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INFLUENCE OF THE HYDRAULIC SHOCK ABSORBERS MODEL IN TROLLEYBUS MULTIBODY SIMULATIONS ON THE SUSPENSION DEFORMATIONS AND COMPARISON WITH THE EXPERIMENTAL RESULTS

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Summary: *Vertical dynamic properties of the ŠKODA 21 Tr low-floor trolleybus were investigated on an artificial test track when driving with a real vehicle and when simulating driving with a mathematical model along a virtual test track. Driving along the artificial test track was aimed at determining vertical dynamic properties of the real trolleybus and on the basis of them at verifying mathematical models. This paper is an introduction to solving the given problems and deals with comparison of the relative displacements between the axles and the chassis frame measured in the course of driving along the test track with the real empty trolleybus and the relative deflections of air springs determined in the course of simulations with the existing empty trolleybus multibody model. Three variants of the hydraulic shock absorbers model were successively considered for simulations.*

1. Introduction

Generally, dynamic properties play a decisive role in the overall quality of every road vehicle. Optimum dynamic properties of the vehicle intended for the passenger transport can usually be achieved, in dependence on its structural design, by the proper choice of axles suspension elements (in some cases in combination with the proper choice of seats), which must be the compromise of the requirements for the vehicle behaviour during driving manoeuvres, for the riding comfort and for the bodywork and chassis parts lifetime when driving along an uneven road surface and for the passenger safety (Vlk, 2000).

Driving along an uneven road surface can reveal a lot about the vehicle vertical dynamic properties and about the suitability of the applied axles suspension elements (Carey & Irick, 1960). Especially time histories of relative deflections of springs, relative velocities in the shock absorbers, stress acting in the axles radius rods or radius arms and acceleration in various points in the vehicle interior are the monitored quantities (Gillespie & Karamihas, 2000). On the basis of relative deflections of springs, relative velocities in shock absorbers and stress acting in radius rods or radius arms it is possible to determine time histories and extreme values of forces acting in those suspension elements of axles, which can be utilize in

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connection with the suitable numerical methods for the stress analysis of structures for the prediction of fatigue life of bodywork and chassis parts of the verified vehicle. FFT results of time histories of acceleration in vehicle interior various points can be used for the assessment of riding comfort (Vlk, 2001).

In order to evaluate the vertical dynamic properties of the vehicle when driving along an uneven road surface knowledge of the surface characteristics, i.e. of statistical properties of unevennesses of the surface or direct its geometry, is necessary (Vlk, 2000). The geometry of an uneven surface profile of the run through section is known in test polygons (in the Czech Republic the most often used is test polygon of Tatra Kopřivnice, the best known polygon focused on testing the vehicles intended for public transport is Altoona in Pensylvania, USA). Test tracks, which are created by distributing artificial vertical unevennesses (obstacles) on the smooth road surface, are also often used (e.g. Polach, Hejman & Růžička, 2001).

Vertical dynamic properties of the ŠKODA 21 Tr low-floor trolleybus were investigated on the artificially created test track when driving with the real vehicle and when simulating driving with the mathematical model along the virtual test track. Driving along the artificial test track was aimed at determining the vertical dynamic properties of the real trolleybus and on the basis of them at verifying mathematical models. The verified mathematical models will be further utilized for the simulations of driving along the virtual uneven road surfaces, which will be generated on the basis of the statistical evaluation of the measured quantities in the course of driving along the real city road with the real trolleybus.

This paper is the introduction to solving the given problems and deals with comparison of the extreme values of time histories of relative displacements between the axles and chassis frame measured in the course of driving along the artificial test track with the real empty vehicle and extreme values of time histories of relative deflections of air springs determined in the course of simulations with the existing multibody model of the empty trolleybus. In the course of simulations three variants of the hydraulic shock absorbers model were successively considered in the trolleybus multibody model.

Fig. 1 The ŠKODA 21 Tr low-floor trolleybus

2. Experimental measurements with the real trolleybus

Experimental measurements on the empty ŠKODA 21 Tr low-floor trolleybus was carried out in depot of Dopravní podnik města Hradce Králové, a.s. (Hradec Králové Public City Transit Co. Inc.) in October 2004.

Test track was formed by three standardized artificial obstacles (according to the Czech Standard ČSN 30 0560 Obstacle II: h = 60 mm, R = 551 mm – see Fig. 2) spaced out on the smooth road surface 20 metres one after another. The first obstacle was run over only with right wheels, the second one with both and the third one only with left wheels (see Fig. 3).

Vertical co-ordinates of the standardized artificial obstacle are given by the formula

$$z(x)=\sqrt{R^2-\left(x-\frac{d}{2}\right)^2}-(R-h) \tag{1}$$

where R is the obstacle radius, h is the obstacle height, d is the obstacle length (500 mm) and x is the obstacle co-ordinate in the vehicle driving direction.

