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# Design of the hydraulic shock absorbers characteristics using relative springs deflections at general excitation of the bus wheels

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**Abstract**

The air-pressure-controlled hydraulic shock absorbers of axles' air suspension are capable of changing their damping forces in dependence on air pressure in air springs. Due to the possibility of improving dynamic properties of all vehicles that use the axles' air suspension, BRANO a.s., the Czech producer of shock absorbers, developed semi-active air-pressure-controlled hydraulic telescopic shock absorbers. The force-velocity characteristics of the controlled shock absorbers were designed on the basis of relative deflections of the air springs. As a criterion for the design of the optimum characteristics of the controlled shock absorbers the maximum similarity of dynamic responses of multibody models of the SOR C 12 bus for all the considered weights to the dynamic response of the reference multibody model was chosen. Time histories of relative deflections of the axles' air springs determined during the simulations are compared. Simulations of running over an obstacle with all the wheels were originally chosen (symmetric kinematic excitation of wheels). Verification of the suitability of the designed force-velocity characteristics of the APCSA described in this paper is performed on the basis of the simulations of general kinematic excitation of wheels. Driving on the artificially created test track according to the ŠKODA VÝZKUM methodology was chosen.


*Keywords:* vehicle dynamics, multibody model, controlled shock absorber, air spring deflection, bus

## 1. Introduction

In 2003, in order to improve the dynamic properties of buses and heavy vehicles, BRANO a.s., the producer of shock absorbers for those types of vehicles, started to develop semi-active hydraulic telescopic shock absorbers controlled by air pressure (see fig. 1). The hydraulic telescopic shock absorber controlled by air pressure is capable of changing its damping force depending on the air pressure in air springs. If the air pressure in the springs rises with increasing vehicle load the shock absorber damping force increases, too. If the vehicle load decreases the pressure in the springs drops and causes a decrease in the damping forces of the shock absorbers. Thus the vehicle keeps a constant driving stability and comfort during various operational situations. This property of the air-pressure-controlled shock absorber (APCSA) can be advantageously used in a suspension design.

The SOR C 12 intercity bus (see fig. 2), produced by SOR Libchavy, spol. s r. o., was the reference vehicle, for which the research and development of the shock absorbers was done and on which the shock absorbers were verified. The main question was which force-velocity characteristics of the shock absorbers could be appropriate for different weights of the vehicle.

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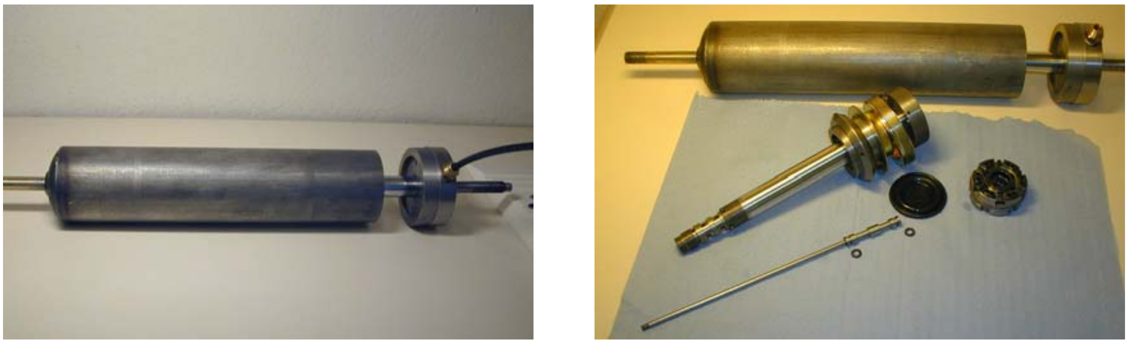

Fig. 1. The air-pressure-controlled hydraulic shock absorber and its structural members

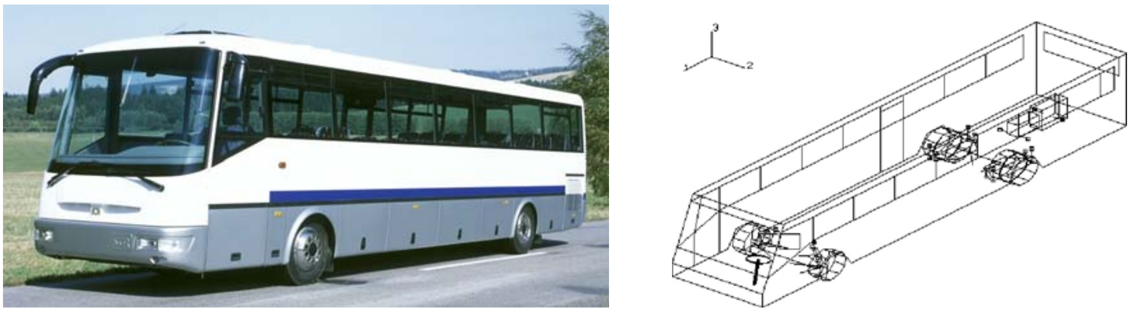

Fig. 2. The SOR C 12 intercity bus — the real vehicle and the multibody model visualization

The answer was found using the results of the computer simulations with the bus multibody models.

