VERIFICATION OF THE STABILIZER BAR OF AN ARTICULATED TROLLEYBUS

Pavel Polach*

At the modernization of the ŠKODA 22 Tr low-floor articulated trolleybus a different type of an articulated joint and a different type of driving axles were used in its construction besides other changes. During test drives with the modernized trolleybus, which were focused on the driving stability of the vehicle, a large roll of the rear section appeared. A suitable structural solution for reducing the rear section roll angle of the modernized trolleybus was the using of a rear section stabilizer bar. The stabilizer effect on dynamic properties of the vehicle and a suitable bar diameter were determined on the basis of the results of the computer simulations with the trolleybus multibody models. The test drives focused on the vehicle driving stability were performed again with the loaded real trolleybus, in the structure of which the designed rear section stabilizer bar was applied. On the basis of computer simulations of the test drives with the trolleybus multibody models the correctness of the experimental-simulation approach used for the stabilizer bar structural design was verified.

Key words: *articulated trolleybus, driving stability, stabilizer bar, multibody dynamics, experiment*

1. Introduction

Using computer simulations for the solution of an unanticipated problem concerning the driving stability of the real ŠKODA 22 Tr low-floor articulated trolleybus, which occurred after the application of a different type of the articulated joint and driving axles, is presented in this article. It was not possible to use a new structural design of the trolleybus because the real vehicles already exist. Only one solution was possible – using a rear section stabilizer bar. Using the active roll control would make the trolleybuses too expensive especially due to the relatively lower production of trolleybuses than of other types of vehicles and due to the higher expenses of the active roll control.

Problems of the stabilizer bars of the vehicles are mentioned only marginally in the publications devoted to multibody dynamics (e.g., [1], [2]). Cars stabilizer bars are premodelled in the modules of some multibody simulation tools – e.g., [3], [4]. The design of the functionality of the stabilizer bars of articulated vehicles from the point of view of multibody dynamics has not been the subject of the relevant publications yet.

2. The stabilizer bar design

ŠKODA VÝZKUM s.r.o. has been co-operating with ŠKODA OSTROV s.r.o., the producer of the city public service vehicles, for a long time [5]. The ŠKODA 22 Tr low-floor

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Fig.1: The ŠKODA 22 Tr low-floor articulated trolleybus

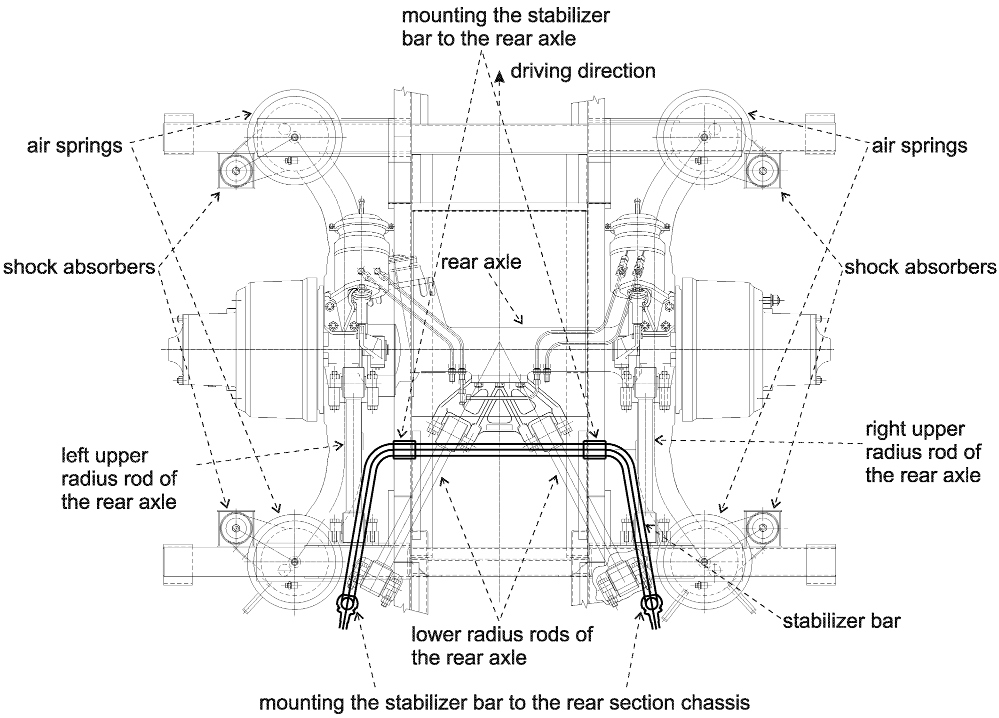

Fig.2: Part of the plan of the rear axle with the stabilizer bar

articulated trolleybus (see Fig. 1) was produced in ŠKODA OSTROV s.r.o. from 1996 till 2005. When it was modernized in 2002 a different type of articulated joint and a different type of driving axles were used in its construction besides other changes. During test drives with the modernized trolleybus, which were focused on the driving stability of the vehicle, a considerable roll of the rear section appeared during all the performed driving manoeuvres. Using a rear section stabilizer bar is a suitable structural solution to reduce the rear section roll angle of the ŠKODA 22 Tr low-floor articulated trolleybus with the HÜBNER articulation and the RÁBA driving axles. A torsional lateral stabilizer of the trolleybus rear section made of the steel bar of a circular cross section was considered in the design (see Fig. 2). The stabilizer effect on the vehicle dynamic properties and the suitable bar diameter