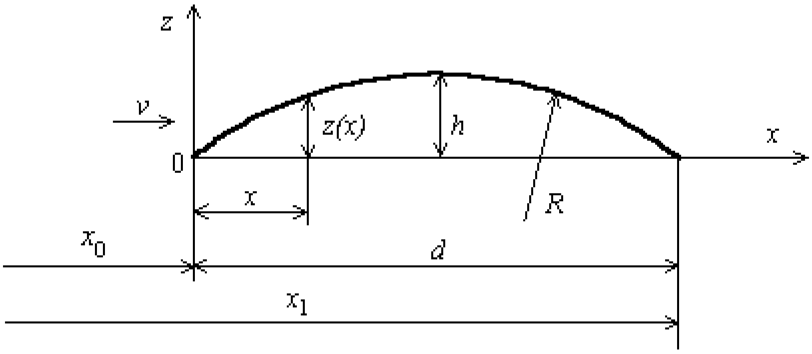

Fig. 2 A standardized artificial obstacle

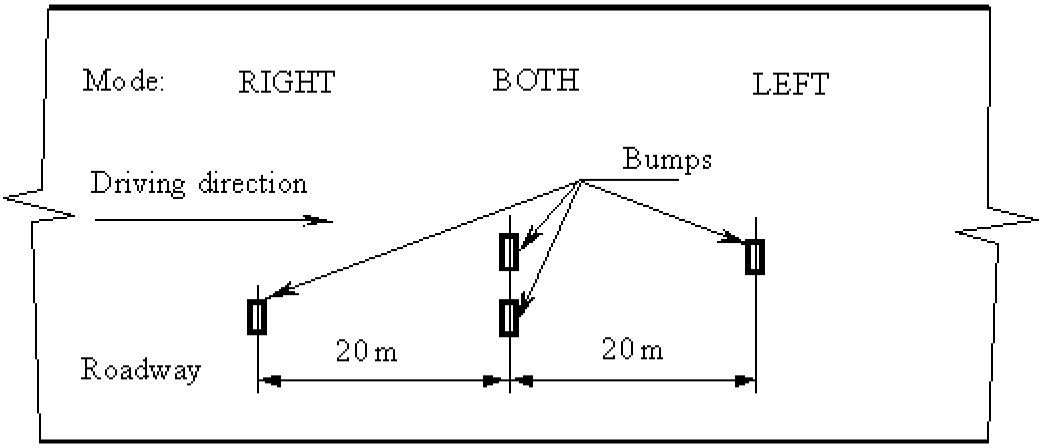

Fig. 3 A test track scheme

In the course of test driving the already mentioned time histories of relative displacements between the axles and the chassis frame were recorded (altogether 4 displacement transducers, which were placed in the lateral direction approximately on the level of air springs: on the left front half-axle, on the right front half-axle, on the rear axle to the left and on the rear axle to the right were used). Further time histories of stress on the lower and upper radius arm of the left front half-axle, on the left lower and upper radius rod of the rear axle and on the eight chosen trolleybus bodywork and chassis frame places (12 strain gauges were used altogether) and time histories of vertical acceleration on the lower radius arms of the left and right front half-axle, on the rear axle and on the four chosen places in the vehicle interior (7 accelerometers were used altogether) were recorded during the test drives. The records of time histories of measured quantities were made during three test drives. Trolleybus speed at that drives was in the range 43 km/h to 47 km/h.

3. Trolleybus mathematical model

In order to simulate drives along the virtual test track, which corresponded with the artificially created test track in depot of DPmHK, a.s. (Hradec Králové Public City Transit Co. Inc.), the multibody model with detailed kinematics of the axles suspension (Polach, 2003a) created in the **alaska** simulation toolbox was used (Maißer et al., 1998).

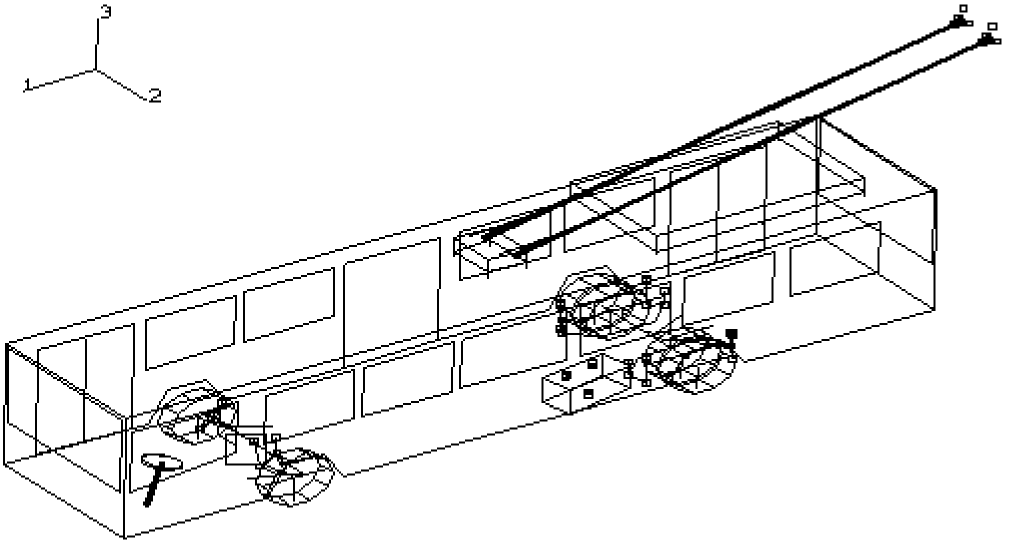

Fig. 4 Visualization of the ŠKODA 21 Tr trolleybus multibody model in the **alaska** software

