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Multibody Models of the Triple Hybrid Hydrogen Fuel Cell Bus and Their Experimental Verification

Pavel Polach[1] & Jaroslav Václavík[2]

Abstract: Two bus multibody models (a basic one and that with more precise kinematics of axles' suspension) were created using the **alaska** simulation tool. The influence of the virtual model complexity on the results of the simulations of the driving on the uneven test track according to the ŠKODA VÝZKUM road vehicles testing methodology with empty and fully loaded bus multibody models was investigated. The results will be compared with the results of the planned experimental measurements on the real bus and on the basis of their evaluation the multibody models will be put more precisely.

Keywords: Material degradation, Experimental measurements, Computer simulations

1. Introduction

As new and progressive fuel systems are designed for the means of public transport dynamic properties of new vehicles should be tested and verified. The paper deals with the influence of the complexity of the multibody models of the TriHyBus (abbreviation of the Triple Hybrid Hydrogen Bus) on the vehicle dynamic response.

Fig. 1. Front view of the TriHyBus

Fig. 2. Hydrogen fuel cell in the back of the TriHyBus

The TriHyBus project, which has been coordinated by Ústav jaderného výzkumu Řež a.s., comprises research and development, implementation and a test operation of a 12-meter city bus (see Fig. 1) with a hybrid electric propulsion using hydrogen fuel cells (see Fig. 2). The bus was manufactured by ŠKODA ELECTRIC a.s. using the chassis of the Irisbus Citelis 12M bus (produced by Iveco Czech Republic, a.s.). The 48-kW Proton Motor membrane fuel cell is used as a main power-source for the 120-kW electric traction motor. Additional

[1] *Dr. Ing. Pavel Polach; Section of Materials and Mechanical Engineering Research, Výzkumný a zkušební ústav Plzeň s.r.o.; Tylova 1581/46, 30100 Plzeň, Czech Republic; polach@vzuplzen.cz*
[2] *Ing. Jaroslav Václavík; Dynamical Testing Laboratory, Section of Testing Laboratories, Výzkumný a zkušební ústav Plzeň s.r.o.; Tylova 1581/46, 30100 Plzeň, Czech Republic; vaclavik@vzuplzen.cz*

28-kWh traction accumulators and ultracapacitors are utilised while the bus accelerates or ascends, working alongside the fuel cell, allowing for energy recuperation while decelerating.

The vehicle driveability is comparable with the characteristics of standard buses. However, the mass distribution and the total bus mass are rather different. It is the reason of verifying the bus chassis strength (connected with vertical dynamics) and investigating the bus stability (i.e. horizontal dynamics).

2. Multibody models of the bus

In order to obtain a tool for dynamic analysis (e.g. [1]) multibody models of an empty (14 tons weight) and a fully loaded (18 tons weight) hydrogen bus were created [2] (see Fig. 3). For the buses of the two weights a basic multibody model and a multibody model with more precise kinematics of axles' suspension were created in the **alaska 2.3** simulation tool [3]. The creation of relatively simple multibody models (in this case of the basic multibody model) and an effort to improve them are important due to the significant shortening of the computational time.

The basic multibody model of the hydrogen bus is formed by 21 rigid bodies mutually coupled by 24 kinematic joints. The number of degrees of freedom of the multibody model in kinematic joints is 39. A kinematic scheme of the TriHyBus basic multibody model is given in [4]. The multibody model with more precise kinematics of the axles' suspension is formed by 24 rigid bodies coupled by 30 kinematic joints. The number of degrees of freedom in kinematic joints is 73. The kinematic scheme of the multibody model with more precise kinematics of the axles' suspension is given in [5].

