National Conference with International Participation
ENGINEERING MECHANICS 2006
Svratka, Czech Republic, May 15 – 18, 2006
paper no. **191**

UTILIZATION OF MULTIBODY MODELLING FOR DESIGN OF CHARACTERISTICS OF AIR PRESSURE CONTROLLED HYDRAULIC SHOCK ABSORBERS IN THE SOR INTERCITY BUS

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Summary: *The air pressure controlled shock absorber of axles air suspension is capable of changing its damping force in dependence on air pressure in air springs. In order to improve dynamic properties of all vehicles that use the axles air suspension, BRANO a.s., the Czech producer of shock absorbers, started to develop air pressure controlled hydraulic telescopic shock absorbers of axles air suspension. The SOR C 12 intercity bus is the reference vehicle, for which research and development of controlled shock absorbers is done and on which the shock absorbers are verified. Force-velocity characteristics of controlled shock absorbers were designed on the basis of results of computer simulations with the bus multibody models created in the* ***alaska*** *simulation toolbox.*

1. Introduction

Generally, dynamic properties play a decisive role in the overall quality of any road vehicle. Optimum dynamic properties of the vehicle meant for the passenger transport can be usually achieved, in dependence on its structural design, by the proper choice of axles suspensions elements (or the proper choice of a type or suspensions elements of seats), which must be a certain compromise of the requirements for the bodywork and chassis components life, its driving stability and safety and driving comfort of a driver and passengers.

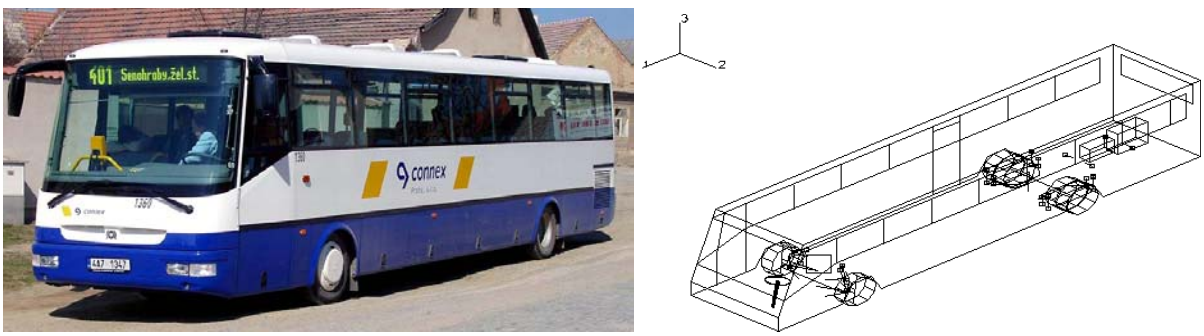

Fig.1 The SOR C 12 intercity bus – real vehicle and multibody model visualization.

In order to improve dynamic properties of buses, trucks, trailers and semitrailers, in 2003 BRANO a.s., the producer of shock absorbers for those types of vehicles, started to

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develop hydraulic telescopic shock absorbers of the air suspension of the axles controlled by air pressure. The SOR C 12 intercity bus, which is produced by SOR Libchavy spol. s r.o., is the reference vehicle, for which the research and development of hydraulic shock absorbers of the axles air suspension controlled by air pressure is done and on which the shock absorbers are verified. The force-velocity characteristics of the controlled hydraulic shock absorbers of the axles suspension were designed on the basis of the results of computer simulations with the bus multibody models.

2. Motivation for the development of shock absorbers controlled by air pressure

The non-controlled hydraulic shock absorber of the axles suspension is not capable of changing its damping force in dependence on vehicle loading. When driving with an empty or a half-empty vehicle, it appears overdamped, stiff, with insufficient driving comfort. Damage of load occurs, impacts are transferred both to the whole vehicle and to the roadway, which leads to a considerable wear. When the vehicle is loaded to maximum loading the opposite phenomenon occurs: the vehicle seems to be underdamped, soft, it rolls considerably during driving manoeuvres and thus it becomes less safe.

Applying the active or the semi-active controlled shock absorbers of the axles suspension is the solution, having been used since the 80´s of the last century and leading to the improvements in the dynamic properties of vehicles. In the field of heavy vehicles and means of public transport, on condition the controlled shock absorbers are used at all, semi-active shock absorbers are usually concerned (Kitching et al., 2000). Using active controlled shock absorbers would, especially due to the lower production than at passenger cars and thus less absorbed expenses for the vehicle development and due to the higher price of the active controlled shock absorbers, made the means of transport too expensive. The principles of function of semi-active shock absorbers, their design and assessing their optimum damping properties are dealt with in a lot of titles of available professional literature. A survey of development of semi-active shock absorbers is given, in addition to already mentioned Kitching et al. (2000), e.g. in the publication by the same authors (Kitching et al., 1996).