That multibody model of the ŠKODA 21 Tr low-floor trolleybus is formed by 35 rigid bodies mutually coupled with kinematic joint. The rigid bodies corresponds to the trolleybus individual structural parts or "auxiliary" bodies, which are used due to limited possibility of choice of kinematic joint types in the **alaska** software (proper introducing the "auxiliary" bodies into multibody models enables to reduce the number of equations solved in the course of simulating operational situations) are concerned. The bodies are mutually coupled with 43 kinematic joints. Number of degrees of freedom of multibody model in kinematic joints is 127. Rigid bodies are defined by inertia properties (mass, centre of gravity co-ordinates and mass moments of inertia). Air springs and hydraulic shock absorbers in axles suspension and silentblocks in the places of mounting some trolleybus structural parts are modelled by connecting the corresponding bodies by nonlinear spring-damper elements. When simulating driving along an uneven road surface the contact point model of tires is used in the multibody model; radial stiffness and radial damping properties of tires are modelled by nonlinear spring-damper elements considering the possibility of bounce of the tire from the road surface (Kovanda, Resl & Socha, 1997).

Due to more precise approximation of dynamic behaviour of the vehicle the bodywork of the ŠKODA 21 Tr trolleybus is virtually divided into the front and rear parts in the multibody model, which are coupled by a spherical kinematic joint – see the kinematic scheme of the

ŠKODA 21 Tr trolleybus multibody model given in (Polach, 2003a) or in (Polach, 2003b). Using appropriately chosen torsional stiffnesses in the kinematic joint the model of bodywork enables to "tune" the values of natural frequencies corresponding to its first bending vibration modes (vertical and lateral) and to its first torsional vibration mode to the natural frequencies of the FEM model of the trolleybus bodywork (Jankovec, 2001) created in the COSMOS/M program (SRAC, 1999).

4. Hydraulic shock absorbers

Dynamic properties of road vehicles are most influenced by tires, suspension springs and hydraulic shock absorbers (Vlk, 2000). In order that vehicle virtual computer model should reliably approximate kinematic and dynamic properties of the real vehicle, knowledge of the characteristics of those decisive spring-damper structural elements is the important presumption (besides the proper approach to the model creating and knowledge of all the substantial vehicle parameters).

Characteristics of air springs (force in dependence on deflection) of the ŠKODA 21 Tr trolleybus were determined on the basis of the Test Reports of ŠKODA OSTROV s.r.o. (air springs of the front axle) and of the Hydrodynamic Laboratory of the Faculty of Mechanical Engineering, TU of Liberec (air springs of the rear axle) (Polach, 2003b). Radial stiffness and radial damping properties of tires (in standard version and with the specified tire inflating) were experimentally measured in the Dynamic Accredited Testing Laboratory ŠKODA VÝZKUM s.r.o. (Bártík & Jozefy, 2004). Evaluation of measured quantities for the purpose of generation of multibody models is given in (Lukeš, Hajžman & Polach, 2005).

At hydraulic shock absorbers it is necessary to know the force acting of the shock absorber in dependence on mutual relative movement of points (places) of a shock absorber mounting to the chassis frame and to the vehicle axle. Functions of shock absorbers, their structure and mathematical models of shock absorbers used in virtual models of vehicles are described in (Blundell & Harty, 2004) and in (Hajžman & Polach, 2004).

In the multibody model of the ŠKODA 21 Tr trolleybus dependence of damping force on the relative velocity of compression and rebound of the shock absorber is used as the shock absorbers characteristics. The characteristics were measured by the BRANO a.s. producer in the Testing Laboratory of Telescopic Shock Absorbers on the Schenck testing device, working part of which is formed by crank mechanism making possible to excite the tested shock absorber harmonically. The measured velocity characteristics of the shock absorbers show higher or lower rate of hysteresis caused especially by compressibility of the shock absorber filling liquid. Magnitude of hysteresis depends on the frequency and amplitude of loading. For the multibody model application the hysteresis curves were given average values so that the resulting characteristics might be a simple curve without hysteresis loop.

In the technical documentation to hydraulic shock absorbers values of damping forces are usually given for the velocities of shock absorber compression and rebound ± 0.5 m/s. On the basis of those values it is possible to set up so called bilinear velocity characteristic of the shock absorber for the purpose of using in multibody models (Hajžman & Polach, 2004).