Multibody simulations had already been used for developing and improving damping properties of the vehicles' suspension. The influence of various control strategies on vehicle handling properties and a ride comfort are discussed and compared in [5]. Many articles deal with the optimum damping properties with respect to the ride comfort of a driver and passengers. The approximation concept [4] is proposed and used for the stroke-dependent damper design. The application to a military vehicle is shown in [9] and a so called vibration dose value based on the computation of accelerations is employed as the ride comfort criterion [10]. The ride comfort of a heavy truck is also improved in [6] using RMS values of accelerations as an objective function. The principles of the shape optimization were used for the suspension design with respect to the optimum ride comfort and riding safety in [2]. A real time damper system suitable for the optimum vehicle handling properties was proposed in [1]. A road friendliness is another criterion in the suspension design. For that purpose a dynamic load stress factor leading to the improvement of road-tire forces is used in [20].

In comparison with the above mentioned selected papers, in which the optimum behaviour was characterized by the minimization of some chosen variables, the optimum behaviour of the shock absorbers in case of the APCSA of the axles' air suspension of the SOR C 12 intercity bus was determined directly by the producer. On the basis of the shock absorbers producer's experience the operational situations in the field of vehicles vertical dynamics were chosen for the design of the optimum force-velocity characteristics of the shock absorbers. Operational situations in the field of a lateral dynamics (i.e. driving manoeuvres) or a longitudinal dynamics (i.e. start or braking) are influenced by the shock absorbers behaviour not as significantly as in the case of the vertical dynamics. For the design of the force-velocity characteristics of the APCSA (which should lead to the defined optimum dynamic behaviour of the vehicle) the objective function was proposed and used in [12, 13, 14, 15, 16] and [17].

As a criterion for the design of the optimum force-velocity characteristics of the semi-active APCSA (see fig. 1) the maximum similarity of dynamic responses of the multibody models of the SOR C 12 bus for various vehicle weights to the dynamic response of the multibody model of the bus of the reference vehicle weight was chosen. Time histories of the relative deflections of the axles' air springs determined during the simulations are compared [1]. Simulations of running over an obstacle (modified obstacle according to ČSN 30 0560 Czech Standard — see fig. 5) with all the wheels citepol1 were originally chosen (symmetric kinematic excitation of wheels). Verification of the suitability of the designed force-velocity characteristics of the APCSA described in this paper is performed on the basis of the simulations of general kinematic excitation of wheels. Driving on an artificially created test track according to the ŠKODA VÝZKUM methodology was chosen (e.g. [19]; see fig. 4).

Suitability of the designed force-velocity characteristics of the controlled shock absorbers of the axles' air suspension of the SOR C 12 intercity bus was evaluated according to other criteria (e.g., [3, 20]). Those criteria are the keeping of the acceleration of the sprung mass within the reasonable limits from the point of view of a driver and passengers (investigated in [13]), minimizing the relative displacement of the engine with respect to the chassis (investigated in [15]) or keeping the amplitude of the tire-road vertical contact forces within reasonable limits (investigated in [16]). But the criterion of the maximum similarity of time histories of the relative deflections of the axles' air springs was the best from the point of view of the APCSA design [13, 15, 16]. This criterion was used at the verification of the suitability of the designed force-velocity characteristics of the APCSA on the basis of the simulations of an asymmetric kinematic excitation of wheels [17] (determination of force-velocity characteristics of the APCSA at symmetric excitation of the wheels was evaluated as more suitable).

The aim of the work is to verify the originally designed force-velocity characteristics of the APCSA of the SOR C 12 intercity bus [12, 14].

## 2. Multibody models of the SOR C 12 intercity bus

Force-velocity characteristics of the APCSA of the axles' air suspension of the SOR C 12 intercity bus (see fig. 1) are designed on the basis of results of computer simulations with the bus multibody models (see fig. 2) created in the *alaska* simulation tool [7].