The hydraulic telescopic shock absorber of the axles air suspension controlled by air pressure s capable of changing its damping force in dependence on the air pressure in air springs. The air pressure in springs rises with the increasing vehicle loading, the shock absorber damping force increases, too. When the vehicle loading decreases the pressure in springs drops, which causes decrease in damping forces in the shock absorbers. Thus the vehicle keeps the constant driving stability and comfort during various operational situations. This property of the controlled shock absorber can be made use of at all the vehicles using the air suspension of the axles. Regarding the safe vehicle handling, in case of air pressure failure the controlled shock absorber automatically transfers itself to the state of the maximum damping forces.

3. Multibody models of the SOR C 12 intercity bus

Using multibody simulations for developing and improving the dynamic properties of vehicles is standard in engineering practice - e.g. Genta (2003), Blundell & Harty (2004). Multibody simulation with means of transport can be, of course, used for designing the optimum characteristics of shock absorbers (Eberhard et al., 2003; Schiehlen & Hu, 2003; etc.) and controlled shock absorbers (Valášek et al., 1998; Holdmann & Holle, 1999; Heo et al., 2003; etc.), too. The force-velocity characteristics of the controlled shock absorbers of the axles air suspension of the SOR C 12 intercity bus were designed on the basis of the results of computer simulations with the bus multibody models created in the **alaska** simulation toolbox (Maißer et al., 1998).

Multibody models of the empty (i.e. of curb weight), the fully loaded (i.e. of maximum weight) and three variants of partly loaded vehicle were created. For the buses of all weights basic multibody models, multibody models with more precise kinematics of the rear axle suspension and multibody models with more precise kinematics of the axles suspension were created. Generation of relatively simple multibody models (in this case of the basic multibody model) and an effort to improve them is important due to the significant shortening of computational time.

Two variants of the multibody models of the partly loaded bus (20 % and 50 % of the maximum loading) were generated because of the design of the force-velocity characteristics of the controlled hydraulic shock absorbers of the axles suspension for those states of vehicle loading. The third variant of the multibody models of the partly loaded bus (71.5 % of the maximum loading) corresponds with the weight of a real vehicle during the operational tests performed at airport in Hoškovice in September 2004. Optimum setting of the force-velocity characteristics of the non-controlled shock absorbers of the SOR 12 C bus loaded to 71.5 % of the maximum loading was the result of the operational tests. On the basis of the records of the experimental measurements documented in Mastník (2004) the created multibody models were verified at the same time.

The module multibody models of the SOR C 12 intercity bus and possible simulated operational situations are described in Polach & Hajžman (2005).

4. Methodology of the design of optimum force-velocity characteristics of controlled hydraulic shock absorbers

As a criterion for the design of the optimum force-velocity characteristics of the controlled shock absorbers, maximum similarity of dynamic responses of the multibody models of the SOR C 12 intercity bus of all the considered weights to dynamic response of the multibody model of the bus with the same loading as during the experimental measurements with the real vehicle at airport in Hoškovice, was chosen. Time histories of relative deflections of the axles air springs determined during the simulations were compared.

The tuning of parameters means the finding of mechanical system parameters in such a way that a certain condition may be fulfilled. On condition it can be formulated as looking for extremes (maximum or minimum) of a certain suitably defined objective function, it is also possible to speak about optimization (maximization or minimization). The problems, which must be solved at designing the suitable methodology, can be divided into the following steps:

1. Parametrization of the problem.
2. Choice of an objective function.
3. Choice of a method of the optimization process.

5. Parametrization of the problem

In case of tuning the force-velocity characteristics of hydraulic shock absorbers it is evident, that the problem parameters are the quantities defining the course of the force-velocity characteristics. The force-velocity characteristics of the non-controlled shock absorbers used in computer simulations were obtained by measuring on a special test stand under specific operational conditions. After processing the measurement, dependence of the damping force in shock absorbers F on the relative velocity of shock absorber rebound and compression v is at disposal. Usually N points of the characteristic, between which the characteristic is interpolated by a linear curve, are measured. The force-velocity characteristic of the front axle shock absorbers of the SOR C 12 bus was specified by five points, the force-velocity characteristic of the rear axle shock absorbers by eleven points (see Fig.2).