It is possible to set up the shock absorber velocity characteristic, which is defined more precisely, on the basis of the test reports of the measurements under specified operational conditions. In the characteristic obtained like that it is possible to identify so called significant point both in the part for compression and in the part for rebound (approx. at velocities ± 0.05 m/s – see Fig. 5). Damping forces are measured in the same range of the shock absorber velocities as in the technical documentation, i.e. ± 0.5 m/s. These pieces of information on the shock absorber damping properties are fully sufficient for the vehicle common operational states. For the purpose of simulating extreme operational states of the vehicle, which is e.g. driving along the significantly uneven road surface, the shock absorber characteristic is (usually) linearly extrapolated for higher velocities of compression and rebound.

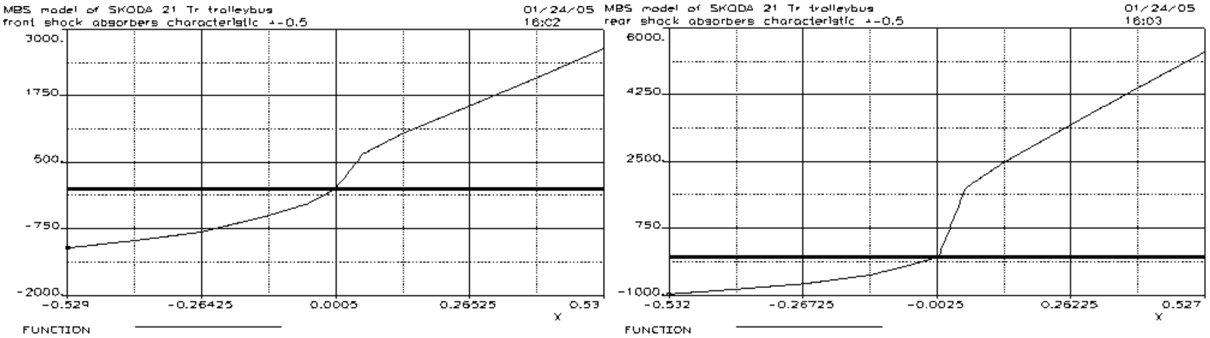

Fig. 5 Measured velocity characteristics of the front and rear axle shock absorbers (in the range of velocities ± 0.5 m/s) (force [N] in dependence on velocity [m/s])

In order to define the ŠKODA 21 Tr trolleybus multibody model more precisely velocity characteristics of the shock absorbers used in the vehicle structure up to the velocities of compression and rebound higher than ± 0.8 m/s (front shock absorber in the velocity range ± 1.5 m/s, rear shock absorber due to the failure in the testing device only in the velocity range from – 1 m/s up to + 0.8 m/s – see Fig. 6) were measured in the BRANO a.s. Testing Laboratory of Telescopic Shock Absorbers in September 2004.

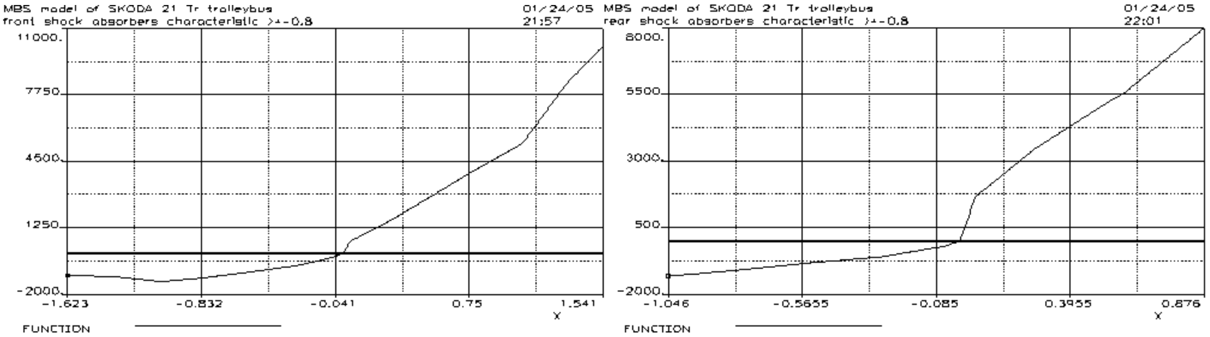

Fig. 6 Measured velocity characteristics of the front and rear axle shock absorbers (in the range of velocities higher than ± 0.8 m/s) (force [N] in dependence on velocity [m/s])

When driving along the virtual test track with the ŠKODA 21 Tr trolleybus multibody model the influence of considering two the most precise characteristics of hydraulic shock absorbers (i.e. measured in the range of velocities ± 0.5 m/s and measured in the range of velocities higher than ± 0.8 m/s) on the results of simulations (to be precise on time histories and extreme values of relative deflections of air springs) is verified.