Multibody models of an empty (i.e., of the curb weight), a fully loaded (i.e., of the maximum weight) and three variants of a partly loaded vehicle were created. Two variants of multibody models of the partly loaded bus (20 % and 50 % of the maximum load) were created because of the design of the force-velocity characteristics of the APCSA for those states of the vehicle load. The third variant of multibody models of the partly loaded bus (71.5 % of the maximum load) corresponds to the weight of the real vehicle during the operational tests performed at the Hoškovice airport in September 2004. The 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 load was the result of operational tests. The vehicle load was realized using barrels filled with water, which were placed on the bus seats and floor. This optimum setting of the force-velocity characteristics of the non-controlled shock absorbers was performed taking into account the BRANO a.s. testing engineers' experience. On the basis of records of the experimental measurements documented in [8], the created multibody models of the SOR 12 C bus loaded to 71.5 % of the maximum load were verified at the same time. As a matter of fact, the

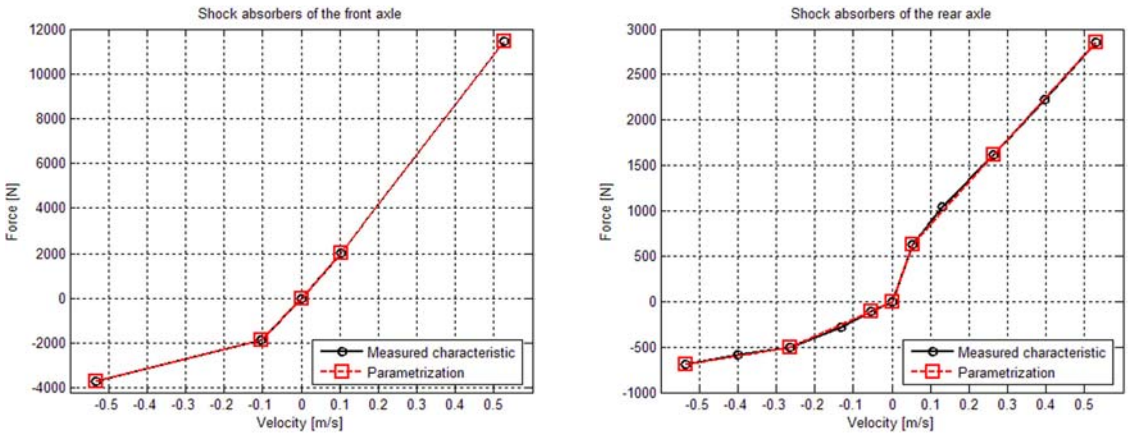


Fig. 3. The force-velocity characteristics of non-controlled shock absorbers of the front and rear axles of the SOR C 12 intercity bus and their parametrization

coordinates of the centre of mass of the bus body, which could not be determined more exactly due to discrete load realized by the barrels filled with water, were given in more detail.

The SOR C 12 intercity bus multibody models are described in [11, 12] or [14] in detail.

## 3. The methodology of the verifying the optimum force-velocity characteristics design of the controlled shock absorbers

As a criterion for the design and verifying the design of the optimum force-velocity characteristics of the semi-active APCSA the maximum similarity of time histories of the relative deflections of the air springs of the SOR C 12 bus multibody models for various vehicle weights to the time histories of the relative deflections of the air springs of the bus multibody model of the reference vehicle weight was chosen. The reference multibody model was the bus model with the same load as during the experimental measurements with the real vehicle at the Hoškovice airport [8].

Simulations of running over an obstacle (a modified obstacle according to ČSN 30 0560 Czech Standard — see fig. 5) with all the wheels [1] were originally chosen (symmetric kinematic excitation of wheels). The suitability of the designed force-velocity characteristics of the APCSA is evaluated on the basis of simulation of general kinematic excitation of wheels at driving on the artificially created test track according to the ŠKODA VÝZKUM road vehicles testing methodology (see fig. 4).

### *3.1. Parametrization of the problem*

In the case of tuning the force-velocity characteristics of the shock absorbers it is evident that the design parameters are the quantities defining the course of the force-velocity characteristics. The force-velocity characteristics of the non-controlled shock absorbers of the SOR C 12 bus (see fig. 3) used in the computer simulations were obtained by measuring on a special test stand under specific operational conditions. After processing the measurement, dependence of damping force $F$ in the shock absorbers on relative velocity $v$ of the shock absorber rebound and compression was available.