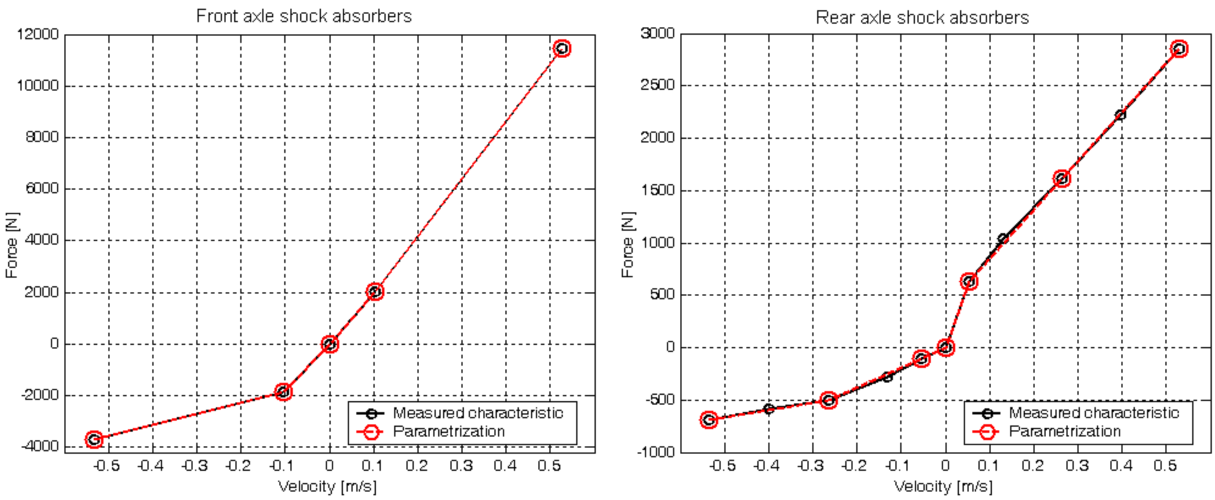

Fig.2 The force-velocity characteristics of the non-controlled shock absorbers of the front and rear axles and their parametrizations.

The values of measured forces and velocities, which will be changed during the tuning process, can be chosen as problem parameters or some other points, originally obtained by linear interpolation, can be selected. It is necessary to consider the possibility of practical realization of the designed force-velocity characteristic.

As problem parameters it is also possible to choose only values of the damping forces F_i, while the velocities v_i will be kept constant, or vice versa to choose variable velocities v_i and constant forces F_i. In the below described design of the characteristics more natural possibility of variable forces F_i and constant velocities v_i was chosen. The problem parameters were arranged into the vector $\boldsymbol{p} = [F_1, F_2, \dots, F_N]^T$.

6. Choice of an objective function

The specification of an objective function or of a certain criterion, which should clearly quantify the degree of the objective achievement when tuning or optimising, is further step in solving the problem.

For the case of tuning the parameters of the force-velocity characteristics of the controlled shock absorbers considering the achievement of the dynamic responses accordance at various loadings of the SOR C 12 bus there are several possibilities how to describe the degree of accordance of two time series of the relative deflections of the air springs:

- Visual comparison of two time series by man is probably the least suitable and the least unambiguous way. The main disadvantage of this approach is its impossibility to be automated.

- Another possibility is using the basic statistical quantities (Rektorys et al., 1995), which are the mean value μ and the variance σ^2, which are defined for discrete time series (Bajpai et al., 1978) as

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \quad , \quad \sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \mu\right)^2 \quad . \tag{1}$$

  Using the mean value μ and the variance σ^2 in defining the objective functions for the solved problem of tuning the shock absorbers characteristics is not suitable because those statistical quantities do not characterize the actual behavior of the compared time series.

- Using other statistical quantities that express directly the relation between two time series (generally two signals) is more suitable. It is particularly the correlation coefficient *R(**p**)* defined for two discrete time series x_1 (reference) and $x_2(\boldsymbol{p})$ (function of design parameters) of the form (Rektorys et al., 1995)

$$R(\boldsymbol{p}) = \frac{\sum_{i=1}^{n}\left(x_i^{(1)} - \mu_1\right)\left(x_i^{(2)}(\boldsymbol{p}) - \mu_2(\boldsymbol{p})\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i^{(1)} - \mu_1\right)^2 \sum_{i=1}^{n}\left(x_i^{(2)}(\boldsymbol{p}) - \mu_2(\boldsymbol{p})\right)^2}} \tag{2}$$

  where μ_1 and $\mu_2(\boldsymbol{p})$ are the mean values of appropriate time series. Values of the correlation coefficient range between zero and one. The more the compared time series are similar to each other, the more the correlation coefficient value approaches to one. The advantage of the correlation coefficient is that it quantifies very well the similarity of two time series by scalar value, which is obtained by means of a simple calculation. After all the approach based on the calculation of the correlation coefficient was chosen for determining the optimum force-velocity characteristics of the hydraulic shock absorbers controlled by air pressure. .

- Of course it is possible to define other types of objective functions, which e.g. will minimize the difference between the individual members of the time series of the relative deflections of the air springs, similarly like the objective function

$$\psi(\boldsymbol{p}) = \sum_{i=1}^{n}\left(x_i^{(2)}(\boldsymbol{p}) - x_i^{(1)}\right)^2 \quad . \tag{3}$$

  There are cases, for which it is more advantageous to use this type of the objective function, e.g. due to the convergence of the optimization process. Other objective functions can be formulated e.g. on the basis of the minimization of differences of time series extremes.