In the structure of the hydraulic shock absorbers rubber silentblocks are used in the places of mounting to the chassis frame and to the axles of the ŠKODA 21 Tr trolleybus (Hajžman & Polach, 2004). When simulating driving with the trolleybus multibody model along the virtual

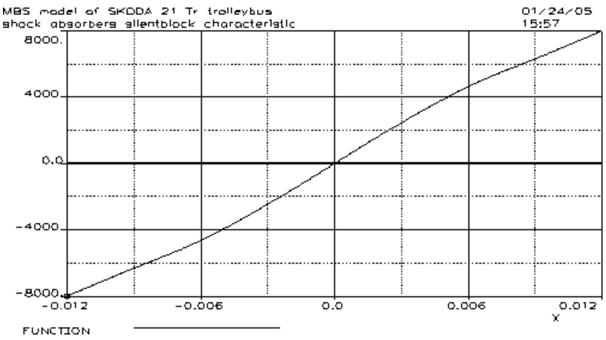

Fig. 7 Characteristic of the silentblock (force [N] in dependence on velocity [m/s])

test track the influence of considering those silentblocks on time histories and extreme values of relative deflections of air springs was investigated as well. The silentblocks are modelled in multibody models by means of spring elements, nonlinear deformation characteristics of which (force in dependence on deflection) was determined experimentally (it is taken over from (Kopenec, 2002) – see Fig. 7), which are joined in series to the damping element representing the hydraulic shock absorber itself. Solving the total force equilibrium of a nonlinear damper and a nonlinear spring in series was a certain problem. That is why in multibody model the "auxiliary" body, mass of which corresponds with mass of the proper shock absorber, is placed between each spring and damper element.

5. Results of the experiment and simulations

In this paper results of the first documented test drive are given at trolleybus speed 43 km/h.

Time histories of relative displacements between the axles and the chassis frame measured in the course of driving with a real empty trolleybus are given in Fig. 8. After run over the last obstacle of the test track step-by-step fading of the recorded relative displacements to zero will not occur. It is caused by subsequent trolleybus braking, which was necessary due to the deviation of traction line from straight direction approx. 50 metres after the end of the last obstacle.

Vehicle speed was the only input data for the simulations of the test drives. All the drives along the virtual test track start 4 seconds after the beginning of the trolleybus multibody model driving simulation. This time is sufficient for dynamic processes fading in multibody model transition from the initial position (it is not identical with the equilibrium position, it is given by the initial setting of the kinematic joints in multibody model) to the steady state before the beginning of the test drive simulation.

When simulating movement with multibody models, nonlinear equations of motion, which are solved by means of numerical time integration, are generated in the **alaska** software using Lagrange's method. Results of the simulations mentioned in this paper were obtained using Shampine-Gordon integration algorithm (in Maißer et al., 1998 reference to Shampine & Gordon, 1984).

In the course of simulations three variants of the hydraulic shock absorbers model were successively considered in the trolleybus multibody model. In Fig. 9 time histories of relative deflections of air springs when considering the shock absorbers characteristics measured in the range of velocities ± 0.5 m/s, in Fig. 10 when considering the shock absorbers characteristics measured in the range of velocities higher than ± 0.8 m/s and in Fig. 11 when considering the shock absorbers characteristics measured in the range of velocities higher than ± 0.8 m/s and at the same time taking into account the rubber silentblocks in the structure of the shock absorbers, are given. Extreme values of relative deflections of air springs read from time responses are in Tab. 1.

