558. Dynamics of loadings acting on coupling device of accelerating auto-train

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Abstract. Analysis of loadings acting on auto-train under most probable and recurring operation conditions is performed in this work. The largest loading exerted both on empty auto-train with empty trailer and on the loaded one is the longitudinal inertia force that depends on trailer mass and longitudinal acceleration determined by longitudinal acceleration acting at its weight centre. With given longitudinal loading acting on the device body attached to empty and loaded trailers being subjected to time-varying acceleration, corresponding to experimental and theoretical results of research of acceleration dynamics, it was established that dynamic factor was observed just after driving acceleration had ceased acting – subsequent vibration of parts of the coupling device did not exceed extreme values obtained in the initial moment.

Keywords: coupling device, dynamics of acceleration, inertia force.

Introduction

Coupling devices of auto-train trailers are attributed to the particularly safe elements of the auto-train. If the coupling device breaks down, the trailer may uncouple from the truck and become completely uncontrollable item moving from inertia. In order to avoid this, the coupling devices are designed and produced in accordance with the rules of procedure determined by experts and certified by legal acts [1]. The most significant factors of the coupler breakdown are the wear and tear of its most important elements or insufficient strength. All these factors are influenced by dynamic loads during trailer operation. Thus, in order to design secure and reliable coupling devices, one should know the dynamic loads of the most essential elements.

During theoretical investigation when the mathematical model of the discussed unit is designed, the following assumptions are made: at the start of the motion, the torque in the driving automobile wheels and the traction increase linearly [2, 3]. Three periods were disclosed during investigation: acceleration, constant speed and deceleration or braking. The first stage is when the vehicle acceleration increases linearly, i.e. it shows the increase of the driving force of the wheels. The second stage is the deformation of the flexible element of the trailer. The third stage or acceleration stage is the time slot from the moment when the trailer makes a move until the beginning of the constant motion, i.e. till the vehicle acceleration is equal to zero. While designing and estimating the reliability, the most important period is the third or acceleration stage, and the regime of the constant speed. In the first instance the loads are of non-recurring nature, and their numerical value is the greatest. Thus this regime governs the mechanical strength of the device, as well as the abrupt breakdowns the intensity of which determines its failure-free performance. The loads of fixed speed mode are cyclic and condition the wear and tear intensity that determines the durability of the coupling device.

Analysis of loadings acting on a coupling device

During the reliability test of the vehicle-trailer coupling device, in the initial stage of the investigation of acceleration dynamics it was essential to define the possible loads of the coupling device with the most likely vehicle driving regimes and the design of the vehicle in mind [4,5]. The longitudinal, horizontal load F_s of the vehicle-trailer coupling device is governed by the longitudinal inertia force of the trailer $F_{In\,p}$ and the force F_f, which results from the longitudinal forces because of the trailer wheel movement resistance. The trailer wheel resistance force depends on the trailer load and essentially does not depend on driving speed. Longitudinal force of inertia $F_{In\,p}$ depends on the trailer mass and longitudinal acceleration a_{xp} in the trailer centre of gravity.

If there is no longitudinal disengagement of the coupling device then the longitudinal acceleration a_{xp} of the trailer depends on the acceleration potential of the whole vehicle trailer (during acceleration) or its braking potential (during braking). Fig. 1 illustrates the loads exerted on the vehicle trailer and its coupling device during acceleration.