(42 mm) were determined on the basis of the computer simulations results with the multibody models of both an empty and a loaded trolleybus [6], [7], [8]. The stabilizer was to have the required effect on reducing the roll angle of the rear section and at the same time permissible deformations and stabilizer bar stress were not to be exceeded. The maximum permissible elastic vertical deformation of the stabilizer bar on both sides was 61 mm, the maximum permissible forces between the stabilizer bar and the rear axle and between the stabilizer bar and the rear section chassis frame are dependent on the diameter of the bar of the circular cross section used for its production (for the bar of the diameter of 42 mm the maximum permitted force between the stabilizer and the rear axle is 13 893 N and between the stabilizer and the rear section chassis frame it is 9 784 N). The test drives focused on the vehicle driving stability were performed again with the real trolleybus [9], in the structure of which the designed rear section stabilizer bar was applied. On the basis of the computer simulations of the test drives with the trolleybus multibody models the correctness of the experimental-simulation approach used for the stabilizer bar structural design was verified.

3. Test drives with the real trolleybus

The test drives focused on the evaluation of the driving stability of the modernized ŠKODA 22 Tr low-floor articulated trolleybus with the rear section stabilizer were performed in September 2002 [9]. The measurements were performed only with the loaded vehicle (loaded to approx. 98 % of the maximum weight) on the trolleybus line between the towns of Ostrov nad Ohří and Jáchymov (the Czech Republic). The performed test drives were to verify the influence of the designed stabilizer bar on the reduction of the rear section roll angle.

Driving manoeuvres performed during the test drives were less demanding for the vehicle than the methodology of a severe lane-change manoeuvre according to ISO 3888-1 requires. The trolleybus is bound to the traction line, which limits both the vehicle path and the speed of lane-change during driving. During the real operation the driving manoeuvre satisfying the conditions of a severe lane-change manoeuvre according to ISO 3888-1 can be performed only theoretically. The test manoeuvres consisted in severe changing the right lane to the left one and immediate severe returning to the right lane. The initial speed of the test drives was set to 30 km/h, the tests were finished at the speed of 55 km/h (regarding the potential damage of the vehicle or the traction line when the collectors drop out).

The time histories of the steering wheel angle, the angle of the mutual position of the trolleybus front and rear sections, the rear section roll angle and the lateral acceleration of the rear section above the rear axle were the measured (and documented) quantities during the test drives.

It follows from the results of the test drives that the behaviour of the rear section (especially its rolling and lateral breakaway) is a limiting factor for the vehicle driving stability even after implementing the rear section stabilizer bar. The vehicle had behaved in a neutral way until the bottoming of the rear section chassis on the rear axle bump stops (approx. from the speed of 40 km/h) occurred.

Comparison of the stability properties of the modernized ŠKODA 22 Tr low-floor articulated trolleybus without the rear section stabilizer [10] and with the rear section stabilizer [9] on the basis of the documented test drives is possible only to some extent because the vehicle was driven by another driver on another test track and the performed driving manoeuvres could not be fully identical due to not laying out the track. But it is evident from the results in [6], [8], [9], [10], [11] and [12] that the driving stability of the ŠKODA 22 Tr trolleybus was generally improved using the rear section stabilizer bar :

1. The situation, during which the impacts caused by exceeding the maximum elastic deformation of the articulated joint were identified in the monitored quantities, did not occur.
2. The extreme values of the time histories of the rear section roll angle and thus also the extreme values of other related quantities – relative deflections of the rear axle suspension and the torsional deformation of the articulated joint – decreased.
3. The trolleybus unfavourable stability properties had not appeared until the driving speeds were higher by approx. 10 km/h–15 km/h [9].

4. Simulations with multibody models

The rear section stabilizer bar of the ŠKODA 22 Tr low-floor articulated trolleybus with the HÜBNER articulation and the RÁBA driving axles was designed on the basis of the results of computer simulations [6] of the test drives documented in [10]. The simulations of the test drives documented in [9] were performed to verify the suitability of the experimental-simulation approach to the stabilizer bar design.

Computer softwares intended for investigating the kinematic and the dynamic properties of the mechanical systems are the indispensable and standard tools for developing and improving the properties of vehicles and also for improving the comfort and the passive safety of a driver and passengers.