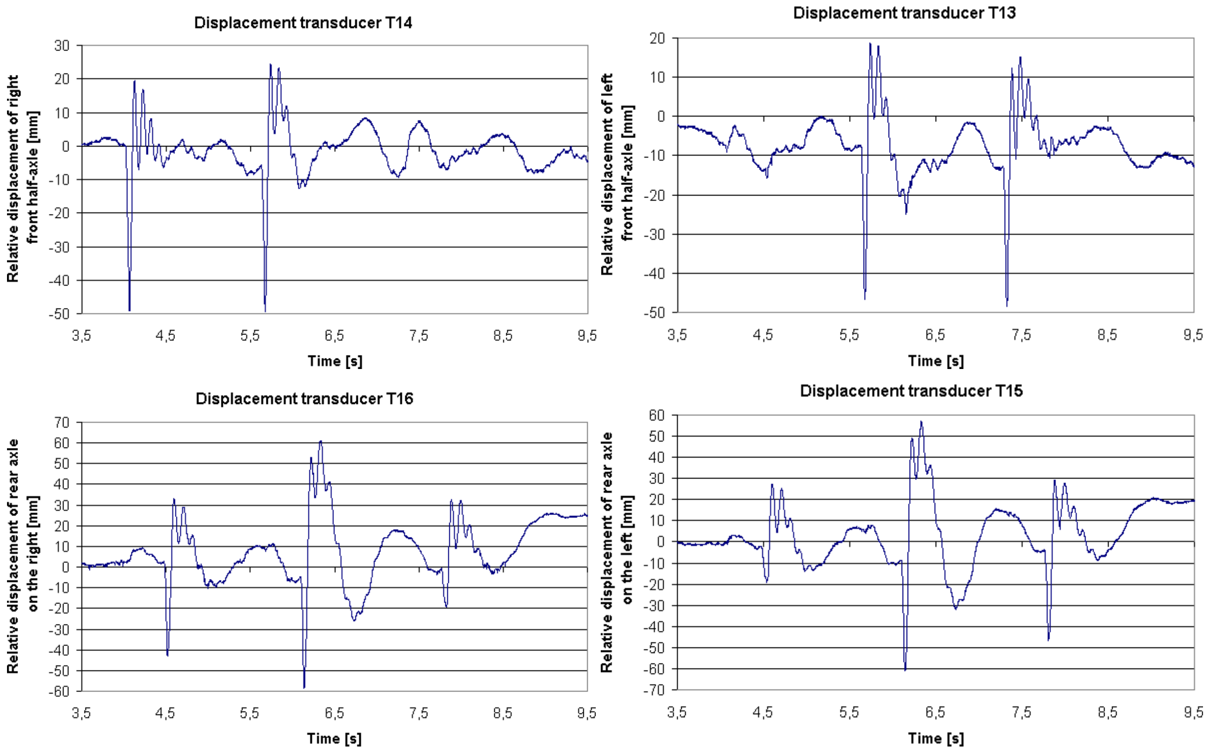

Fig. 8 Experimentally measured time histories of relative displacements between the trolleybus axles and the chassis frame
(right front | left front / right rear | left rear)

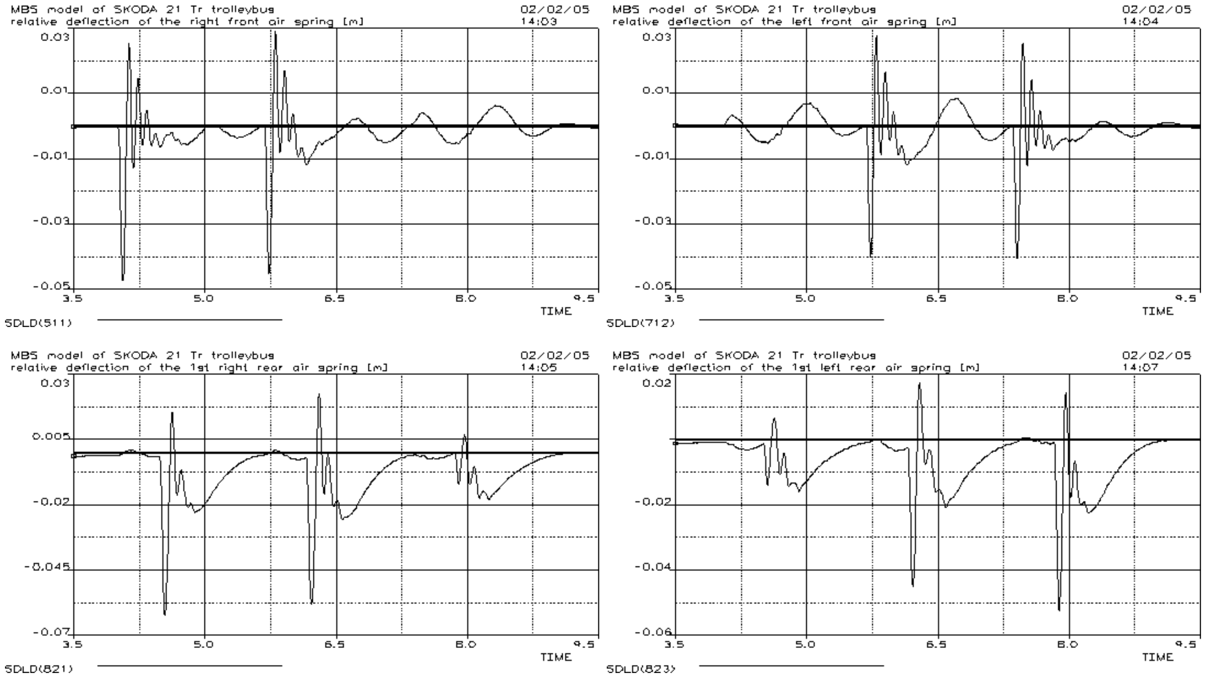

Fig. 9 Time histories of relative deflections of air springs determined in the course of simulations - the shock absorbers characteristics measured in the range of velocities ± 0.5 m/s
(right front | left front / right rear | left rear)