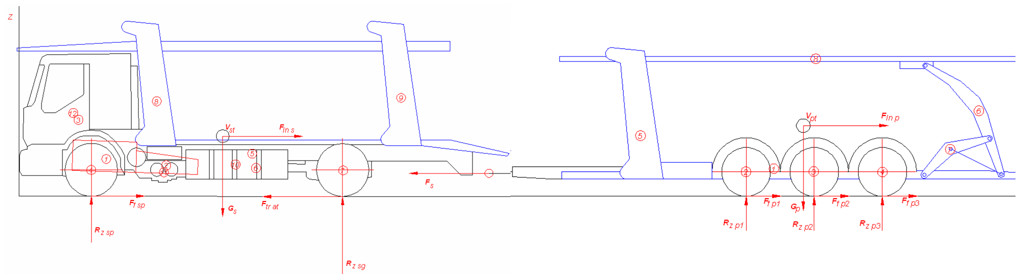


Fig. 1. Forces acting on the truck (a) and trailer (b) during acceleration: G_s – weight force of the truck with an extension, $\underline{R_{z\,sp}}$ – vertical reaction of the truck front wheels on the road, $R_{z\,sp}$ – vertical reaction of the truck rear wheels on the road, $F_{f\,sp}$ – resistance-to-motion force of the truck front wheels, $F_{tr\,at}$ – traction force exerted on the truck real wheels during the contact with the road, $F_{In\,s}$ – inertia force applied to the truck centre of gravity, F_s – longitudinal force applied to the coupling device; G_p – force of the trailer weight, $R_{z\,p1,\,2,\,3}$ – vertical reaction of the trailer wheels on the road, $F_{f\ \ p1,\,2,\,3}$ – resistance-to-movement forces of the trailer wheels, $F_{In\,p}$ – inertia force applied to the trailer centre of gravity [6]

Loading of the vehicle trailer has significant impact on the load of the coupling device. The acceleration dynamics of the vehicle trailer has been discussed when the road is horizontal with asphalt paving. The situation when only the trailer is loaded is hardly possible in reality because the truck mass is greater than the mass of the loaded trailer (the mass ratio is n = 0.758) may impact significantly the controllability of the whole vehicle trailer. Because of the lower total mass of the vehicle trailer the acceleration dynamics on the good road paving is much better if compared with that of the fully loaded vehicle trailer.

Because of the better dynamics of the vehicle trailer, the inertial component – $F_{in\,p}$ of the longitudinal force F_s of the coupling device increases. This force also increases because of the larger trailer mass, which consequently results in increase of the trailer wheel resistance to running – $F_{f\,pl,\,2,\,3}$ and simultaneously increases the force F_s exerted on the coupling device. It is likely that at such load the greatest longitudinal force F_s is exerted on the coupling device during acceleration.

Empty vehicle trailer has the best acceleration dynamics. Because of the greatest acceleration a_{xp} in the trailer centre of gravity increases the inertial component $F_{in\,p}$ of the longitudinal force of the coupling device, but at the same time it also decreases because of the smaller trailer mass. In this case, the value of the force $F_{in\,p}$ depends on the potential of the vehicle-trailer acceleration. Because of the lower trailer mass forces $F_{f\,pl,\,2\,,\,3}$ minimize as well. In all events, the value of the longitudinal force F_s in the coupling device should be checked at such load of the vehicle trailer.

Research of auto-train acceleration dynamics

In order to define the accuracy of results of theoretical analysis of dynamics of auto-train acceleration [6], an experimental research of the maximum acceleration of an empty auto-train with trailer considered has been performed with help of the available measurement equipment at KTU Transport engineering department. In order to define longitudinal accelerations acting on the auto-train during acceleration devices „DL1 data logger“ for recording dynamics parameters, attached on lower platforms of the truck and the trailer, the acceleration sensors of longitudinal movement during the test have recorded values of required longitudinal accelerations. Devices „DL1 data logger“ have been used in the test and their attachment on the auto-train is indicated in Fig. 2.