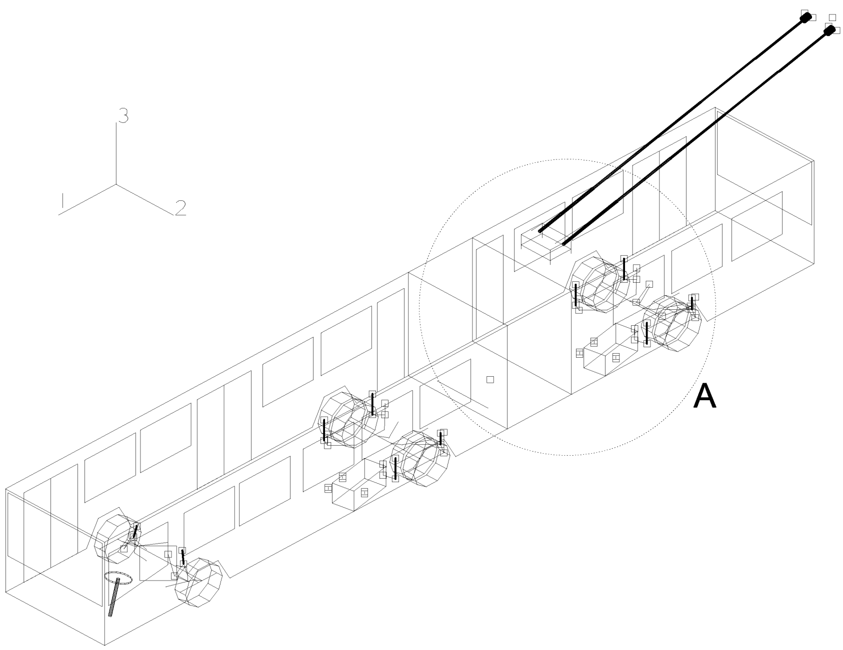

Fig.3: Visualization of the ŠKODA 22 Tr low-floor articulated trolleybus multibody model in the alaska 2.3 simulation tool

The multibody models of the modernized ŠKODA 22 Tr low-floor articulated trolleybus with the rear section stabilizer (Fig. 3) are created in the alaska 2.3 simulation tool [13]. The multibody model of the loaded ŠKODA 22 Tr low-floor articulated trolleybus [14] was modified on the basis of the vehicle total mass (27 860 kg) given in [9] for the purpose of the test drives simulations. It is formed by 47 rigid bodies, which correspond to the individual trolleybus structural parts or they are 'auxiliary' bodies. The rigid bodies correspond to the trolleybus individual structural parts or 'auxiliary' bodies, which are used due to the limited possibility of choice of kinematic joint types in the alaska 2.3 simulation tool (proper introducing the 'auxiliary' bodies into multibody models enables to reduce the number of equations solved in the course of simulating the operational situations), are concerned. The bodies are mutually coupled by 57 kinematic joints, the number of degrees of freedom is 157. Air springs and hydraulic shock absorbers in the suspension and bushings in the positions of mounting some trolleybus structural parts are modelled by connecting the corresponding bodies by nonlinear spring-damper elements. The stationary tire model is used to describe the directional properties of the tires.

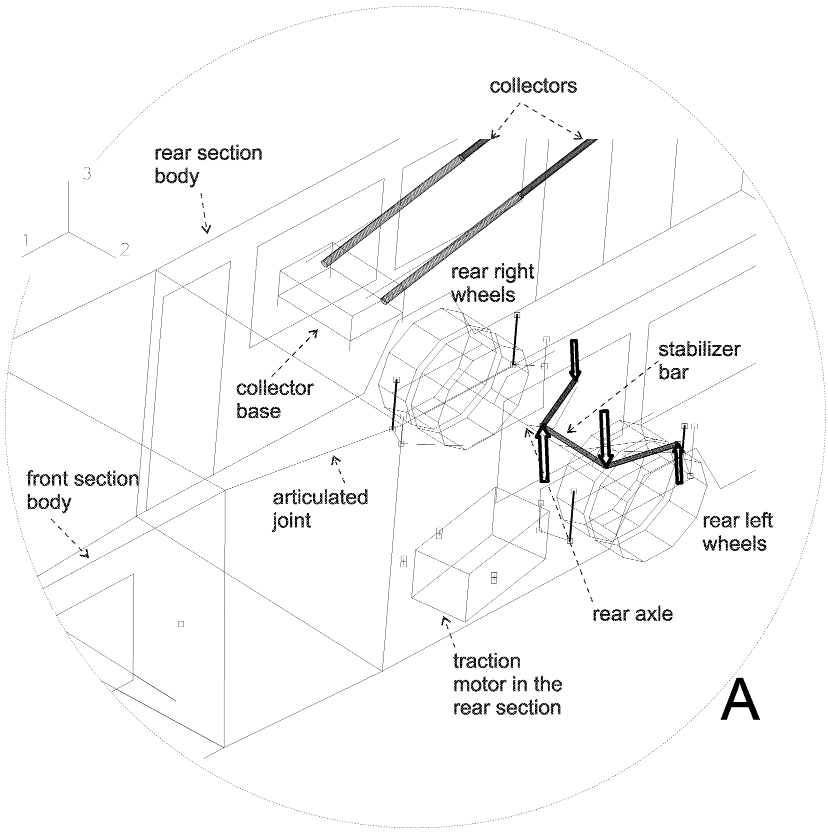

Fig.4: Visualization of the stabilizer bar detail (points of external force action) in the alaska 2.3 simulation tool