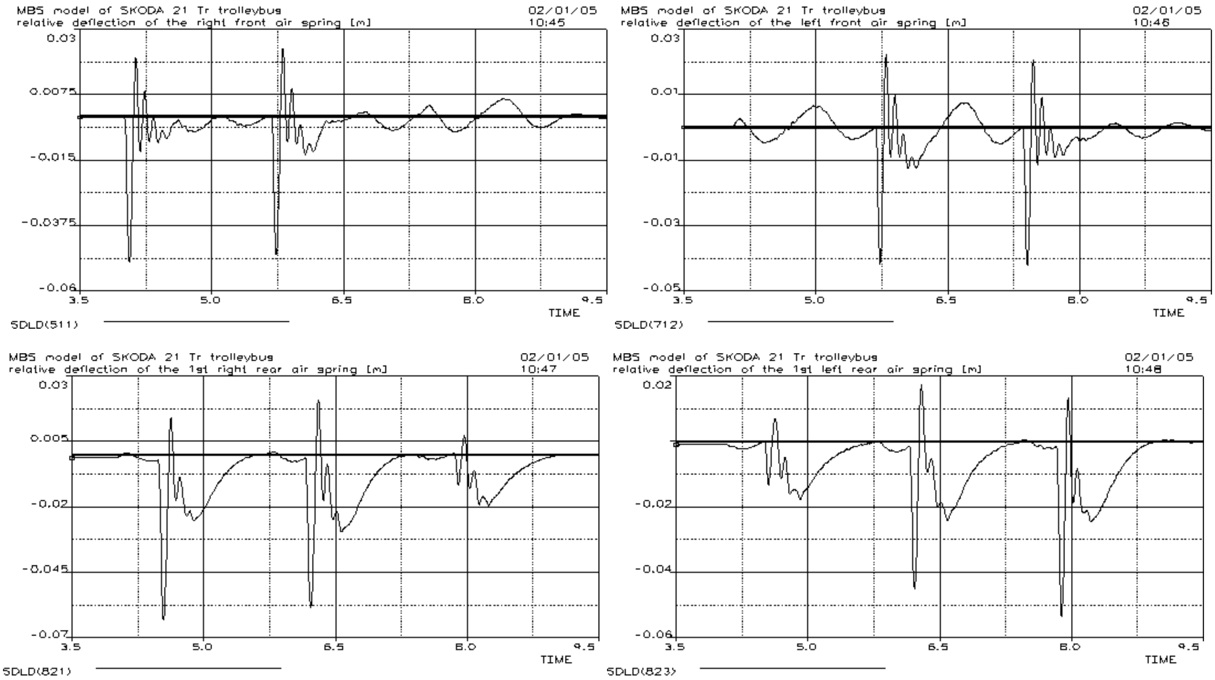

Fig. 10 Time histories of relative deflections of air springs determined in the course of simulations - the shock absorbers characteristics measured in the range of velocities higher than ± 0.8 m/s
(right front | left front / right rear | left rear)