7. The optimization process method

The methodology of the optimization of the force-velocity characteristics of hydraulic shock absorbers using the computer simulation results, which will be also applied in the design of the characteristics of the telescopic hydraulic shock absorbers of the SOR C 12 intercity bus axles suspension controlled by air pressure, is mentioned in Hajžman & Polach (2005).

If the model is parametrized and if the objective function is defined, it is necessary to choose the appropriate tuning or optimization method. The schemes of all approaches to the optimization process are identical. Till the terminal condition given beforehand is not achieved iteration loop procees in two steps.

1. Problem analysis, in this case computer simulation of the run of the bus.
2. The optimization parameters change on the basis of the objective function evaluation (tuning criteria).

In case of the computer simulations with the multibody models of the SOR C 12 intercity bus in the **alaska 2.3** simulation toolbox the whole process of the optimization was limited by the impossibility of evaluating the results of simulations without the necessary intervention of man. The whole process could not be automated, which also influenced the execution of the second step of the optimizing process. “Manual” change in the parameters on the basis of sense and estimate of the man performing the calculations can be the solution. The partial advantage is, that in the evaluation the analyst can consider more complicated objective functions and criteria, which are not necessary to be strictly mathematically specified. Due to the shorter computational time, the basic multibody models of the SOR C 12 bus were chosen for the numerical simulations in the first phase (it followed from test calculations that the suitability of the design characteristics would not be negatively influenced by this choice).

8. Selected procedure for tuning the parameters of force-velocity characteristics of controlled shock absorbers

It had to be decided, for which operational situation simulations in the **alaska 2.3** simulation toolbox (Maißer et al., 1998) the shock absorbers characteristics would be tuned. On the basis of experience running over the modified standardized obstacle according to ČSN 30 0560 standard (see Fig.3) at bus speed 40 km/h was selected. The obstacle is cylindrical section shaped and vertical co-ordinates of the artificial obstacle are given by the formula

$$z(x) = \sqrt{R^2 - \left(x - \frac{d}{2}\right)^2} - (R - h) \tag{4}$$

where R is the obstacle radius (0.551 m), h is the obstacle height (0.06 m), d is the obstacle length (0.5 m) and x is the obstacle co-ordinate in direction of the vehicle driving. Standardized dimensions of the Obstacle II are given in brackets.

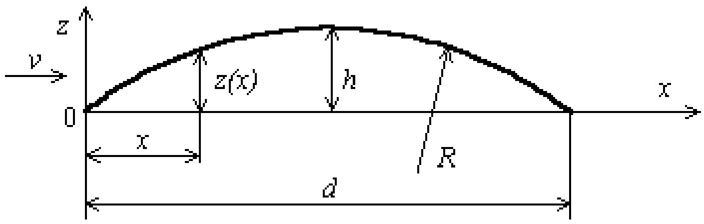

Fig.3 Artificial obstacle according to ČSN 30 0560 standard.

Runs over can be performed using various obstacles configurations. Simulations of running over one obstacle with all the wheels (both right and left side at a time) were used for tuning the force-velocity characteristics of the controlled shock absorbers. In order to guarantee that the tuned characteristics may be applied in the whole range of the required operational velocities of the shock absorbers approx. between -0.5 m/s and 0.5 m/s, the parameters of the artificial obstacle during the individual tuning phases for the various SOR C 12 bus weights were modified (see Tab.1). In case of using the standardized obstacle height the limits would be significantly exceeded.

Tab.1 The used obstacle heights *h* in tuning the force-velocity characteristics.

Bus weight	**Obstacle height *h* [m] in tuning**	
	The force-velocity characteristics of the front axle shock absorbers	The force-velocity characteristics of the rear axle shock absorbers
Empty	0.023	0.014
20 % of the maximum loading	0.023	0.014
50 % of the maximum loading	0.025	0.014
Fully loaded	0.025	0.014

For the front axle hydraulic shock absorbers only a measured five-point force-velocity characteristic was parametrized in all the non-zero points (see Fig.2). The original measured eleven-point characteristic of the rear axle hydraulic shock absorbers (in Fig.2 a black full line) included too many points for "manual" tuning. That is why the original characteristic was reduced to a seven-point one (in Fig.2 a red dashed line). Point [0,0] of the characteristics was constant, because it is obvious, that for a zero velocity a zero force must act in the shock absorbers. The facts that both the shock absorbers of the front axle suspension have identical force-velocity characteristics and that all four shock absorbers of the rear axle suspension also have identical characteristics were respected in the tuning process.

Dynamic responses of the vehicle from the moment immediately prior to running up the obstacle with the front wheels (3.5 second) to 10 seconds of the simulation (practically decay of the responses) were compared. Already mentioned time histories of relative deflections of the air springs were the compared quantities. The reference time histories were the relative deflections of the air springs calculated by the simulation with the multibody model of the bus loaded to 71.5 % of the maximum loading in all cases.