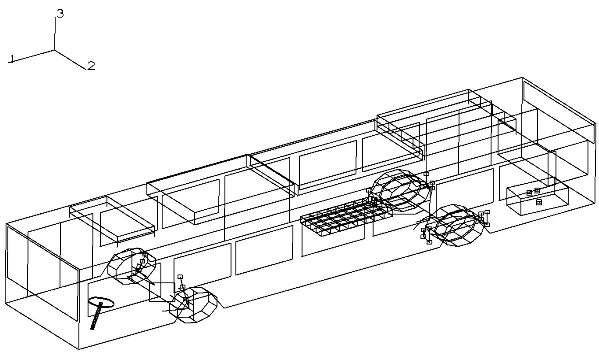

Fig. 3. The TriHyBus multibody model visualization in the **alaska** simulation tool

The rigid bodies correspond to the bus individual structural parts (and to one "auxiliary" body) and are defined by mass, centre of gravity coordinates and mass moments of inertia. Air springs and hydraulic shock absorbers in axles' suspension and bushings in the places of mounting certain bus 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.

The multibody models of the hydrogen bus were created especially on the basis of data (numerical data and technical documentation) provided by ŠKODA ELECTRIC a.s. Since producers of some constructional bus parts had not been willing to provide data needed for the creation of multibody models certain input data were derived or taken from the multibody models of the ŠKODA 21 Ab low-floor bus [6] and the SOR C 12 intercity bus [7]. Characteristics of axles' air springs [2] were determined on the basis of static loadings of axles derived from the data provided by Iveco Czech Republic, a.s. The biggest drawback of multibody models is the ignorance of force-velocity characteristics of shock absorbers in axles' suspension. That is why the information capability of simulations with multibody models in the field of vertical dynamics has not been verified yet. Characteristics of shock absorbers are supposed, due to the constructional similarity of the vehicles, to be the same as the force-velocity characteristics of the shock absorbers of the SOR C 12 intercity bus [7]. Stiffness data of bushings in assembly eyes for connecting radius rods to axles and chassis frame are taken from the documentation of the Lemförder Metallwaren and the Autófelszerelési Vállalat Sopron companies [2].

Multibody models can be used for the solution of the bus vertical dynamics with various types of excitation by uneven road surface as well as for the solution of horizontal dynamics problems (i.e. handling and stability analyses) [4].

The effort will be made to verify the vertical dynamics qualities of the multibody model. On the basis of the experimental measurements with the real TriHyBus the force-velocity characteristics of shock absorbers in axles' suspension in the multibody models will be improved. At this improvement the experience from the improving of the force-velocity characteristics of the shock absorbers of the Neoplan DMA bus [8] and the ŠKODA 21 Tr trolleybus [9] will be utilized.

3. Experimental measurements

The operational tests will be focused on both vertical dynamics and horizontal dynamics of the TriHyBus. On the basis of the experimental measurements the bus multibody models will be verified and, if need be, put more precisely.

In the field of the vertical dynamics the operational tests on an uneven test track (so called bump tests) will be carried out in a standard way according to the ŠKODA VÝZKUM road vehicles testing methodology (e.g. [10]). An artificial test track will be created on a common bitumen road with a set of four portable standard bumps (obstacles), the shape of which is defined in the ČSN 30 0560 Czech Standard (Obstacle II: h = 60 mm, d = 500 mm – see Fig. 4).

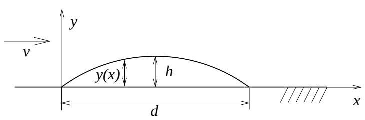

Fig. 4. The standardized artificial obstacle

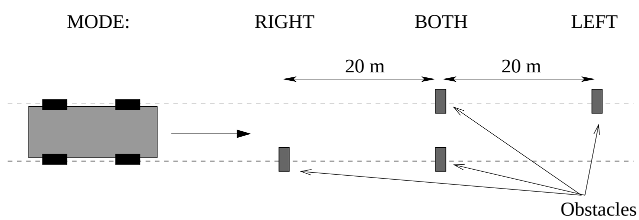

Fig. 5. Scheme of the track according to the ŠKODA VÝZKUM road vehicles testing methodology

Artificial obstacles are spaced out on the smooth road surface 20 meters apart. The first obstacle is run over only with right wheels, the second one with both and the third one only with left wheels (Fig. 5) at bus speed 40 km/h. During the test the relative displacement between the axles and the chassis frame will be (among others) measured and will be compared with the results of simulations with the multibody models.