The values of measured damping forces $F_i$, ($i = 1, 2, \ldots, N$, where $N$ is the number of the force-velocity characteristic points), which will be changed during a tuning process, were chosen to be the design parameters (like in [12, 13, 14, 15, 16] and [17]). In practice it is

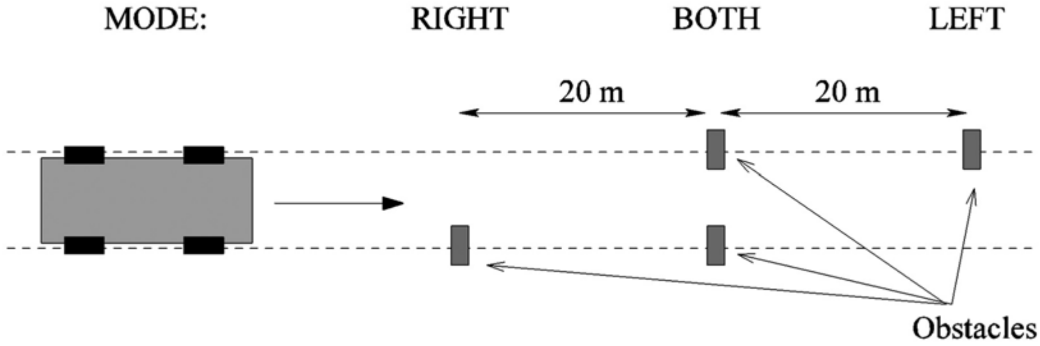


Fig. 4. Scheme of the track according to the ŠKODA VÝZKUM road vehicles testing methodology

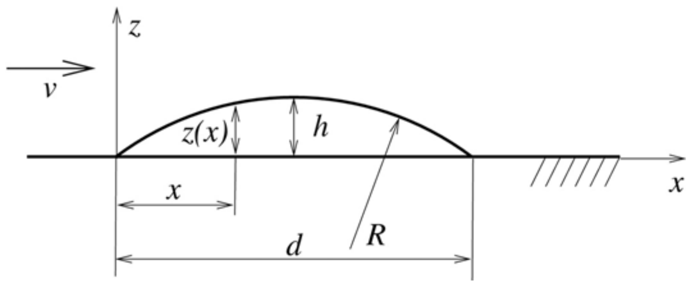


Fig. 5. The standardized artificial obstacle

not suitable to choose too many points because it is not possible to design a hydraulic shock absorber with too complicated course of the force-velocity characteristic. The requirement for the relatively small number of points of the characteristic as the design parameters is also suitable regarding the computational time of optimization. The design parameters are arranged into vector $\boldsymbol{p} = [F_1, F_2, \ldots, F_N]^T$.

The measured five-point force-velocity characteristic of the front axle hydraulic shock absorbers was parametrized in all non-zero points (see fig. 3). The measured eleven-point characteristic of the rear axle hydraulic shock absorbers (in fig. 3, a full line with circular markers) included too many points the position of which could be tuned for the optimization process. That is why the original characteristic was reduced to a seven-point one (in fig. 3, a dashed line with square markers). The 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 optimization process.

### *3.2. Choice of the objective function*

The specification of the objective function, which should clearly quantify the degree of the objective achievement, is a further step in solving the problem. At first it had to be decided for which operational situation the force-velocity characteristics of the APCSA would be optimized. Simulations of driving on a artificially created test track according to the ŠKODA VÝZKUM road vehicles testing methodology (see fig. 4) were chosen. The test track according to the ŠKODA VÝZKUM road vehicles testing methodology (e.g. [19]) consists of three standardized artificial obstacles (according to the Czech Standard ČSN 30 0560 Obstacle II — see fig. 5) 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. 4) at bus speed 40 km/h. I.e. the simulation of another driving situation than in [12, 13, 14, 15, 16] (or [17]), was chosen.

Vertical coordinates of the standardized artificial obstacle $z(x)$ are given by the formula

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

where $R = 551$ mm is the obstacle radius, $h = 60$ mm is the obstacle height, $d = 500$ mm is the obstacle length and $x$ is the obstacle coordinate in the vehicle driving direction.

Dynamic responses of the vehicle from the moment immediately prior to running over the obstacle with front wheels to 6 seconds of the simulation (practically decay of the responses) were compared. Time histories of relative deflections of the axles' 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 load in all cases.

The approach based on the calculation of the statistical quantities that express directly the relation between two time series was chosen (like in [12, 13, 14, 15, 16] or [17]) for the design of the force-velocity characteristics of the APCSA.

Correlation coefficient $R(\boldsymbol{p})$ defined for two discrete time series $x^{(1)}$ (the relative deflections of the air springs of the bus loaded to 71.5 % of the maximum load) and $x^{(2)}(\boldsymbol{p})$ (the relative deflections of the air springs of the bus of other examined weights, function of design parameters $\boldsymbol{p}$) [18] was calculated

