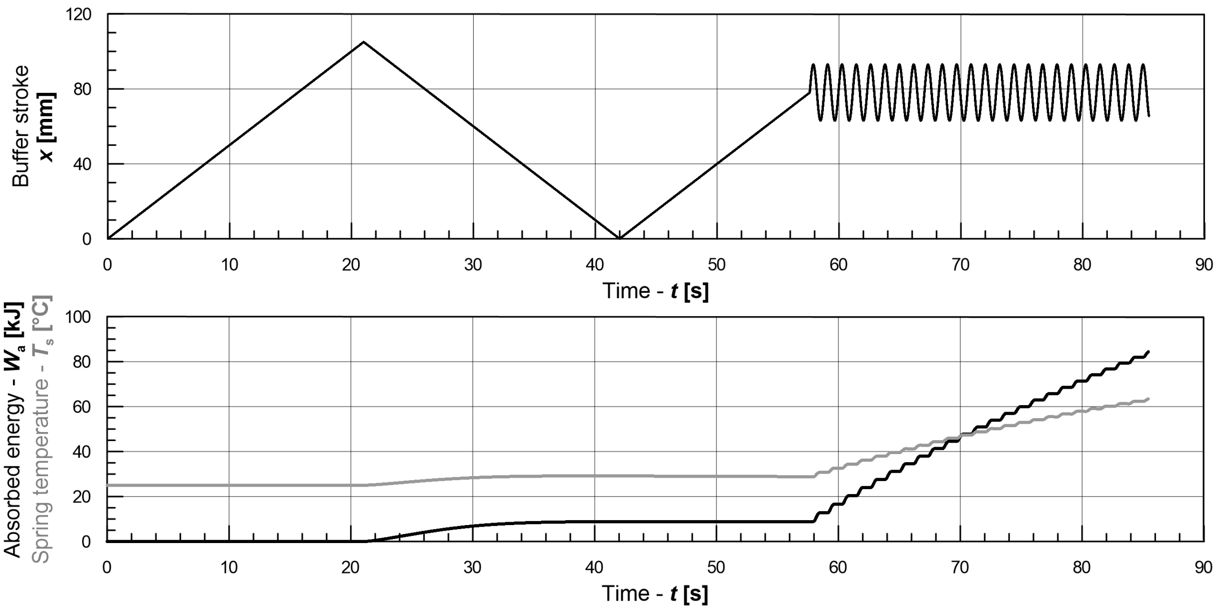


Fig. 11. Definition of the loading scenario for verification of the new elastomer spring model (*top*) and the corresponding time behaviour of the total amount of energy absorbed and the spring temperature (*bottom*)

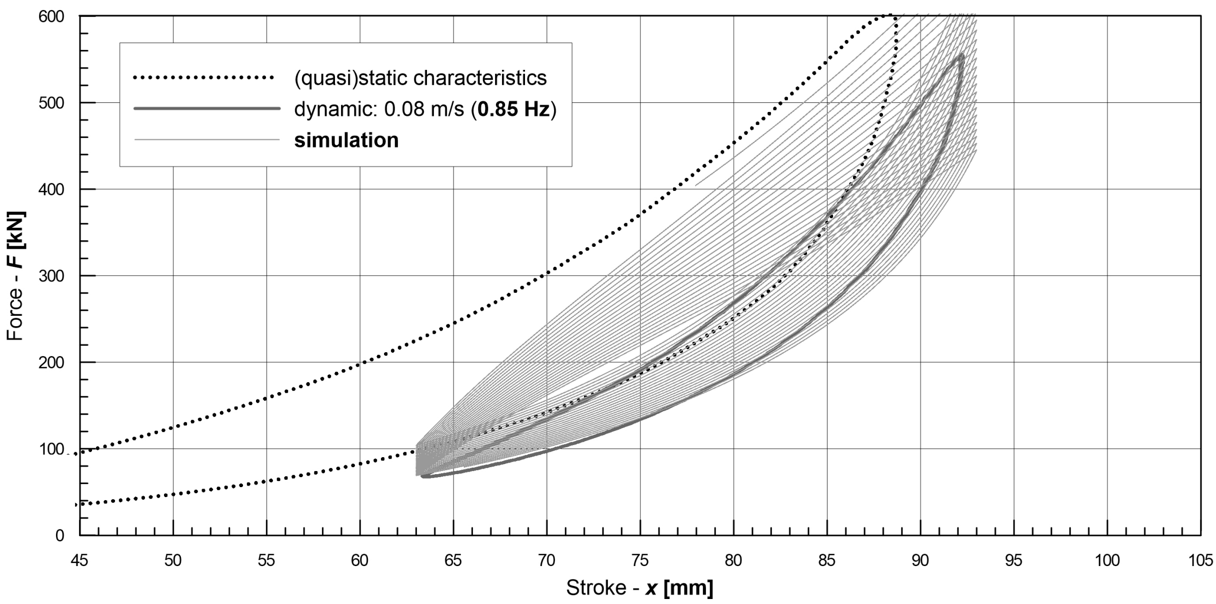


Fig. 12. Comparison of the measured (quasi)static and selected dynamic characteristics of a railway freight wagon buffer of category A equipped with an elastomer spring with a set of simulated dynamic characteristics obtained by means of the newly proposed MBS spring model considering the energy dissipation and relevant temperature effects (prestress: 78 mm, amplitude: 15 mm, loading frequency: 0.85 Hz, initial spring temperature and environment temperature: 25 °C)

energy Q_a, creating an input into (6), can be quantified as

$$Q_a = (F_l(x) - F(x)) \frac{|\Delta x|}{\Delta t}, \tag{8}$$

where

- $F_l(x)$ defines the force corresponding to the given buffer stroke x of the loading curve of (quasi)static stiffness characteristic (at the current spring temperature T_s),
- $F(x)$ is the actual force in the spring,
- Δx is the change in buffer stroke within the relevant time step Δt of the simulation.