In the multibody models of the ŠKODA 22 Tr articulated trolleybus the rear section stabilizer bar is not considered to be an individual rigid body, its function is modelled by the external forces acting on the rear section chassis frame and the rear axle. The forces acting against the rear section roll angle and their points of action are in the positions of mounting the stabilizer bar to the rear section chassis frame and the rear axle (see Fig. 4). A linear dependence is considered between the magnitudes of the forces and the stabilizer bar deformations. Magnitudes of the forces are dependent only on the rear section roll angle, vertical displacements between the rear section chassis frame and the rear axle do not influence their magnitudes at all (this fact is given by the used structural design of the stabilizer bar).

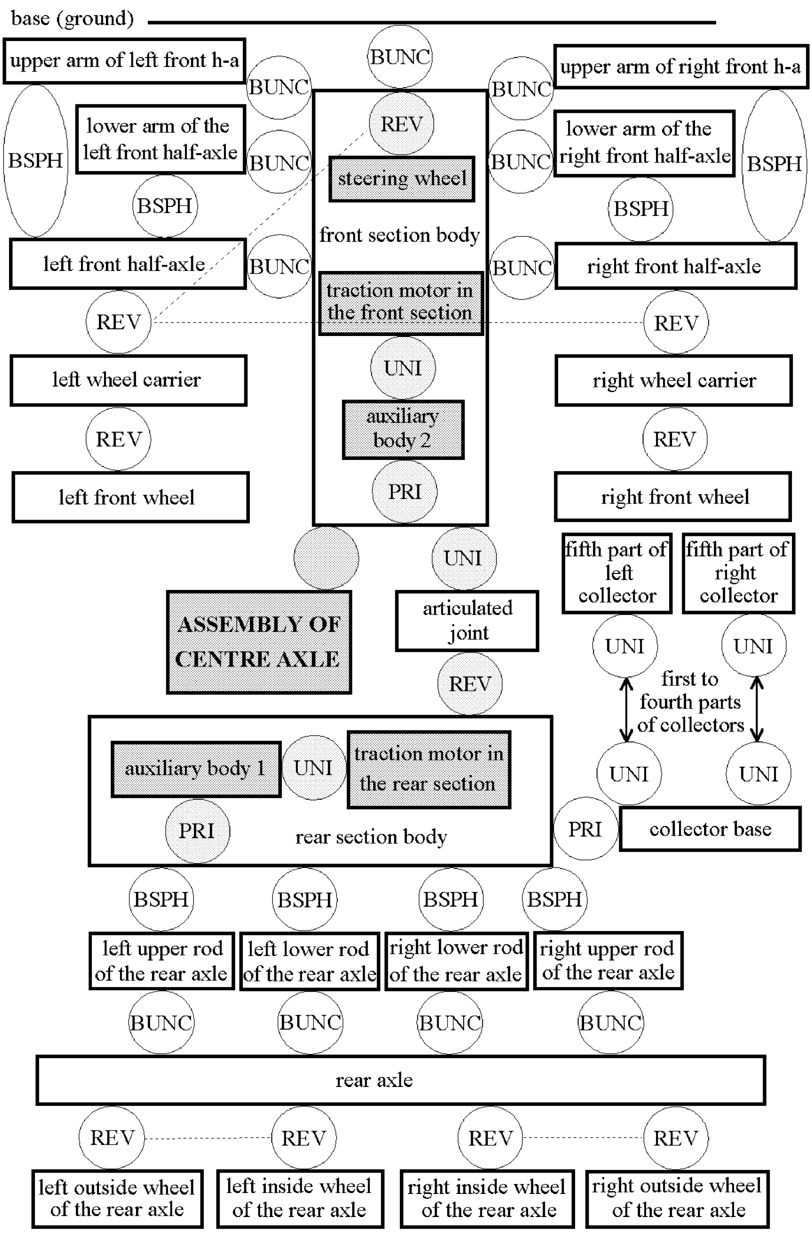

Fig.5: Kinematic scheme of the multibody model of the ŠKODA 22 Tr articulated trolleybus

The kinematic scheme of the multibody model of the ŠKODA 22 Tr low-floor articulated trolleybus with the HÜBNER articulation and the RÁBA driving axles is in Fig. 5 (the kinematic scheme of the centre axle is in Fig. 6) [6], [8]. Rectangles designate bodies; circles (or ellipses) designate kinematic joints (BUNC = unconstrained, REV = revolute, PRI = prismatic, BSPH = spherical, UNI = universal). Dashed lines connect mutually dependent kinematic joints. In some kinematic joints the degrees of freedom are constrained by introducing spring-damper elements representing especially the properties of bushings (in Figs 5 and 6 the constraints are not introduced). This approach to the modelling of the kinematic joints is given by the philosophy of the alaska 2.3 simulation tool.