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

where $\mu_1$ and $\mu_2(\boldsymbol{p})$ are mean values of the appropriate time series and $n$ is the number of the member of the discrete time series $x^{(1)}$ and $x^{(2)}(\boldsymbol{p})$. The correlation coefficient values range between zero and one. The more the compared time series are similar to each other, the more the correlation coefficient tends 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 a simple calculation. In order to verify the designed force-velocity characteristics of the APCSA the problem was formulated (like in [12, 13, 14, 15] or [16]) as the minimization of the objective function

$$\psi(\boldsymbol{p}) = \left[1 - R(\boldsymbol{p})\right]^2. \tag{3}$$

### 3.3. *The optimization procedure*

The whole optimization procedure is summarized in figs. 6 and 7. The methodology can be divided into two loops. The first one is shown in fig. 6 and together with tab. 1 it describes the procedure of the subsequent selection of the force-velocity characteristics and their design for the particular bus weights. The initial designs of the force-velocity characteristics and the constraints defining bounds in the optimization process are given in tab. 1. The second inner loop is shown in fig. 7. It illustrates the design procedure for the given force-velocity characteristic of the APCSA.

In order to guarantee the applicability of the optimized force-velocity characteristics within the whole range of the required operational velocities (approx. between $-0.5$ m/s and $0.5$ m/s)