Then, the increase of the total amount of energy absorbed by the spring within the time integration step Δt can be expressed as

$$\Delta W_a = Q_a \, \Delta t. \tag{9}$$

As follows from the bottom graph of Fig. 11, the spring is gradually warming up as a consequence of the energy absorbed during the harmonic loading. From the point of view of the dynamic stiffness characteristics, the results of this computational experiment are presented in Fig. 12. In this graph, the measured (quasi)static characteristics (for the initial spring temperature of approximately 25 °C) and a selected measured dynamic stiffness characteristic (for the required prestress of 80 mm, the amplitude of 15 mm and the loading frequency of 0.85 Hz, but for an unknown spring temperature) are shown. In addition to that, the simulation outputs in the form of dynamic stiffness characteristics of the gradually warmed elastomer spring model are also depicted in the graph. It is evident that the gradually increasing spring temperature brings the simulation results closer to the measured data. For this investigated case, the simulated and measured force at the bottom dead point of the cycle have similar values under the condition of a considered spring model temperature of approximately 60 up to 65 °C.

However, it should also be noted that while the amount of energy absorbed follows from the dynamic behaviour of the spring, its transformation into the spring temperature is influenced by the relevant coefficients (the thermal capacity of the spring C and the coefficient of thermal losses of the buffer λ) used in (7). For purposes of application within the above described example, specific values of these coefficients ($C = 2\,000\,\mathrm{J\,K^{-1}}$, $\lambda = 10\,\mathrm{W\,K^{-1}}$) were chosen in order to demonstrate the principal behaviour of the newly proposed computational elastomer spring model, but they are not results of any measurements.

The temperature behaviour of the stiffness characteristics of the buffer spring – i.e., especially the coefficient of temperature sensitivity c_{ts}, see (5) – was derived from the measured data corresponding to the elastomer suspension element of a drawbar hook (see Fig. 9); specifically, the value of $c_{ts} = 0.01\,\mathrm{K^{-1}}$ was considered within the above described example.

5. Conclusions

This paper deals with the stiffness characteristics of suspension elements for components of the draw and buffing gear of railway vehicles, especially freight wagons. Nowadays, elastomers are often used as a material for these springs. As follows from the analysis of the requirements on these suspension elements (see Section 2), practically only the (quasi)static stiffness characteristics of the new railway buffers must meet some defined normative requirements. Also, in the framework of the maintenance process (realised basically in 6-year inspection intervals), any kind of verification of the relevant stiffness characteristics is usually not required. However, the knowledge of stiffness characteristics of the components of draw and buffing gear is essential for multibody simulations of longitudinal train dynamics or some type of running safety investigations. In addition to that, the elastomer springs show distinctive properties from the point of view of dynamic loading. Therefore, knowledge of their (quasi)static stiffness characteristics is generally not sufficient for their accurate description under the conditions of dynamic loading.

To obtain relevant input data for multibody simulations, measurements of the dynamic stiffness characteristics of real samples of railway freight wagon buffers, as well as the suspension elements of the drawbar hook, were carried out at the Faculty of Transport Engineering of the University of Pardubice within the framework of the Master thesis in 2020 [6]. The most important measurement results are presented in this paper (see Section 3) and used for further development of a new computational model of elastomer spring, which can be typically used for the modelling of railway buffers in multibody simulations. The main distinctive properties of the elastomer buffer springs, following from the measurement results, are

- influence of frequency of dynamic loading on their dynamic stiffness and also on the amount of absorbed energy relative to the stored (accumulated) energy in the spring,
- a very significant influence of the spring temperature on the stiffness characteristics of the elastomer spring.

At the current state of research, the presented proposal of the new computational model (see Section 4) is able to describe the nonlinear nature of the (quasi)static stiffness characteristics of the elastomer springs, as well as to integrate the effects of energy dissipation on temperature-dependent behaviour of the spring. The results obtained by means of the new buffer model were validated by their comparison with measurement results to demonstrate the ability of the proposed modelling method to reflect the real behaviour of the dynamic characteristics of the railway buffer.

From the point of view of a further application of the newly proposed model reflecting the temperature behaviour of the buffers, its significance can be found especially in the field of running safety investigation of vehicles, specifically in the following two points:

- the influence of significantly negative temperatures on the lateral force effects, safety against derailment and damaging effects of the vehicles within a train in small-radius curves (it is possible to expect that the negative temperatures can lead to opposite effects – i.e., an increase in stiffness – than those observed when the samples were being warmed);
- the influence of the reduced ability of energy dissipation at higher temperatures on the longitudinal train dynamics effects, especially in heavy long trains. Generally, the question of dynamic behaviour of suspension elements for the coupling device of railway vehicles is also currently important in the development of the new European standard solution for vehicle coupling, the digital automatic coupler (DAC); see, e.g., [10].

In the next steps of development of the general railway buffer model for the application in multibody simulations, attention should be paid to a more precise determination of coefficients of the new model (e.g., by means of further measurements) and also to an additional integration of the effect of loading frequency on the dynamic buffer characteristics.

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