The tuning of the force-velocity characteristics of the hydraulic shock absorbers of the front and rear axles of the SOR C 12 bus of various weights was performed in two subsequent phases as follows:

1. Tuning the parameters of the force-velocity characteristic of the front axle shock absorbers:
   a) At first the height of the obstacle was adjusted in such a way, so that the front axle shock absorbers characteristic could be applied in the whole range of the required operational velocities of the shock absorbers between -0.5 m/s and 0.5 m/s (see Tab.1).
   b) At the beginning of tuning the reference dynamic response of the bus loaded to 71.5 % of the maximum loading was calculated for the optimally adjusted obstacle height.
   c) The reference response was compared with the results of the simulations of the run over the obstacle of the same height with the multibody model of the bus of a different weight.
   d) The correlation coefficient was the criterion for the assessment of the accordance of the compared dynamic responses – see equation (2). The time histories of the relative deflections of the front air springs were compared. By changing the force-velocity characteristic of the front axle shock absorbers, due to the correlation coefficient values, the accordance of the time histories of the relative deflections of the rear air springs was being improved at the same time.
   e) On the basis of comparing the correlation coefficient values after finishing each iteration step it was decided on a new change in the parameters of the force-velocity

characteristic of the front axle shock absorbers. The aim was to approach the correlation coefficients to value one. The iteration loop was finished when it was not possible to achieve better values of the correlation coefficient changing the force-velocity characteristic parameters.

Figs 4 and 5 show the example of the time histories of the relative deflections of the left air springs when tuning the force-velocity characteristic of the front axle shock absorbers.

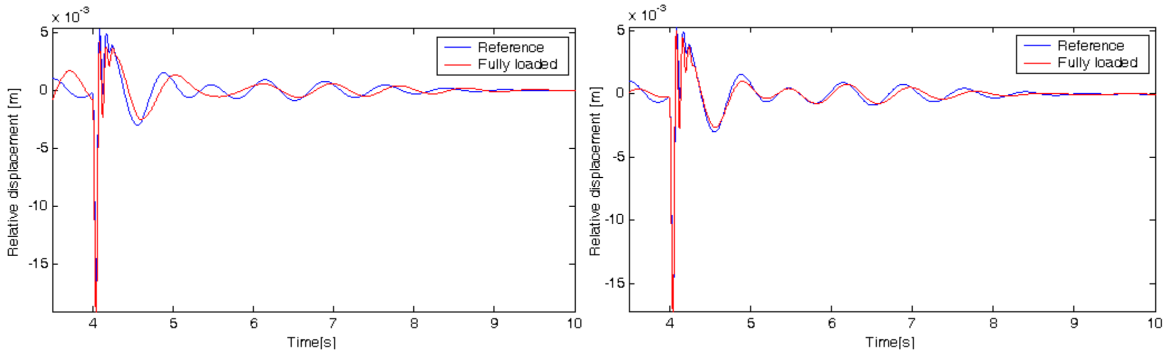

Fig.4 Time histories of relative deflections of the left front air spring of the fully loaded bus with the original force-velocity characteristics of the shock absorbers with the reference time history and with the optimally tuned force-velocity characteristics of the front axle shock absorbers with the reference time history – first phase of tuning.

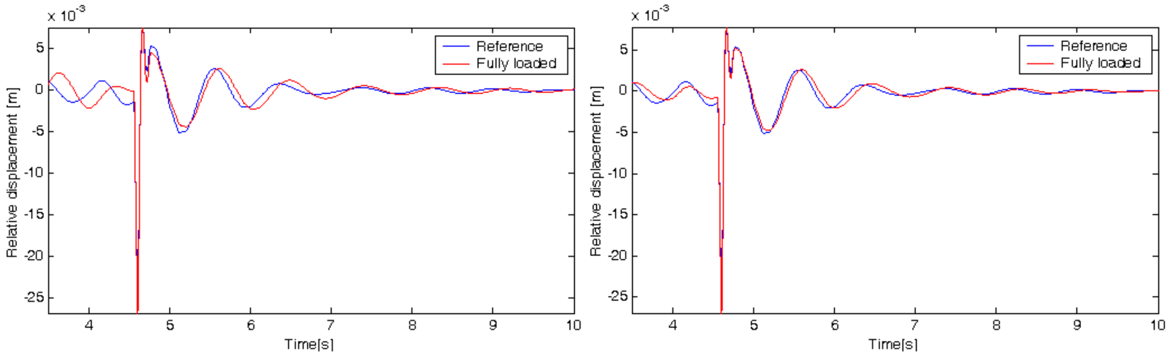

Fig.5 Time histories of relative deflections of the left rear air spring of the fully loaded bus with the original force-velocity characteristics of the shock absorbers with the reference time history and with the optimally tuned force-velocity characteristics of the front axle shock absorbers with the reference time history – first phase of tuning.