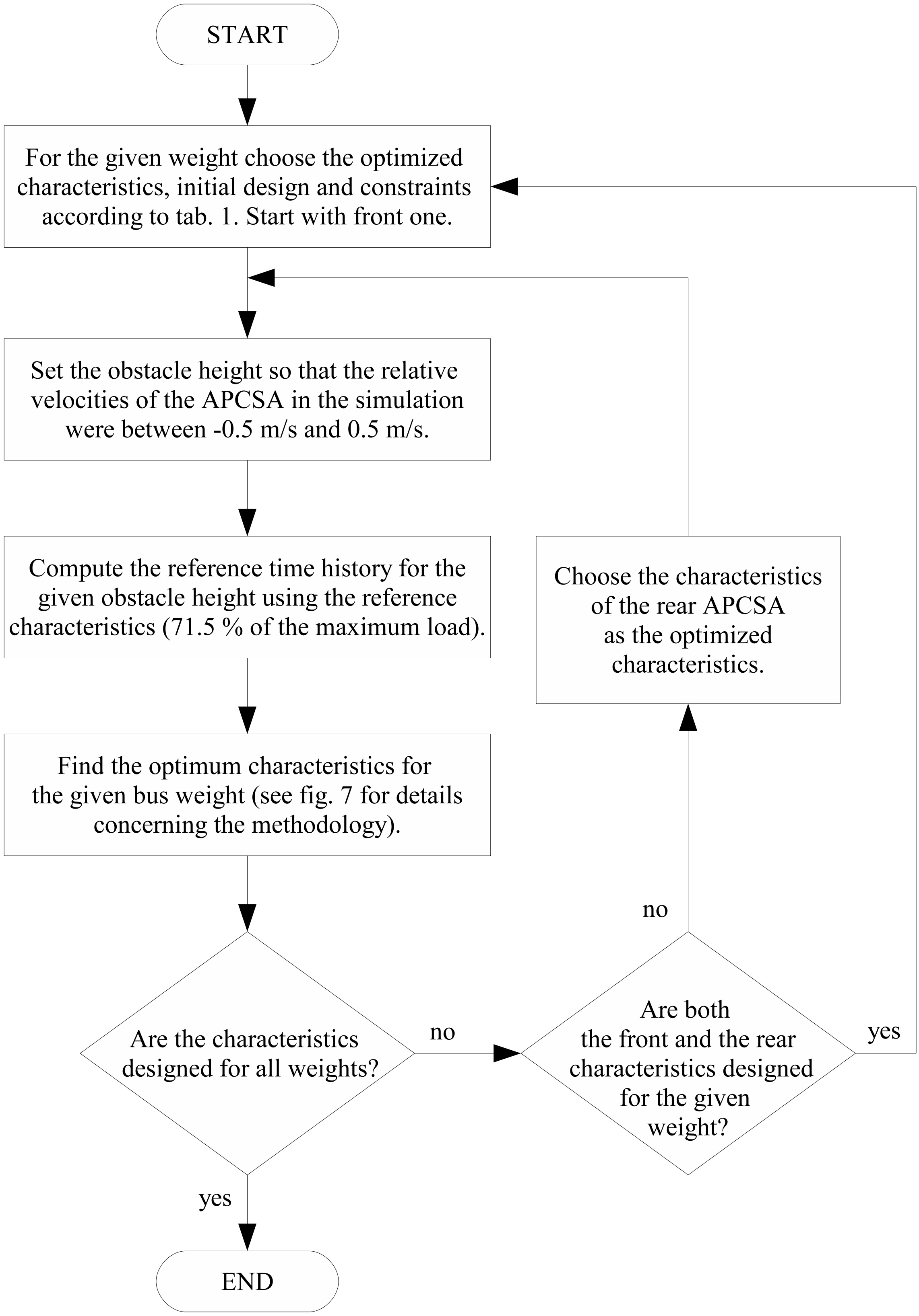


Fig. 6. The methodology of the design of the APCSA optimum characteristics

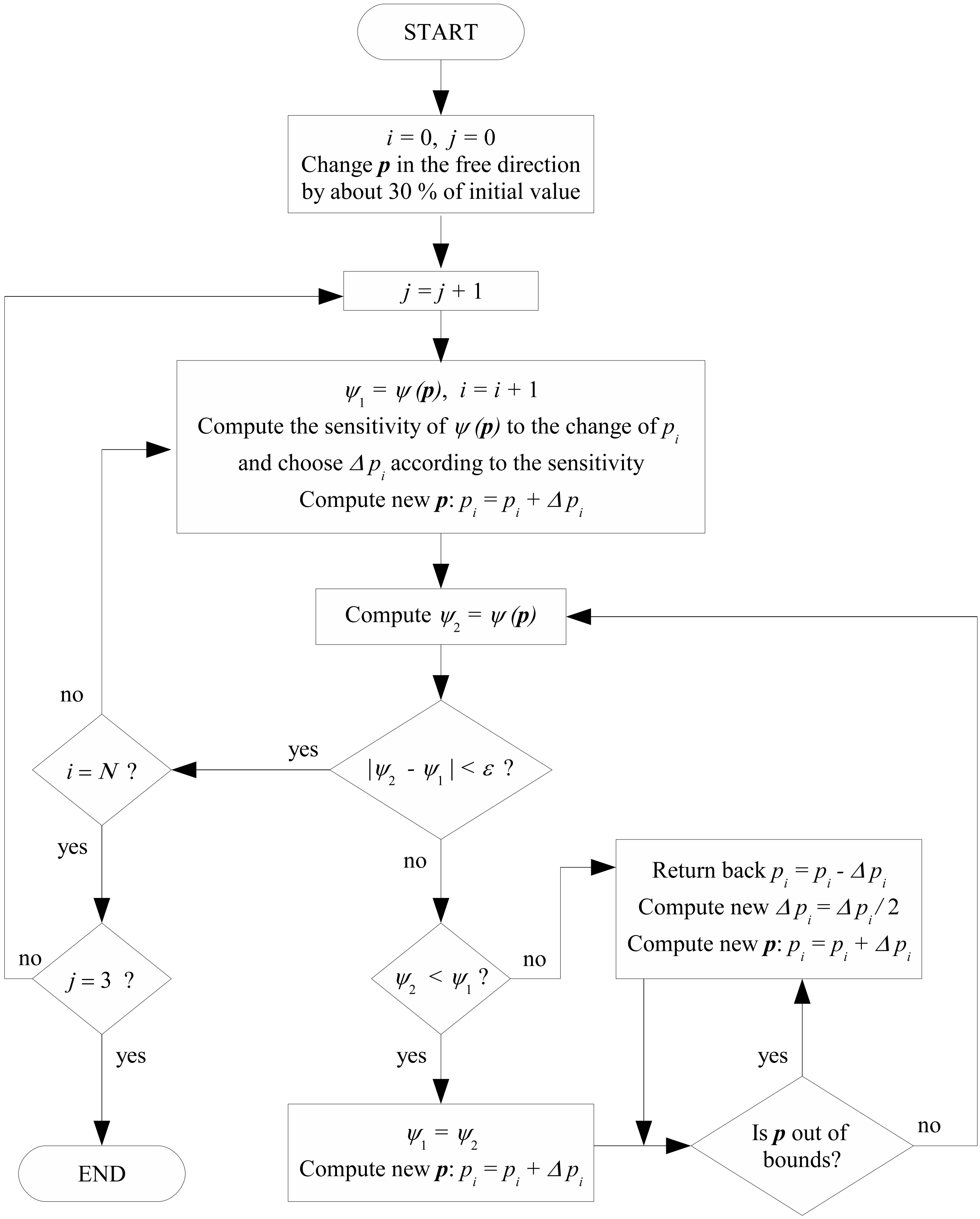


Fig. 7. The optimization methodology for the design of the APCSA characteristics for the given bus weight

Table 1. The initial designs and the constraints defining bounds in the optimization process of the force-velocity characteristics of the APCSA

| Step | Optimized force-velocity characteristics for the bus weight | Initial design of the force-velocity characteristics | Constraints |
|---|---|---|---|
| 1st | Fully loaded bus | 71.5 % of the maximum load | 71.5 % of the maximum load (lower bound for $v > 0$, upper bound for $v < 0$) |
| 2nd | 50 % of the maximum load | 71.5 % of the maximum load | 71.5 % of the maximum load (upper bound for $v > 0$, lower bound for $v < 0$) |
| 3rd | 20 % of the maximum load | Optimum design for 50 % of the maximum load | Optimum design for 50 % of the maximum load (upper bound for $v > 0$, lower bound for $v < 0$) |
| 4th | Empty bus | Optimum design for 20 % of the maximum load | Optimum design for 20 % of the maximum load (upper bound for $v > 0$, lower bound for $v < 0$) |