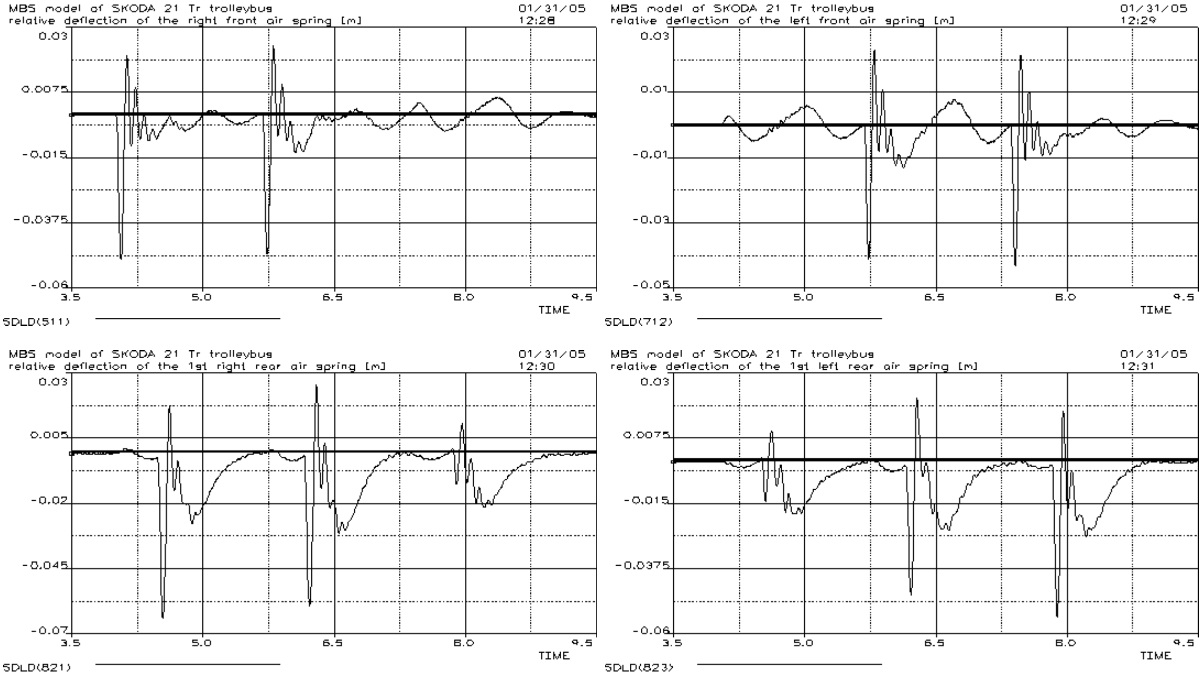

Fig. 11 Time histories of relative deflections of air springs determined in the course of simulations - the shock absorbers characteristics measured in the range of velocities higher than ± 0.8 m/s plus taking into account the rubber silentblocks
(right front | left front / right rear | left rear)

Tab. 1 Extreme values of relative deflections

EXPERIMENT		Value	Relative displacement between the axles and the chassis frame [mm]			
			On right front side	On left front side	On right rear side	On left rear side
1st obstacle		minimum	-49	-16	-43	-18
		maximum	19	-2	32	27
2nd obstacle		minimum	-49	-47	-59	-61
		maximum	24	18	61	57
3rd obstacle		minimum	-9	-48	-19	-46
		maximum	8	14	32	29
SIMULATIONS		Value	Relative deflection of air springs [mm]			
Shock absorbers characteristics measured in the range of velocities	Obstacle		Right front	Left front	Right rear	Left rear
± 0.5 m/s	1st	minimum	-47	-5	-64	-15
		maximum	25	3	16	7
	2nd	minimum	-45	-40	-62	-49
		maximum	29	28	24	18
	3rd	minimum	-5	-41	-13	-54
		maximum	4	25	8	15
higher than ± 0.8 m/s	1st	minimum	-50	-5	-64	-14
		maximum	20	3	15	8
	2nd	minimum	-48	-42	-62	-49
		maximum	23	22	22	18
	3rd	minimum	-5	-42	-13	-55
		maximum	4	21	8	14
higher than ± 0.8 m/s plus considering rubber silentblocks	1st	minimum	-50	-5	-65	-15
		maximum	20	3	18	11
	2nd	minimum	-48	-41	-63	-51
		maximum	23	23	27	22
	3rd	minimum	-6	-43	-14	-56
		maximum	4	21	11	18

6. Conclusions

Models of hydraulic shock absorbers in the ŠKODA 21 Tr trolleybus multibody model defined more precisely influence the improvement in agreement of results of simulations and experimental measurements only negligibly. The greatest differences are in suspension elements rebound stage (i.e. in the field of positive values) of the rear axle: extreme values (see Tab. 1) of experimentally measured relative displacements between the axles and the chassis frame are as much as three times higher than extreme values of relative deflections of air springs determined in the course of simulations. It is evident from the time histories of the monitored relative deflections (Figs 8 to 11) that in the field of rebound of air springs of the rear axle more significant damping of relative deflections determined in the course of simulations occurs (at the front axle air springs this damping is less evident). It is possible to conclude on the basis of the simulations results, that the shock absorbers characteristics measured on the laboratory testing device under specified conditions (i.e. under harmonic exciting and displacement 100 mm) do not correspond in rebound field with loading conditions of shock absorbers in the real vehicle in the course of running over the significant road unevennesses. When compressing the axles suspension elements (i.e. in the field of negative values) the agreement of the results of experimental measurements and simulations both in the time histories and in the extreme values of monitored relative deflections is very good.

The cause of some deviations of the simulations results from the experimental measurements results is of course, in addition to the shock absorbers characteristics, also in ignorance of all the conditions of test drives with the real trolleybus needed for more precise performing the simulations (a real height of the air springs was not measured, the pressure of the tires inflating was not found out and the vehicle was not weighted – the constructional data were used in the multibody model) and in substance itself of computer models (a virtual model is always the simplification of a real structure). So far not published research calculations, which investigated the influence of changes in the significant road surface unevennesses model, of changes in the characteristics of radial spring-damper properties of tires and of changes in air spring characteristics, confirmed, that the main cause of different results of experimental measurements and simulations is in the considered loading characteristics of hydraulic shock absorbers. The following stage of the ŠKODA 21 Tr trolleybus multibody model verification will be devoted to the determination of “less steep” characteristics of shock absorbers (especially of the rear axle) in the rebound field.

Mutual comparison of the simulations results revealed the expected behaviour of the considered models of hydraulic shock absorbers. The shock absorbers characteristics measured in the range of velocities higher than ± 0.8 m/s are steeper than linearly extrapolated shock absorbers characteristics measured in the range of velocities ± 0.5 m/s and that is why the determined extreme values of relative deflections of air springs are lower when simulating the test drives. If the rubber silentblocks are taken into account in the shock absorbers structure effects of shock absorbers are “decreased”. Thus extreme values of relative deflections of air springs are higher at simulations than when the effect of silentblocks is neglected.

7. Acknowledgement

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