2. Tuning the parameters of the force-velocity characteristic of the rear axle shock absorbers:
   a) The height of the obstacle was reduced in such a way, so that the whole range of the required operational velocities of the rear axle shock absorbers between -0.5 m/s and 0.5 m/s could be applied (see Tab.1). The force-velocity characteristic of the front axle shock absorbers was identical with resulting one in the first phase of tuning.
   b) The time histories of the relative deflections of the air springs of the bus loaded to 71.5 % of the maximum loading were the reference dynamic response again.
   c) The reference response was compared with the results of the simulations of the run over the obstacle of the same height with the bus multibody model of a different weight.
   d) The response on the rear axle was compared above all. In contradiction to tuning the force-velocity characteristic of the front axle shock absorbers, when tuning the force-

velocity characteristic of the rear axle shock absorbers, the accordance of the time histories of the relative deflections of the front air springs was rather deteriorating regarding the correlation coefficient values.

e) Iteration process of tuning the force-velocity characteristic of the rear axle shock absorbers was similar as when tuning the force-velocity characteristic of the front axle shock absorbers. Due to deterioration of the accordance of the compared time histories of the relative deflections of the front air spring, the correlation coefficients of the time responses on both axles were taken into account in the course of designing the force-velocity characteristic of the rear axle shock absorbers, unlike the first phase of tuning.

Figs 6 and 7 show the example the time histories of the relative deflections of the left air springs when tuning the force-velocity characteristic of the rear axle shock absorbers.

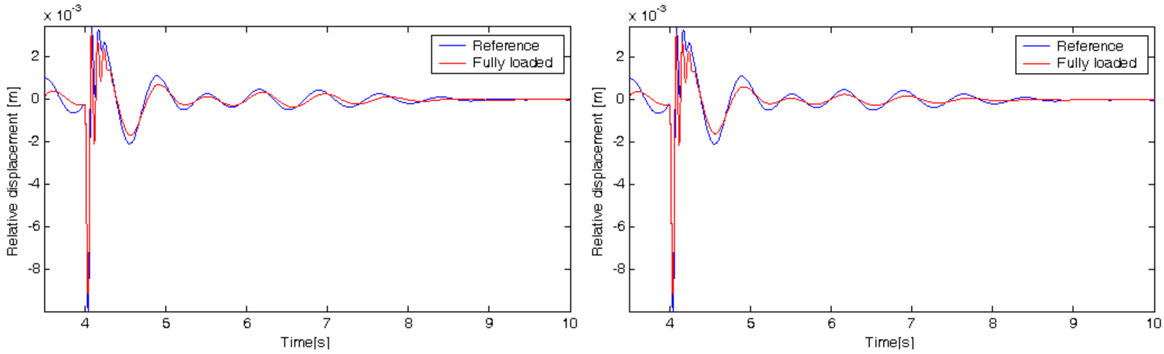

Fig.6 Time histories of relative deflections of the left front air spring of the fully loaded bus with the force-velocity characteristics of the shock absorbers from the first phase of tuning with the reference time history and with the optimally tuned force-velocity characteristics of both axles shock absorbers with the reference time history – second phase of tuning.

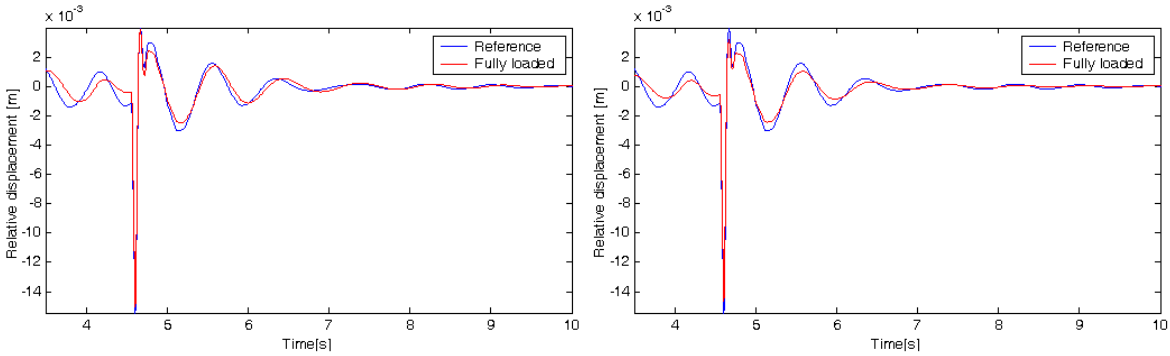

Fig.7 Time histories of relative deflections of the left rear air spring of the fully loaded bus with the force-velocity characteristics of the shock absorbers from the first phase of tuning with the reference time history and with the optimally tuned force-velocity characteristics of both axles shock absorbers with the reference time history – second phase of tuning.

After tuning-up the force-velocity characteristics of the shock absorbers of both axles the force-velocity characteristics of the shock absorbers of the bus of other weight were tuned according to the same methodology.