Table 2. Summary of the used obstacle heights in tuning the force-velocity characteristics of the shock absorbers

| Bus weight | Obstacle height in tuning | |
|---|---|---|
| | Force-velocity characteristics of the front axle shock absorbers | Force-velocity characteristics of the rear axle shock absorbers |
| Empty bus | 0.016 0 m | 0.012 0 m |
| 20 % of the maximum load | 0.024 5 m | 0.013 0 m |
| 50 % of the maximum load | 0.025 0 m | 0.013 5 m |
| Fully loaded bus | 0.025 0 m | 0.013 5 m |

the height of the artificial obstacle during the particular cycles (see fig. 6) was changed in such a way that the extremes of the time histories of the shock absorbers velocities might get closer to the required limits. Operational velocities of the shock absorbers were given on the basis of the producer's demands. Limit velocities, for which the producer is able to guarantee their damping properties on the basis of the customers' requirements, are concerned. The specific obstacle heights used in the optimization of the force-velocity characteristics of the shock absorbers for the various bus weights are summarized in tab. 2.

In order to automatically calculate the correlation coefficient and compare two numerical time series of the same length, the *Data Comparer* in-house software [12] was programmed in the MATLAB system.

## 4. Force-velocity characteristics of the air-pressure-controlled shock absorbers of the SOR C 12 bus

The optimum force-velocity characteristics of the APCSA of the SOR C 12 bus axles' suspension for various vehicle weights were designed during the simulations with the bus multibody models using the described methodology (figs. 8 and 9 show the example of the time histories of the relative deflections of the air springs before and after optimizing the force-velocity characteristics of the shock absorbers).

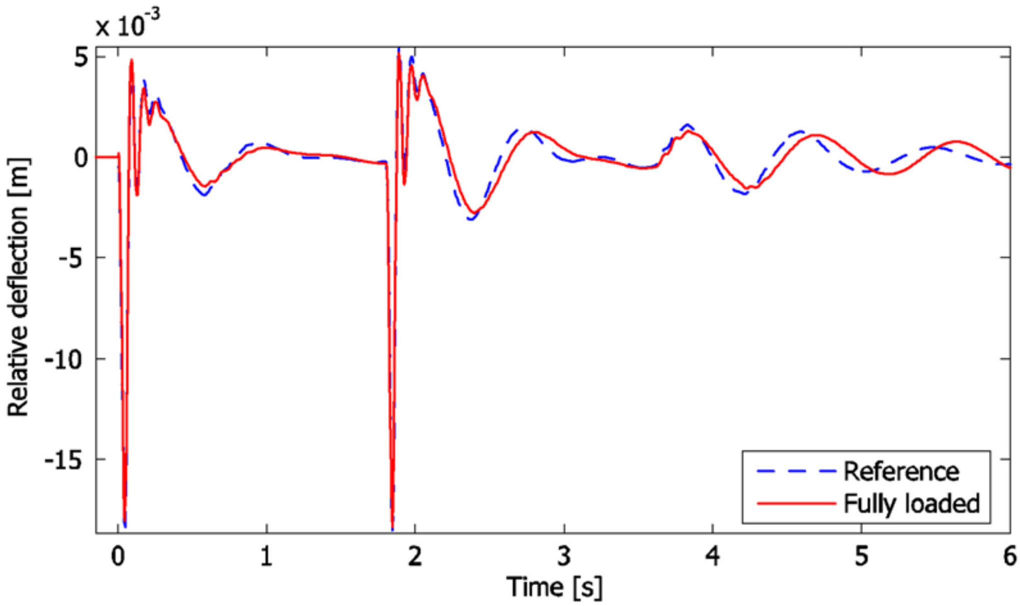


Fig. 8. Time histories of relative deflections of the right front air spring of the fully loaded bus and of the bus of the reference load (comparison of the reference case with the original force-velocity characteristics)