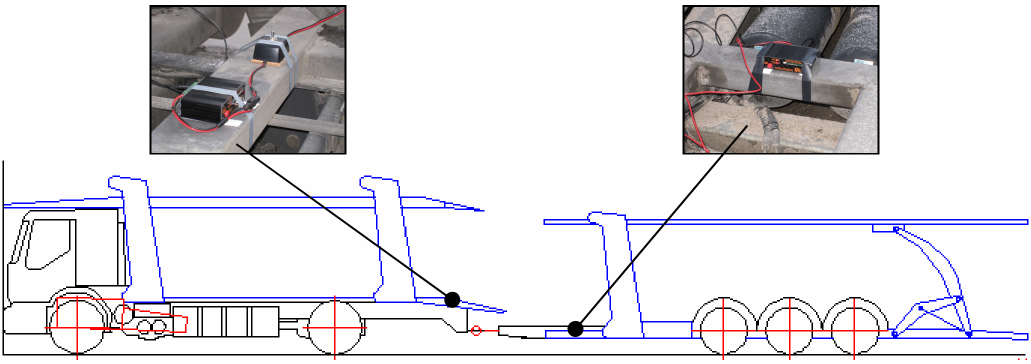


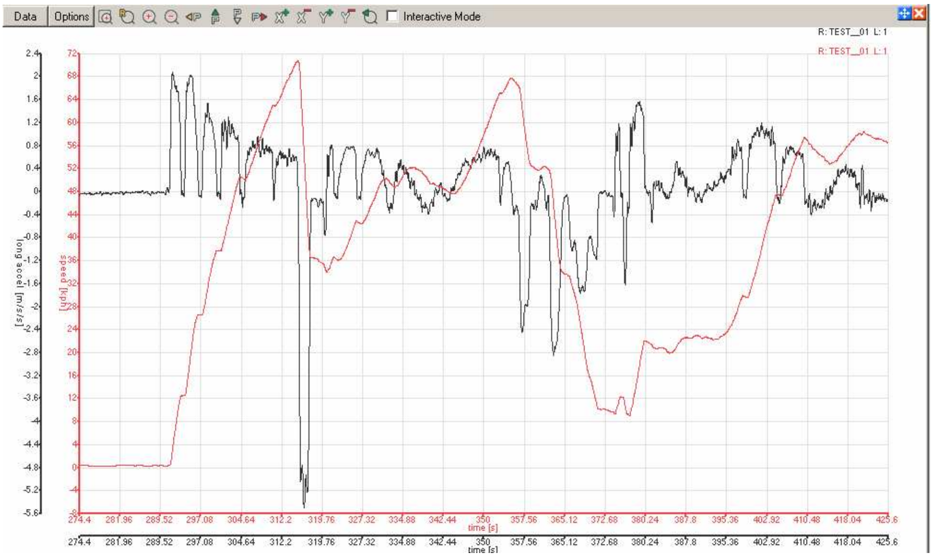
Fig. 2. Device „DL1 data logger“ for recording dynamic parameters is attached on the truck platform and the trailer platform

Each of the devices „DL1 data logger“ has its own global positioning system (GPS) antenna, which enables tracking of vehicle position in space. According to varying vehicle position with time and accelerations readings the device calculates speed of vehicle with an accuracy of 0,16 km/h every 0,1 fraction of second. Longitudinal and transversal acceleration sensors mounted in the devices record accelerations up to 2*g*.

Experimental auto-train acceleration dynamics parameters (acceleration and speed as a function of time) are presented in Fig. 3. Research results have revealed that maximum longitudinal acceleration a_x =2 m/s^2 was acting on the auto-train truck during its acceleration. At the same moment maximum longitudinal acceleration acting on the trailer was a_x =2,18 m/s^2.

In comparison of maximum theoretical acceleration defined on auto-train (a_x =2,536 m/s^2) with longitudinal acceleration (a_x =2 m/s^2), determined in exterior tests, one may observe that obtained values are of the same order. Difference between maximum theoretical acceleration value and determined in exterior tests is 22 %. The main reason for larger maximum theoretical acceleration value is omission of the resistance-to-movement forces of the trailer wheels $F_{f\,p1,2,3}$. This is impossible to take into account in the used programme of theoretical calculations.