Besides the criterion of the possible best coincidence of compared dynamic responses, on the basis of discussion the parameters of the force-velocity characteristics of the hydraulic shock absorbers were logically limited. In the process of tuning it was kept, that the characteristic of the shock absorber for the less weighty bus would be situated bellow the characteristic of the weightier vehicle in the field of rebound ($v>0$) and vice versa in the field of compression ($v<0$) it would be situated above it.

In order to automatically calculate the correlation coefficient and compare two numerical series of the same length, the support program was generated in the MATLAB system (MathWorks, 2004). It enables the user to load two data files, which contain two time series in ASCII output format of the **alaska 2.3** simulation toolbox, and to compare their basic statistical quantities (the mean value and the standard deviation), the correlation coefficient and statistical quantities of the data difference.

9. Design of force-velocity characteristics of controlled shock absorbers of the SOR C 12 bus

The optimum force-velocity characteristics of the hydraulic shock absorbers of the SOR C 12 bus axles suspension for the various vehicle weights were designed on the basis of the results of simulations of running over the modified standardized artificial obstacle with the basic multibody models of the SOR C 12 bus using the described methodology. The tuning of the course of the characteristics was finished during the simulations with the bus multibody models with more precise kinematics of the axles suspension. As it was written before, the multibody model complexity did not influence significantly the course of the designed optimum force-velocity characteristics of the hydraulic shock absorbers of the SOR C 12 bus axles suspension.

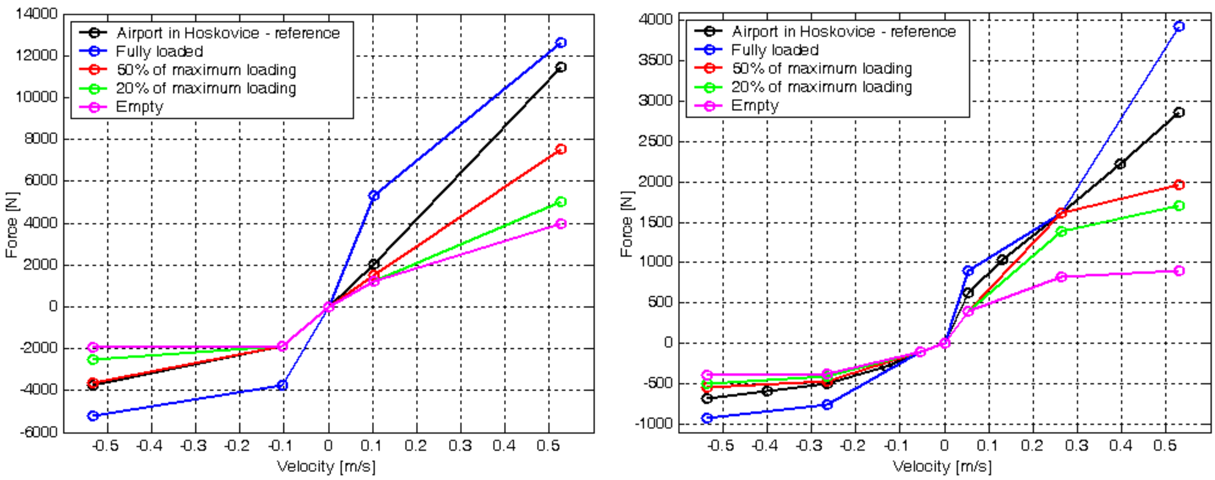

Fig.8 The designed force-velocity characteristics of the front and rear axles controlled shock absorbers for the various bus weights.

The designed force-velocity characteristics of the controlled shock absorbers of the front and rear axles of the SOR C 12 intercity bus are shown in Fig.8. The characteristics were linearly interpolated between the points, in which the characteristics were tuned.

Certain singularity in the designed force-velocity characteristic of the rear axle shock absorbers of the fully loaded vehicle at speed 0.264 m/s, when the magnitude of the damping force for the fully loaded vehicle is equal to the magnitude of the damping force for two less loaded vehicles, follows from the used methodology of tuning (on the basis of the scalar value of the correlation coefficient) and from the nonlinear character of numerical simulations.

10. Simulations of a severe lane-change manoeuvre

The optimum force-velocity characteristics were designed on the basis of the computer simulations of driving along an uneven road surface, which rank among the problems of the vertical dynamics of vehicles. Design of the characteristics on the basis of the computer simulations of various manoeuvres, so called horizontal (directional) dynamics of vehicles, is another possibility. The numerical simulation of a severe lane-change manoeuvre according to ISO 3888-1 standard is one of the problems like that. The bus speed during the manoeuvre was 50 km/h.

Only a slight influence of the tuned force-velocity characteristics using the vertical dynamics on the dynamic responses in the horizontal dynamics appeared. Coincidence of the time series data sets from the point of view of the correlation coefficient values slightly decreased but it was evident from the visual inspection of the obtained time histories of the relative deflections of the air springs that in the monitored limited period directly in the course of a severe lane-change manoeuvre the time histories did not differ significantly. Greater differences could be observed in the phase of the dynamic response decay of the bus after a severe lane-change manoeuvre for the vehicles of certain weights.