The results of the simulations with the verified multibody models will be used for a dynamic calculation of skeleton stresses using finite element analysis (FEA).

Another reason for performing the bump test is the verification of the FEA model by measuring the stress-time histories at selected structural joints. The results of this test and/or its FEA simulation are also used for the preliminary evaluation of a fatigue life of critical joints using design spectra. The design spectra represent a histogram of symmetrical loading cycles, the main parameters of which (maximum stress amplitude and predominant frequency of mechanical vibration) can be obtained from the bump test and other ones can be derived from expected operational conditions. It is supposed on the basis of the empirical knowledge that the maximum stress amplitudes on heavy damaged roads achieve 80 % to 100 % of the values of the bump test. In the phase of a vehicle operation design spectra can be compared with real spectra and further modified.

In the field of the horizontal dynamics a severe double lane-change manoeuvre with the real bus will be performed. The severe double lane-change manoeuvre according to ISO 3888-1 is a widespread testing method for a subjective evaluation of the dynamic properties of vehicles. It is a dynamic process consisting in a rapid driving of a vehicle from its initial lane to another lane parallel to the initial lane and returning to the initial lane without exceeding the lane boundaries. The scheme of the test track, which must be run through, is in Fig. 6. The total length of the track for the severe double lane-change manoeuvre is 125 meters; the individual track sections' width is dependent on the vehicle width. Dimensions of the individual sections of the test track for the TriHyBus, the width of which is 2.5 meters, are given in Table 1.

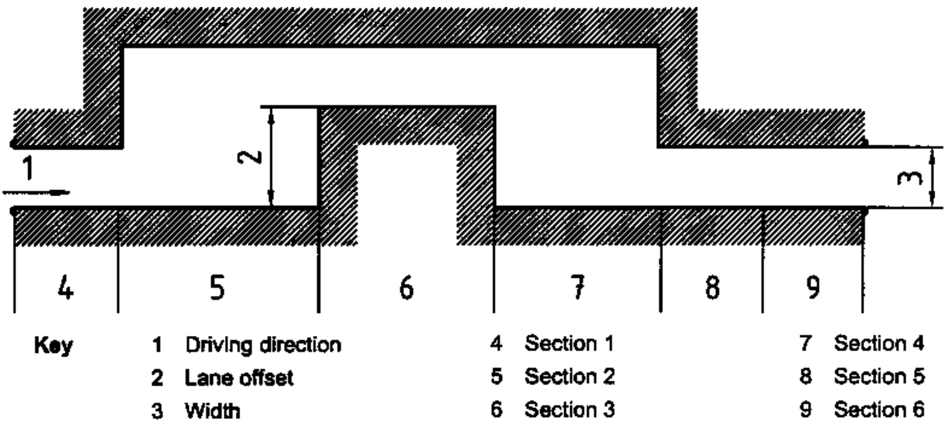

Fig. 6. Scheme of the track for the double lane-change manoeuvre according to ISO 3888-1

Table 1. Dimensions of the double lane-change track for the TriHyBus

Section (see Fig. 6)	Section length [m]	Lane offset [m]	Section width [m]
1	15	-	3
2	30	-	-
3	25	3.5	3.25
4	25	-	-
5	15	-	3.5
6	15	-	3.5

During this manoeuvre, the bus velocity, the acceleration at several structure points, the tilt of the bus as well as the form of a driven test curve are also measured and evaluated.

The results of the simulation of the severe double lane-change manoeuvre with the TriHyBus multibody models are given in [4].

4. Results of simulations of the driving on the uneven test track

Vertical dynamic properties of the TriHyBus were investigated on an artificial test track when simulating driving with multibody models on a virtual test track according to the ŠKODA VÝZKUM road vehicles testing methodology. As it has been already stated the simulations at the TriHyBus speed 40 km/h are performed.

Time histories and extreme values of the air springs relative deflections are the monitored quantities – e.g. [9, 11, 12].