The difference between the defined maximum acceleration acting on the auto-train and the trailer might have been determined both by technical factors and testing environment. In further research stage there was assumed that the biggest longitudinal acceleration acting on the trailer was equal to the maximum value defined by testing - a_x =2,18 m/s^2. With the empty mass of auto-train trailer - m_{pt} = 6430 kg and maximum acceleration acting in mass centre of the trailer a_x =2,18 m/s^2, the maximum inertia force acting on the trailer coupling device with an empty trailer is defined: $F_{In\_pt} = m_{pt} \cdot a_x = 6430 \cdot 2{,}18 = 14017{,}4$ N. In this loading mode of coupling device longitudinal forces originating from the trailer wheels are not calculated separately since in real-life conditions these forces impact auto-train acceleration automatically. The resistance-to-movement forces of the trailer wheels are evaluated through longitudinal acceleration acting on the auto-train. Thus, in this loading mode total force acting on a coupling device - F_s: $F_s = F_{In\_pt}$.



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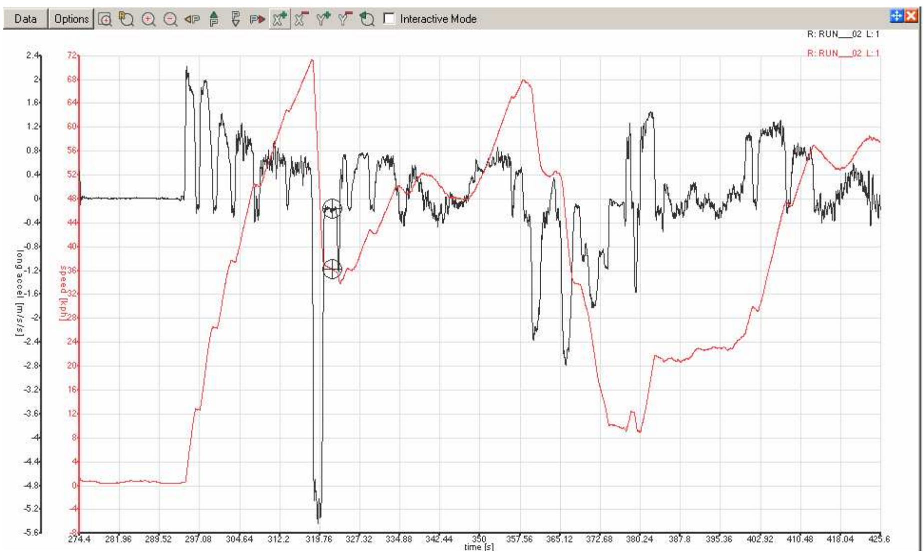
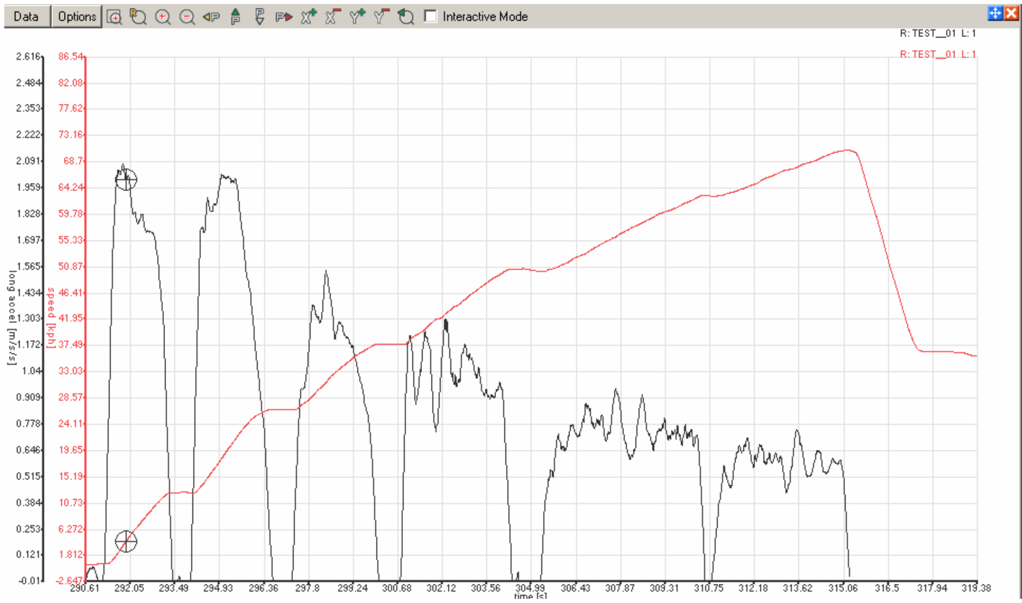
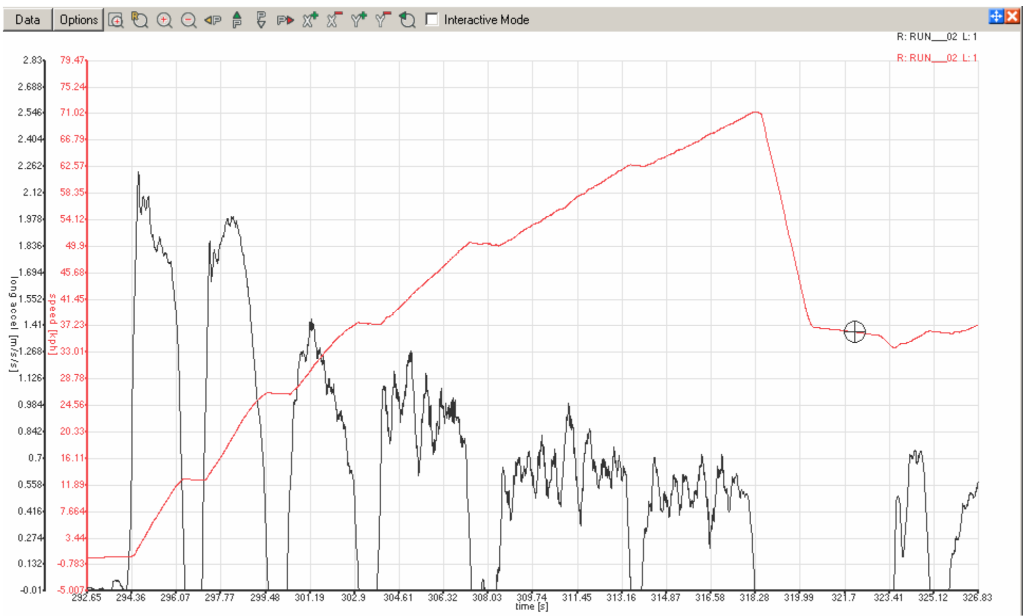