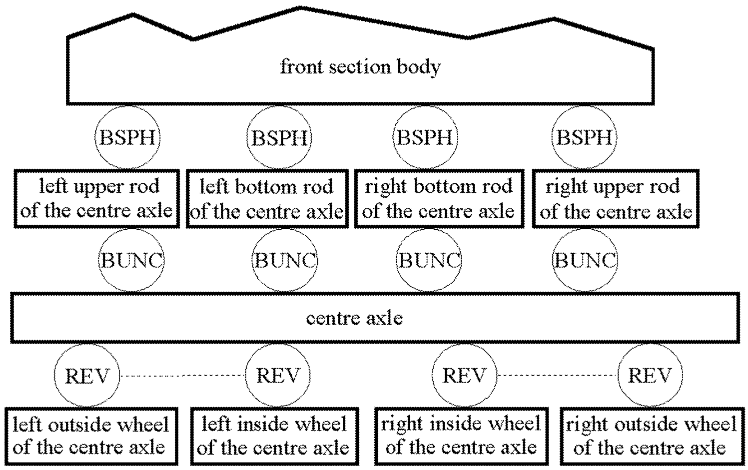

Fig.6: Kinematic scheme of the centre axle in the ŠKODA 22 Tr trolleybus multibody model

Dynamic properties of road vehicles are influenced most by suspension air springs, hydraulic shock absorbers and tires (e.g. [15]). In order that vehicle virtual computer model should reliably approximate kinematic and dynamic properties of the real vehicle knowledge of the above mentioned crucial spring-damper structural elements' characteristics is the important presumption.

The air springs characteristics (force in dependence on deflection) of the ŠKODA 22 Tr articulated trolleybus were determined on the basis of the Test Reports of ŠKODA OSTROV s.r.o. (front axle air springs) and the Hydrodynamic Laboratory of the Faculty of Mechanical Engineering, TU of Liberec (centre and rear axles air springs) [16]. The non-linear deformation characteristics of the air springs were determined for each air spring on the basis of their static load, viz. by interpolation springs characteristics for various air pressures. The deformation characteristics of the springs for various air pressures are in Fig. 7. These characteristics include the air springs bump stops characteristics.

From the point of view of multibody simulations at hydraulic shock absorbers it is necessary to know the force acting in the shock absorber in dependence on the mutual relative movement of points of a shock absorber mounting to the chassis frame and to the vehicle axle. Functions of the shock absorbers, their structure and mathematical models of shock absorbers used in virtual models of vehicles are described e.g. in [1] and in [17]. In the multibody model of the ŠKODA 22 Tr articulated trolleybus dependence of damping force

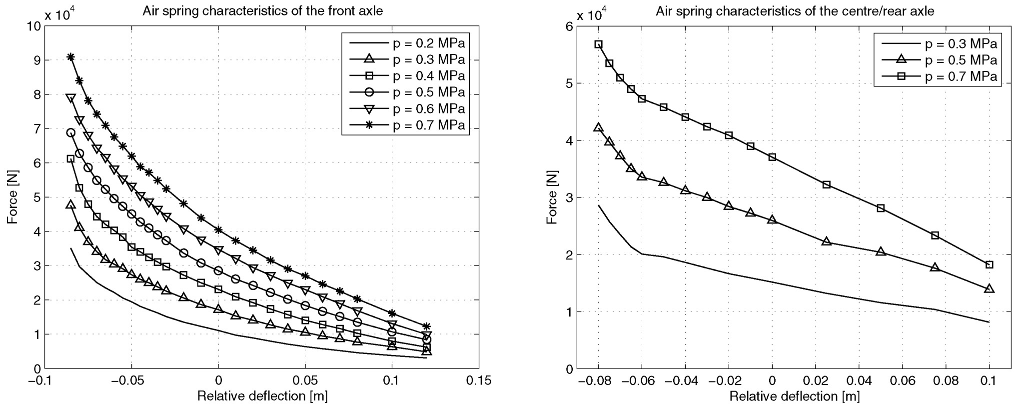

Fig.7: The force-deflection characteristics of the air springs of the front and the centre/rear axles

on the relative velocity of compression and rebound of the shock absorber is used as the shock absorbers characteristics. The characteristics were measured on the premises of BRANO a.s., the shock absorber producer, in the Testing Laboratory of Telescopic Shock Absorbers on the Schenck testing device, working part of which is formed by crank mechanism exciting harmonically the tested shock absorber. The measured velocity characteristics of the shock absorbers show higher or lower rate of hysteresis caused especially by the compressibility of the shock absorber filling liquid. In the multibody model application the hysteresis curve values were averaged so that the resulting characteristics might be a simple curve without a hysteresis loop [17], see Fig. 8.