Table 2. Relative deflection of air springs

Simulations	Obstacle	Value	Relative deflection of air springs [mm]			
			Right front	Left front	Right rear	Left rear
Basic multibody model of the empty bus	first	min.	-53	-4	-64	-12
		max.	36	6	17	12
	second	min.	-50	-49	-62	-63
		max.	43	45	32	31
	third	min.	-12	-48	-13	-60
		max.	12	45	17	23
Multibody model with the more precise kinematics of axles' suspension of the empty bus	first	min.	-53	-4	-63	-11
		max.	36	6	18	13
	second	min.	-50	-49	-61	-62
		max.	43	45	32	31
	third	min.	-13	-47	-13	-59
		max.	14	46	17	22
Basic multibody model of the fully loaded bus	first	min.	-52	-3	-61	-13
		max.	36	4	17	12
	second	min.	-51	-49	-60	-60
		max.	41	43	29	29
	third	min.	-12	-50	-11	-59
		max.	12	42	15	20
Multibody model with the more precise kinematics of axles' suspension of the fully loaded bus	first	min.	-52	-3	-60	-12
		max.	36	4	18	12
	second	min.	-51	-49	-59	-60
		max.	41	43	29	29
	third	min.	-13	-49	-9	-57
		max.	13	44	14	21

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 the Lagrange method. Results of the simulations mentioned in this paper were obtained using the Shampine-Gordon integration algorithm [3].

Deriving from the values given in Table 2 and from the time histories of air springs relative deflection (see Figs. 7 to 14) the coincidence of all results is evident or even „suspicious". When speaking about coincidence both multibody models of a different complexity and empty and fully loaded buses are concerned. The coincidence gives evidence for both a good information capacity of the basic multibody models and the multibody models with the more precise kinematics of axles' suspension (which, of course, has already been confirmed at this approach to the creation of multibody models of public means of transport – e.g. [11]) and for shock absorbers used in a proper way. As it has been already stated, the characteristics of shock absorbers are supposed to be the same as the force-velocity characteristics of the shock absorbers of the SOR C 12 intercity bus [7]. But this does not correspond in case of the TriHyBus with reality and force-velocity characteristics of the shock absorbers will only have to be identified.

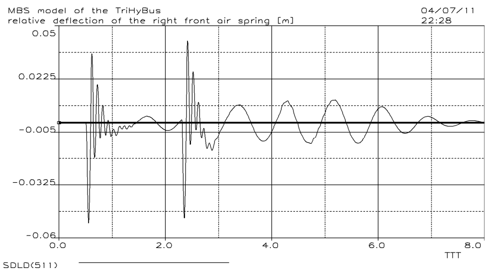

Fig. 7. Time histories of the right front air spring relative deflection when simulating the test drive with the basic multibody model of the empty TriHyBus

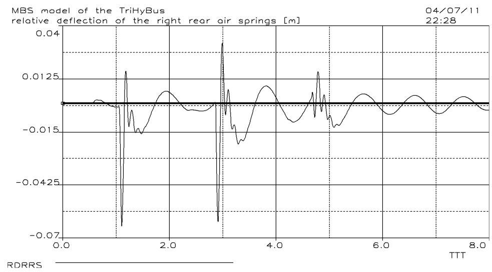

Fig. 8. Time histories of the right rear air springs relative deflections when simulating the test drive with the basic multibody model of the empty TriHyBus

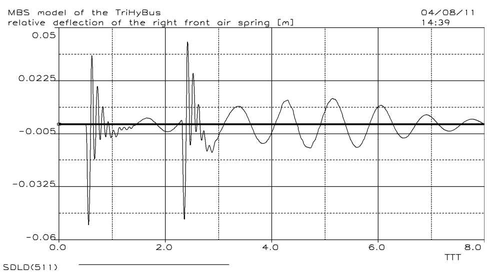

Fig. 9. Time histories of the right front air spring relative deflection when simulating the test drive with the multibody model with the more precise kinematics of axles' suspension of the empty TriHyBus