b)

Representative measurement results



a)



b)

Period of biggest acceleration

Fig. 3. Dependences of experimental speed and acceleration of auto-train truck on time: a)–truck, b)-trailer

Maximum longitudinal loadings acting on the trailer coupling device are determined for two cases: the empty complete auto-train and the auto-train with the loaded trailer. Since there was no possibility to perform natural testing of the auto-train with loaded trailer, so maximum longitudinal acceleration acting on the trailer during acceleration period is evaluated after theoretical analysis of auto-train acceleration has been accomplished. It was assumed, as well, that results of the theoretical analysis were of the sufficient accuracy.

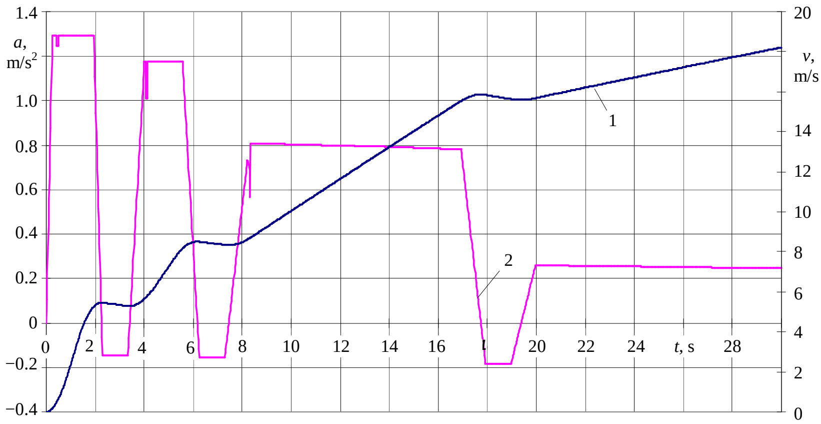


Fig. 4. Dependences of acceleration (2) and speed (1) of auto-train vs. time obtained by theoretical analysis of maximum acceleration dynamics for the auto-train with loaded trailer

So, analogical theoretical analysis of the auto-train acceleration dynamics is performed, but total auto-train mass in this case is – m_a = 22560 (kg). Results of the theoretical analysis of acceleration dynamics of the auto-train with the loaded trailer (Fig. 4) have demonstrated that the largest acceleration acting on the auto-train with loaded trailer is - a_x = 1,291 m/s^2. It is assumed that this longitudinal acceleration is the largest. Thus inertia force acting on the trailer is: $F_{In\_pp} = m_{pp} \cdot a_x = 12830 \cdot 1{,}219 = 16563{,}53$ N.

Analysis of loadings on auto-train coupling device has demonstrated that when the auto-train accelerated with loaded trailer, bigger inertia force acted in trailer mass centre than in the case of empty trailer. In this case there was assumed that maximum longitudinal force acting on coupling device is $F_s = F_{In\_pp}$ = 16563,53 N ($F_{In\_pp} > F_{In\_pt}$).

Reliability analysis of coupling device by FE method

Software CosmosWorks based FE analysis has been chosen to investigate reliability of auto-train coupling device. The static problem has been solved in an initial stage, with the device loaded with maximum loadings presented in its technical passport. The dynamic task deals with a digital model of mounted unit, loaded with loadings varying with time. A geometric model of an auto-train coupling device has been corrected by eliminating geometrical elements, attachment elements and rejecting other details without any significant impact on device strength evaluation [7].

In order to ensure reliability of the coupling device and avoid fragile disintegration, caused by possible dynamic, impact loadings during operation, the main auto-train coupling elements responsible for road safety are made of alloy steel 40X, distinguished for its strength and plasticity. Through relatively small contact surface of coupling device body attached to the trailer and bush all interaction forces of the truck and the trailer are transmitted, in some cases reaching extreme sizes. So in order to reduce the friction factor between surfaces of intense contact during operation, the bush of the coupling device is made of bronze.

The purpose of static task is to check the device reliability under extreme loadings, determine stress distribution in details, device danger areas, and evaluate character of deformation of the device elements. Fixation of the coupling device is evaluated by fixing the body attachment surface to the vehicle stationary, and restricting displacements of the body attached to trailer in vertical direction. The body attached to the trailer is loaded with horizontal force $F_h = 120kN$ and vertical force $F_v = 90kN$ (Fig. 5a). Contacting surfaces of separate parts are connected rigidly. After calculations of the static strength task according to loading scheme presented in Fig. 5a have been performed, it was established that maximum equivalent von Misses stresses generated in the device are smaller than yield limit of material $\sigma_Y = 785\,MPa$. Strength margin of safety achieved $n = \sigma_Y / \sigma_{\max} = 785/199.4 = 3.9$. Equivalent stress distribution indicates dangerous – mostly loaded area of the device, i.e. in the thinnest zone of the coupling device sphere.