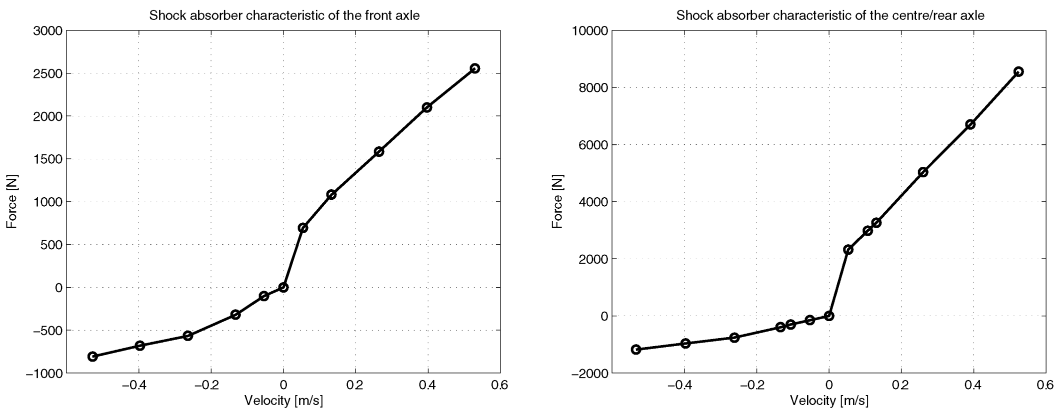

Fig.8: The force-velocity characteristics of the shock absorbers of the front and centre/rear axles

Rubber bushings used in the points of mounting the hydraulic shock absorbers to the chassis frame and the axles of the trolleybus are not included in the multibody model. On the basis of previous experience consideration of deformation characteristics of these bushings has only a negligible influence on the results of the simulations of the anticipated operational situations [18].

Torsional stiffnesses of the front suspension radius arms bushings were taken from the technical documentation of ŠKODA OSTROV s.r.o. (see e.g. [16]). Stiffnesses of the bushings in the assembly eyes for connecting rear axle radius rods and chassis frame were taken from the technical documentation of the Lemförder Metallwaren and Autófelszerelési Vállalat Sopron companies (see e.g. [16]).

The traction characteristics of the ŠKODA 22 Tr articulated trolleybus were provided by ŠKODA OSTROV s.r.o. The specification of dependence of a motor driving force transmitted to the rear wheels on the trolleybus running speed is used in the multibody model. In the trolleybus multibody model this characteristic is converted to driving torque transmitted from the traction motor to the driving axles wheels. Transmission of driving torque is controlled by the demand on the trolleybus instantaneous running speed.

When simulating movement with multibody models, nonlinear equations of motion, which are solved by means of numerical time integration, are generated in the alaska 2.3 simulation tool using Lagrange's method. The results of the simulations mentioned in this article were obtained using the Shampine-Gordon integration algorithm [19].

The vehicle speed and mass and the documented time histories of the steering wheel angle [9] were the input data for the simulations of the test drives. The simulations were performed with the multibody models of the trolleybus both without and with the rear section stabilizer bar. The monitored quantities were the same as in case of the experimental measurements: the time histories and the extreme values of the angle of mutual position of the trolleybus front and rear sections, the rear section roll angle and the lateral acceleration of the rear section above the rear axle. In addition during the simulations with the multibody models the extreme values of the time histories of the relative deflections of the rear axle suspension and of the torsional deformation of the articulated joint were monitored. Further during the simulations with the trolleybus multibody model with the rear section stabilizer the extreme values of the time histories of the stabilizer bar vertical deformation were monitored.

Approximately constant speed of the trolleybus multibody models is assured by acting the driving torque on the wheels of the driving axles during the simulations of the test drives. When the trolleybus front section speed decreases below the required value continuous driving torque acts in the driving direction, when the required speed is re-achieved it equals zero.

When simulating a dry road surface without vertical unevennesses is considered.

In this article results of the simulation of only one chosen (more demanding) test drive with the trolleybus at the speed 45 km/h (the test drive No. 3) are presented. The time history of the steering wheel angle (one of the input data for the simulations) is given in Fig. 9 (time history of the steering angle of the front wheels is given in the Fig. 10). The time histories of the rear section roll angle during the test drive (measured and determined during the simulations with the multibody model) are given in Figures 11 and 12. The values of the angles in all the graphs are given in degrees.

The extreme values of the time histories of the monitored quantities are given in Tab. 1. The extreme values of the time history of the stabilizer bar vertical deformation are given only for the trolleybus right side (the extreme values of those quantities on the trolleybus left side are of the same absolute values but the opposite signs).

The time histories of the monitored quantities are of the positive values in accordance with the orientation of the axes of the right hand Cartesian system of co-ordinates '123' from Fig. 3.