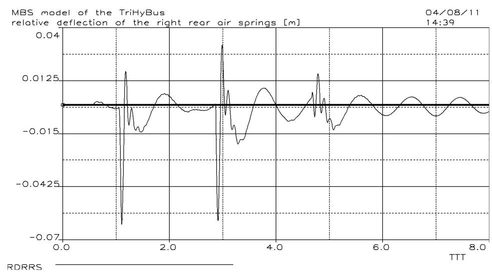

Fig. 10. Time histories of the right rear air springs relative deflections when simulating the test drive with the multibody model with the more precise kinematics of axles' suspension of the empty TriHyBus

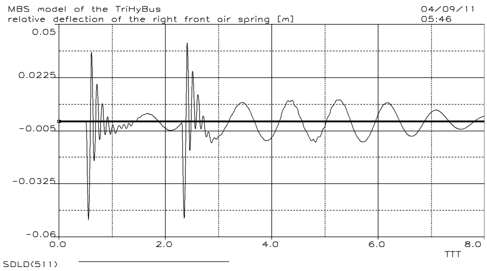

Fig. 11. Time histories of the right front air spring relative deflection when simulating the test drive with the basic multibody model of the fully loaded TriHyBus

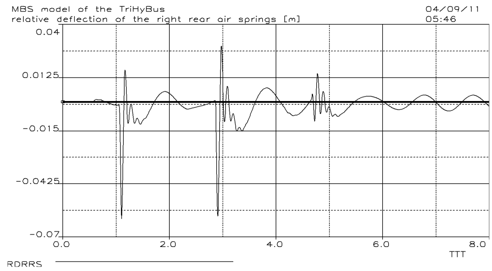

Fig. 12. Time histories of the right rear air springs relative deflections when simulating the test drive with the basic multibody model of the fully loaded TriHyBus

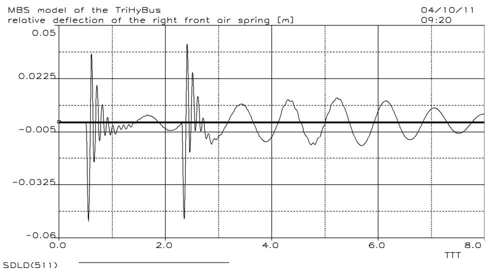

Fig. 13. Time histories of the right front air spring relative deflection when simulating the test drive with the multibody model with the more precise kinematics of axles' suspension of the fully loaded TriHyBus

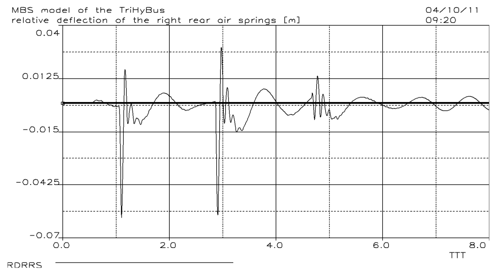

Fig. 14. Time histories of the right rear air springs relative deflections when simulating the test drive with the multibody model with the more precise kinematics of axles' suspension of the fully loaded TriHyBus

5. Conclusion

In the paper the multibody models of the TriHyBus are described. The multibody models can be used for the investigation of the bus horizontal and vertical dynamics. The planned operational tests at the experimental measurements with the real bus are described. The simulations of the driving on the uneven test track according to the ŠKODA VÝZKUM road vehicles testing methodology were performed with the multibody models. The influence of the bus multibody models complexity was monitored.

On the basis of comparison of the simulations results (time histories and extreme values of the air springs relative deflections) and the relative displacement between the axles and the chassis frame (e.g. [9, 11, 12]), that are planned to be measured at the testing drives with the real TriHyBus, will be improved the force-velocity characteristics of shock absorbers in axles' suspension in the multibody models. Criteria for determining the improved characteristics will be as follows: keeping the similar character of course as at the "usual" characteristics of shock absorbers, achieving as high coincidence as possible of the extreme values of time histories of relative deflections of air springs with the extreme values of time histories of relative deflections between the axles and the chassis frame determined at the experimental measurement and achieving as similar character as possible of time histories of relative deflections of air springs with time histories of relative deflections between the axles and the chassis frame [9].