11. Conclusions

The force-velocity characteristics of the controlled shock absorbers of the axles air suspension of the SOR C 12 intercity bus were designed on the basis of the results of the computer simulations performed in the **alaska** simulation toolbox (Maißer et al., 1998) with the created multibody models of the empty, the fully loaded and three variants of partly loaded vehicle (Polach & Hajžman, 2005). The values of the damping forces in the selected points of the force-velocity characteristics of the non-controlled shock absorbers were the parameters of the optimization problem. Running over the modified standardized artificial obstacle was the selected simulation for the force-velocity characteristics tuning. As a criterion for the design of the optimum force-velocity characteristics of the controlled shock absorbers, maximum similarity of dynamic responses of the multibody models of the bus of all the considered weights to the dynamic response of the multibody model of the bus loaded to 71.5 % of the maximum loading (the same loading as during the experimental measurements with the real vehicle), was chosen. Time histories of relative deflections of the axles air springs determined during the simulations were compared. Values of the correlation coefficient between the time histories were used as a suitable criterion of similarity.

Verification of the suitability of the designed force-velocity characteristics of the controlled shock absorbers of the axles air suspension of the SOR C 12 intercity bus will also be evaluated according to other approaches mentioned e.g. in Valášek et al. (1998). These approaches are on the one hand keeping acceleration of the sprung mass within reasonable limits from the point of view of a driver and passengers and on the other hand maintaining ride safety and road-friendliness (i.e. minimization the amplitudes of the tire-road contact forces).

12. Acknowledgement

The paper has originated in the framework of solving the research plan of the Ministry of Education, Youth and Sports of the Czech Republic MSM4771868401 “Research into Service Degradation of Advanced Constructional Materials”.

13. References

Bajpai, A.C., Calus, I.M. & Fairley, J.A. (1978) *Statistical Methods for Engineers and Scientists: Student's Course Book*. John Wiley & Sons Ltd., Chichester.

Blundell, M. & Harty, D. (2004) *The Multibody Systems Approach to Vehicle Dynamics*. Elsevier Butterworth-Heinemann, Norfolk.

Eberhard, P., Piram, U. & Bestle, D. (1999) Optimization of damping characteristics in vehicle dynamics. *Engineering Optimization*, 31, pp. 435-455.

Genta, G. (2003) *Motor Vehicle Dynamics: Modeling and Simulation*. World Scientific, II ed., Singapore.

Hajžman, M. & Polach, P. (2005) Optimization methodology of the hydraulic shock absorbers parameters in trolleybus multibody models on the basis of trolleybus dynamic response experimental measurement, in: *Proc. International Scientific Conf. held on the occasion 55th anniversary of founding the Faculty of Mechanical Engineering of the VSB - Technical University of Ostrava* (J. Zapoměl & R. Sikora eds), VSB-TU, Ostrava, pp. 117-122.

Heo, S.-J., Park, K. & Son, S.-H. (2003) Modeling of continuously variable damper for design of semi-active suspension systems. *International Journal of Vehicle Design*, 31, 1, pp. 41-57.

Holdmann, P. & Holle, M. (1999) Possibilities to improve the ride and handling performance of delivery trucks by modern mechatronic systems. *Journal of Society of Automotive Engineers of Japan*, 20, pp. 505-510.

Kitching, K.J., Cole, D.J. & Cebon, D. (1996) The development of a heavy vehicle semi-active damper, in: *Proc. International Symposium on Advanced Vehicle Control AVEC´96*, Aachen.

Kitching, K.J., Cole, D.J. & Cebon, D. (2000) Performance of a semi-active damper for heavy vehicles. *ASME Journal of Dynamic Systems Measurement and Control*, 122, 3, pp. 498-506.

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

Mastník, Z. (2004) *Test Report No. 5-21-1004/Mz*. BRANO a.s., Jablonec nad Nisou. (in Czech)

Polach, P. & Hajžman, M. (2005) Approaches to the creation of the intercity SOR bus multibody models, in: *Proc. 21st conference with international participation Computational Mechanics 2005* (J. Vimmr ed.), FAS UWB, Hrad Nečtiny, II, pp. 477-484. (in Czech)

Rektorys, K. et al. (1995) *Survey of Applicable Mathematics. Vol. II*. Prometheus Publishing House, Prague. (in Czech)

Schiehlen, W. & Hu, B. (2003) Spectral simulation and shock absorber identification. *International Journal of Non-Linear Mechanics*, 38, pp. 161-171.

Valášek, M., Kortüm, W., Šika, Z., Magdolen, L. & Vaculín, O. (1998) Development of semi-active road-friendly truck suspensions. *Control Engineering Practise*, 6, 6, pp. 735-744.

MathWorks (2004) *MATLAB®, Documentation version 7*. The MathWorks, Inc. http://www.mathworks.com/