Results of the test drive No. 3 (at the speed 45 km/h)				
Monitored quantity		**Extremes of time histories**		
		with the stabilizer bar		without the stabilizer bar
		experiment	simulation	
Angle of the mutual position of the front and rear sections [deg]	min.	−15.13	−15.40	−15.18
	max.	18.59	15.10	15.05
Lateral acceleration of the rear section [m/s^2]	min.	−5.17	−5.31	−5.40
	max.	4.90	5.30	5.22
Rear section roll angle [deg]	min.	−7.46	−7.66	−8.81
	max.	6.62	7.79	8.94
Torsional deformation of the articulated joint [deg]	min.	not measured	−3.81	−4.03
	max.	not measured	3.53	3.79
Relative deflection of the right rear air springs [m]	min.	not measured	−0.075	−0.080
	max.	not measured	0.116	0.143
Relative deflection of the left rear air springs [m]	min.	not measured	−0.059	−0.065
	max.	not measured	0.122	0.149
Vertical deformation of the stabilizer bar (right) [m]	min.	not measured	−0.066	—
	max.	not measured	0.063	—

Tab.1: The extreme values of the monitored quantities during the test drive No. 3

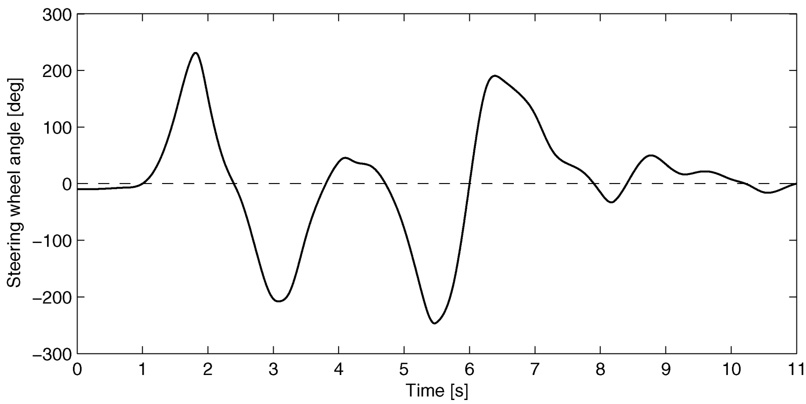

Fig.9: The time history of the steering wheel angle during the test drive No. 3 [9]

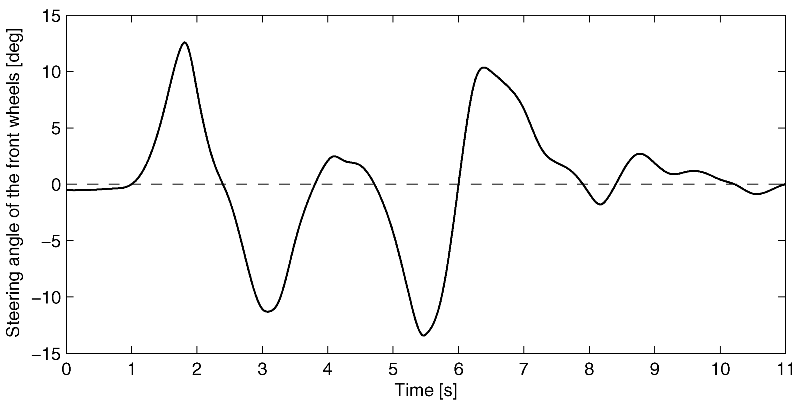

Fig.10: The time history of the steering angle of the front wheels during the test drive No. 3

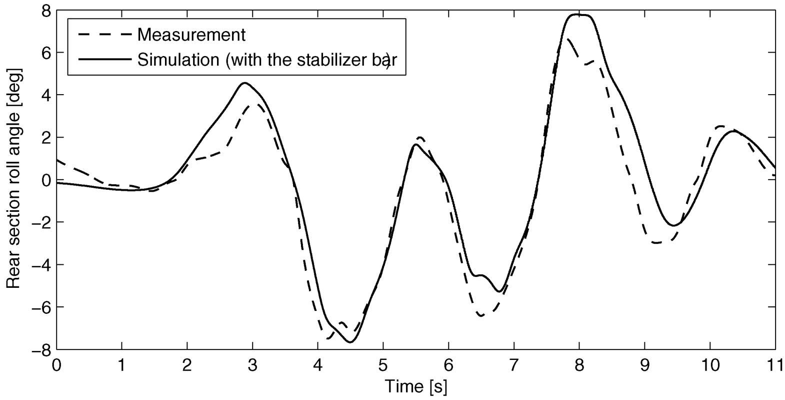

Fig.11: The time history of the rear section roll angle during the measurement and during the simulation of the test drive No. 3 with the stabilizer bar