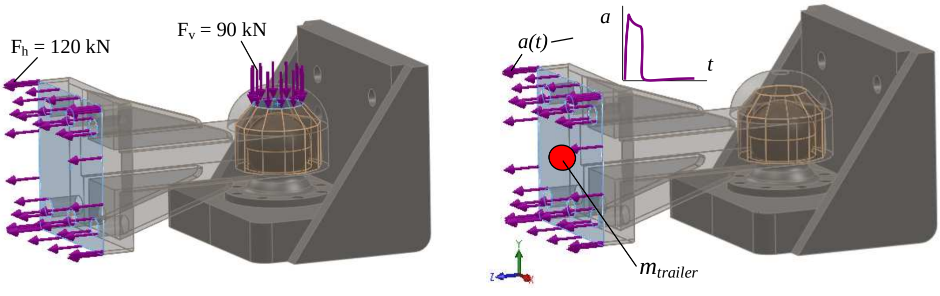


Fig. 5. Loading scheme of the coupling device for static (a) and dynamic (b) analyses

In dynamic strength analysis only longitudinal loadings were considered. Evaluation scheme of boundary conditions (Fig. 5b) is common both to static and dynamic strength analyses. Attachment of the coupling device is evaluated by fixing displacement of body attachment surface to the vehicle in all three directions, and displacements of the body attached to the trailer in vertical direction. The loading in the dynamic simulation is assigned with varying acceleration with longitudinal time acting on the body attached to the trailer. To the surface of body attachment to the trailer the trailer mass is assigned (empty trailer – $m_t = 6430\,kg$, loaded trailer – $m_p = 12830\,kg$). This allows evaluation of inertia characteristics of the trailer.

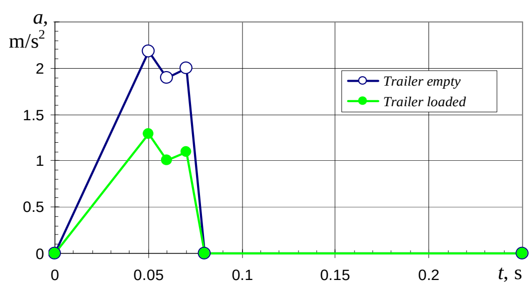


Fig. 6. Functions of given acceleration variation with an empty trailer and loaded one

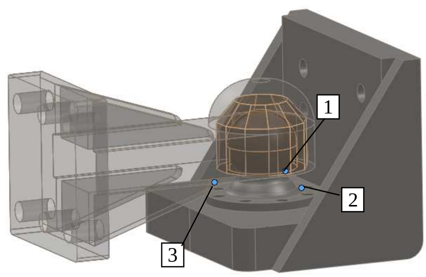
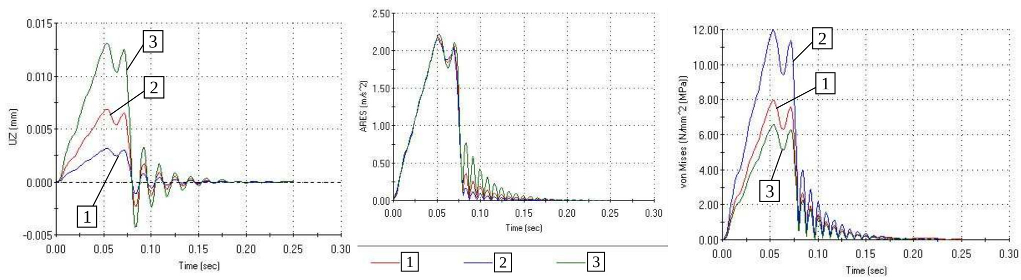