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References

[1] Hegazy S., Rahnejat H. and Hussain K., "Multi-Body Dynamics in Full-Vehicle Handling Analysis under Transient Manoeuvre," Vehicle System Dynamics, 34(1), pp. 1-24 (2000). ISSN 0042-3114.

[2] Polach P., Multibody Models of the TriHyBus Hydrogen Bus in the alaska Simulation Tool, Research Report VYZ 1319/10 (ŠKODA VÝZKUM s.r.o., Plzeň, 2010). (in Czech)

[3] Maißer P., Wolf C.-D., Keil A., Hendel K., Jungnickel U., Hermsdorf H., Tuan P.A., Kielau G., Enge O., Parsche U., Härtel T. and Freudenberg H., alaska, User Manual, Version 2.3 (Institute of Mechatronics, Chemnitz, 1998).

[4] Polach P. and Hajžman M., "The influence of the TriHyBus multibody models complexity on simulations results," in Proceedings of the 5th International Conference on Dynamics of Civil Engineering and Transport Structures and Wind Engineering DYN-WIND´2011, Jasná pod Chopkom, May 2011 (University of Žilina, Žilina, 2011). (in print)

[5] Polach P. and Hajžman M., "Investigation of vertical dynamics of a hydrogen fuel bus," in Proceedings of the 17th International Conference Engineering Mechanics 2011, Svratka, May 2011 (Institute of Thermomechanics, Prague, 2011). (in print)

[6] Polach P., MBS – Model of the ŠKODA Bus II, COPERNICUS Project No. 94-0520, Deliverable D51/2 (ŠKODA RESEARCH Ltd., Plzeň, 1997).

[7] Polach P. and Hajžman M., "Approaches to the creation of the intercity SOR bus multibody model," in Proceedings of the 21st Conference Computational Mechanics 2005, Vimmr J., ed., Hrad Nečtiny, November 2005 (University of West Bohemia in Pilsen, Plzeň, 2005), Vol. II, pp. 477-484. ISBN 80-7034-400-7. (in Czech)

[8] Polach P., Verified Multibody Model of the Empty NEOPLAN DMA Low-floor Articulated Trolleybus and Results of Running over the Large Road Unevenness Simulations, Research Report VYZ 0726/2004 (ŠKODA VÝZKUM s.r.o., Plzeň, 2004).

[9] Polach P. and Hajžman M., "The Influence of Modifications of Hydraulic Shock Absorbers' Characteristics of the ŠKODA Low-floor Trolleybus on the Improvement of the Accordance of the Results of Simulations and an Experimental Measurement," in Proceedings of 3rd International Conference Dynamics of Rigid and Deformable Bodies 2005, Skočilasová B., ed., Ústí nad Labem, October 2005 (UJEP in Ústí nad Labem, Ústí nad Labem, 2005), pp. 103-112. ISBN 80-7044-688-9. (in Czech)

[10] Řehoř P., Kepka M., Kotas M., Václavík J. and Frémund J., Operating Test of the ŠKODA 14Tr San Francisco Trolleybus on a Test Track, Research Report VYZ 0204/98 (ŠKODA RESEARCH Ltd., Plzeň, 1998).

[11] Polach P. and Hajžman M., "Various Approaches to the Low-floor Trolleybus Multibody Models Generating and Evaluation of Their Influence on the Simulation Results," in Proceedings of ECCOMAS Thematic Conference Multibody Dynamics 2005 on Advances in Computational Multibody Dynamics, Goicolea J. M., Cuadrado J., Orden J.C.G., eds., Madrid, June 2005 (Universidad Politécnica de Madrid, Madrid, 2005), CD-ROM. ISBN 84-7493-353-6.

[12] Polach P. and Hajžman M., "Multibody simulations of trolleybus vertical dynamics and influences of tire radial characteristics," in Proceedings of The 12th World Congress in Mechanism and Machine Science, Merlet J.-P., Dahan M., eds., Besançon, June 2007 (Comité Français pour la Promotion de la Science des Mécanismes et des Machines, Besançon, 2007), Vol. 4, pp. 42-47.