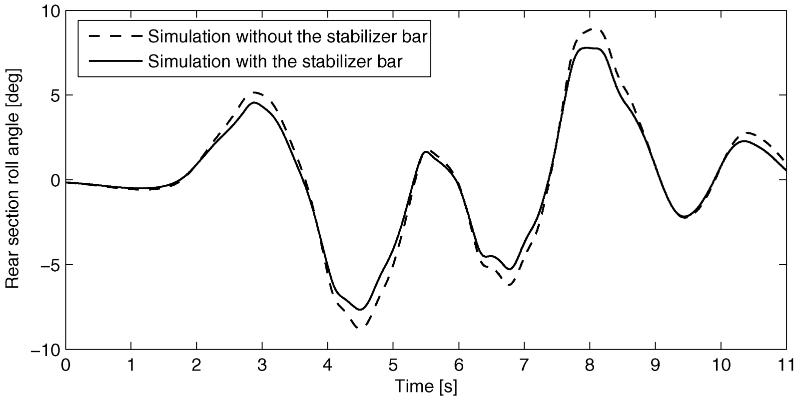

Fig.12: The time history of the rear section roll angle during the simulations of the test drive No. 3 with and without the stabilizer bar

5. Conclusions

The time histories and the extreme values of the monitored quantities identified during the experimental measurements on the real trolleybus with the rear section stabilizer bar and during the simulations with the multibody models are not fully identical (see Tab. 1, Fig. 11). Differences are caused on the one hand by the ignorance of all the conditions of the test drives with the real trolleybus needed for more precise simulations (initial conditions at recording the experimental measurements were not fully known; e.g., the distances of the rear section chassis frame and the rear axle bump stops are not known, the time histories of the real trolleybus speed are not known as well – keeping constant speed for all the duration of the driving manoeuvre is improbable) and on the other hand by the computer models character itself (the virtual model is always the simplification of the real construction). But in any case those facts do not affect the information abilities of the simulations results, especially the verification of the approach to the trolleybus rear section stabilizer bar design.

During the simulations of the test drives with the multibody models of the ŠKODA 22 Tr low-floor articulated trolleybus with the HÜBNER articulation, the RÁBA driving axles, and with the rear section stabilizer, the time histories and the extreme values of the angle of the mutual position of the front and rear sections and the lateral acceleration of the rear section above the rear axle differ only minimally from the time histories and the extreme values identified during the simulations with the multibody model of the trolleybus without the stabilizer. The extreme values of the time histories of the rear section roll angle and thus also the extreme values of the other related values – relative deflections of the rear section suspension and torsional deformations of the articulated joint – decreased. During the simulated drives the rear section roll angles decreased by 10 % to 18 % owing to the stabilizer bar in comparison with the case when the vehicle would be considered without the rear section stabilizer (see Tab. 1, Fig. 12).

It is evident both from the documented time histories of the monitored quantities during the test drives with the modernized ŠKODA 22 Tr trolleybus without the stabilizer [10] and with the rear section stabilizer [9] and from the results of the simulations ([6], [7], [8], [11], [12] and this article), that during the test drives with the vehicle with the rear section stabilizer the driver drove much more aggressively. It is obvious that this way of driving was enabled by the improvement in driving properties of the trolleybus after the stabilizer bar having been mounted – the test drives with the loaded trolleybus without the stabilizer [10] had to be stopped at the speed 45 km/h due to the problematic behaviour of the vehicle, the test drives with the vehicle with the stabilizer [9] at the speed as high as 55 km/h. Exceeding the permissible stabilizer bar deformations (maximum permissible elastic vertical deformation is within the range ± 0.061 m) and the HÜBNER articulation deformation (maximum permissible elastic torsional deformation is within the range $\pm 3°$) monitored during the test drives simulations was the consequence of the aggressive way of driving starting from the speed of 40 km/h. In contradiction to the simulations, exceeding the maximum elastic deformation of the articulated joint was not identified during the test drives with the real trolleybus [9]. It can be judged that in the records of the experimental measurements impacts caused by the rear section chassis frame bottoming on the rear axle bump stops appeared more significantly. From 40 km/h the rear section chassis frame bottoming on the rear axle bump stops (in multibody models the distance of the rear section chassis and the rear axle bump stops is considered to be in a steady state 0.06 m) was identified during both the experimental measurements and the simulations of the test drives. But it is highly probable that during transporting the passengers in the modernized ŠKODA 22 Tr low-floor articulated trolleybus with the rear section stabilizer in the common city traffic the way of driving will be less aggressive than during the test drives when the vehicle was loaded up to the total mass by means of load bags placed on the floor.

On the basis of the results of the test drives (documented in [9]) simulations it is possible to confirm the suitability of the designed rear section stabilizer bar of the ŠKODA 22 Tr low-floor articulated trolleybus with the HÜBNER articulation and the RÁBA driving axles from the point of view of improving the driving stability [6], [7], [8]. Consideration of the fact that the maximum permissible deformations of the stabilizer bar and the articulated joint were exceeded during the test drives is the matter of the possible evaluation of those structural parts from the point of view of strength and service life.

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