Fig. 7. Three optional points for dynamic analysis

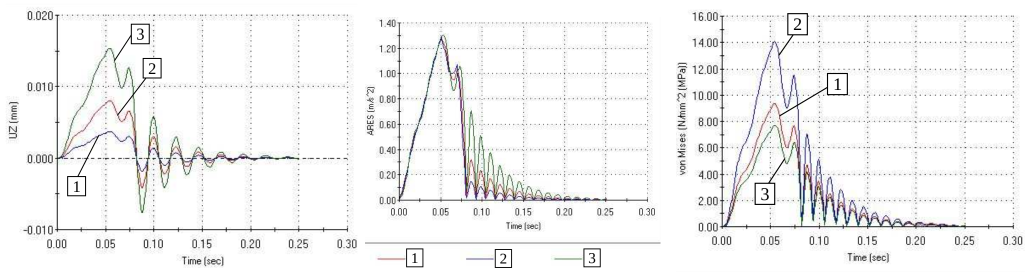
In the case of an empty trailer function of acceleration varying with time corresponds to experimental research results and in the case of the loaded trailer – to theoretical calculation results. Just a short acceleration variation period has been chosen (t = 0,25 s) (Fig. 6). Damping factor of the mechanical system considered has been chosen 0,05. The task calculation duration is t = 0,5 s, with step of 0,001s. Three points have been chosen for further results analysis (Fig.7).

From the results presented in Fig. 8 and Fig. 9 one may observe that dynamism impact asserts just when an exciting acceleration stops acting, but further vibration of coupling device parts does not exceed extreme values having been reached at an initial moment therefore the dynamism impact is not important. Results of finite element analysis of the coupling device strength indicate that during normal acceleration the stress acting in the coupling device with an empty trailer and the loaded one is considerably smaller than material marginal stress. The value of stress acting on the coupling device depends on function of the given acceleration variation. In turn acceleration values depend not only on auto-train thrust characteristics, but on backlashes in the coupling device as well. Regulated permitted maximum sphere wear of the auto-train coupling device does not exceed 3 mm. Influence of such wear on dynamical interaction forces in the coupling device is undoubted. Small difference in results is obtained due to negligence of relatively gradually varying acceleration obtained in experimental research and seemingly possible gap, which causes impact loadings during operation.



a) b) c)

Fig. 8. Dependences of points of displacements (a), accelerations (b) and stress (c) on time (empty trailer)



a) b) c)

Fig. 9. Dependences of points of displacements (a), accelerations (b) and stress (c) on time (loaded trailer)

In order to achieve more accurate evaluation of reliability of the coupling device, it is reasonable in further studies to analyze fatigue phenomenon – sphere is loaded in cyclic mode, i.e. inclined to one and to another side.

Conclusions

Analysis of loadings acting on auto-train coupling device performed under common operating conditions of the auto-train demonstrated that maximum loading exerted on empty auto-train with empty trailer and with loaded one is longitudinal inertia force depending on the trailer mass and acceleration acting at its weight centre determined by longitudinal acceleration.

Experimental research results indicate that during acceleration the auto-train truck is exposed to the largest longitudinal acceleration of a_x =2 m/s^2, and at the same moment maximum longitudinal acceleration acting on the trailer is a_x =2,18 m/s^2. The difference between the maximum longitudinal acceleration of the auto-train with empty trailer defined theoretically and the one obtained experimentally is due to the exclusion of the resistance-to-movement forces of the trailer wheels in the numerical analysis programme used for investigation and testing conditions – possible movements of mobile elements on the trailer, vertical trailer movements, occasional road roughness.

Numerical analysis of the loadings in auto-train coupling device revealed that during the auto-train acceleration with the loaded trailer, larger inertia force acts at the trailer mass centre with respect to the case of the empty trailer – the highest longitudinal force exerted on the device is $F_s=F_{In\_pp}$=16563,53 N ($F_{In\_pp} > F_{In\_pt}$). FE analysis demonstrated that upon loading the device with maximum longitudinal and vertical loadings prescribed in its technical passport, maximum stress generated in the structure does not exceed material yield limit – safety factor is equal to n=3,9.

Dynamic finite element analysis, performed by assuming longitudinal loading acting on the device with empty and loaded trailer and the body attached subjected to varying acceleration, corresponding to experimental and theoretical acceleration research results, revealed that dynamism factor asserts just when acceleration stops acting – subsequent vibration of parts of the coupling device does not exceed extreme values obtained at the initial moment.

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