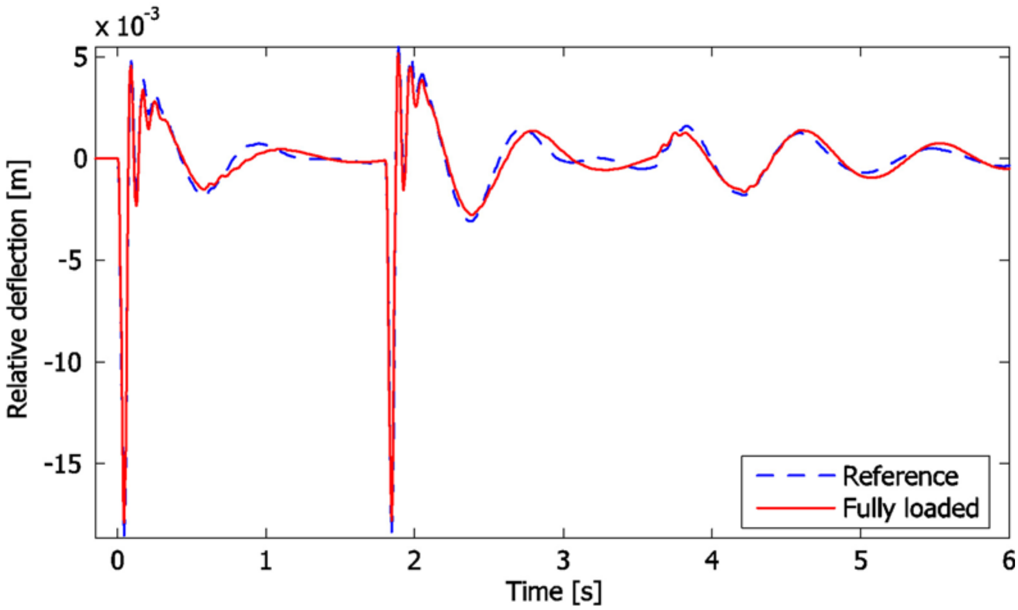


Fig. 9. Time histories of relative deflections of the right front air spring of the fully loaded bus and of the bus of the reference load (comparison of the reference case with the optimally tuned force-velocity characteristics)

From comparing the originally designed [12, 14] and the verified force-velocity characteristics of the APCSA of the front and rear axles of the SOR C 12 intercity bus in figs. 11 and 12 (the characteristics are linearly interpolated between the points in which the characteristics were tuned) it is evident that the verified force-velocity characteristics have less variance of points for all the considered vehicle weights, i.e. the range of magnitudes of forces is narrower than the originally designed force-velocity characteristics.

In fig. 10 there are differences of the right front air spring relative deflections of the fully loaded bus and of the bus of the reference load (comparison of the original and optimally tuned force-velocity characteristics). From the courses of relative deflections differences improvement in coincidence is not evident at first sight. The courses are given by the chosen approach based on the calculation of the scalar value of the correlation coefficient for the design of the force-velocity characteristics of the APCSA. It is necessary to note that the value of the correlation coefficient (equation (2)) changes (in the case of tuning the force-velocity characteristics of the APCSA of the front axle of the fully loaded bus) from the original value $0.985\,5$ to the value $0.988\,0$ at optimally tuned force-velocity characteristics (the value of correlation coefficient at total coincidence of two discrete series is 1). In order to prove the efficiency of the optimization process another quantity can be used for the difference evaluation. The norm of both curves in fig. 10 was evaluated according to

$$\|\varepsilon\| = \int_0^T |\varepsilon(t)| \, \mathrm{d}t, \tag{4}$$

where $\varepsilon(t)$ is the difference of two time histories. The value of this norm is $0.002\,07$ for the difference between the original and the reference time histories of the relative air spring deflections. The value of the norm for the difference between the optimized and the reference time histories is $0.001\,67$. It is obvious that the second value means a better coincidence of the optimally tuned and the reference dynamic response in comparison with the original dynamic response and the reference dynamic response.

The characters of designed force-velocity characteristics of the APCSA, when comparing time histories of the relative deflections of the axles' air springs determined during the simulations of running over the obstacle (symmetric excitation of wheels) and determined during the simulations of driving on the artificially created test track (general excitation of wheels), are similar. Both in the originally designed and the verified force-velocity characteristic of the rear axle shock absorbers of the fully loaded bus at speed 0.264 m/s a certain singularity occurs — see fig. 12. The singularity follows from the used methodology of optimization (on the basis of the scalar value of the correlation coefficient) and from the nonlinear character of numerical simulations [12, 14].

## 5. Conclusion

The modified methodology for the design of the force-velocity characteristics of the semi-active air-pressure-controlled shock absorber (APCSA) described in [12, 14] is used for the verification of the originally designed force-velocity characteristics of the APCSA of the axles' air suspension of the SOR C 12 intercity bus.

As a criterion for both the design and the verifying of the design of the optimum force-velocity characteristics of the semi-active APCSA the maximum similarity of time histories of the relative deflections of the air springs of the SOR C 12 bus multibody models for various vehicle weights to the time histories of the relative deflections of the air springs of the multibody

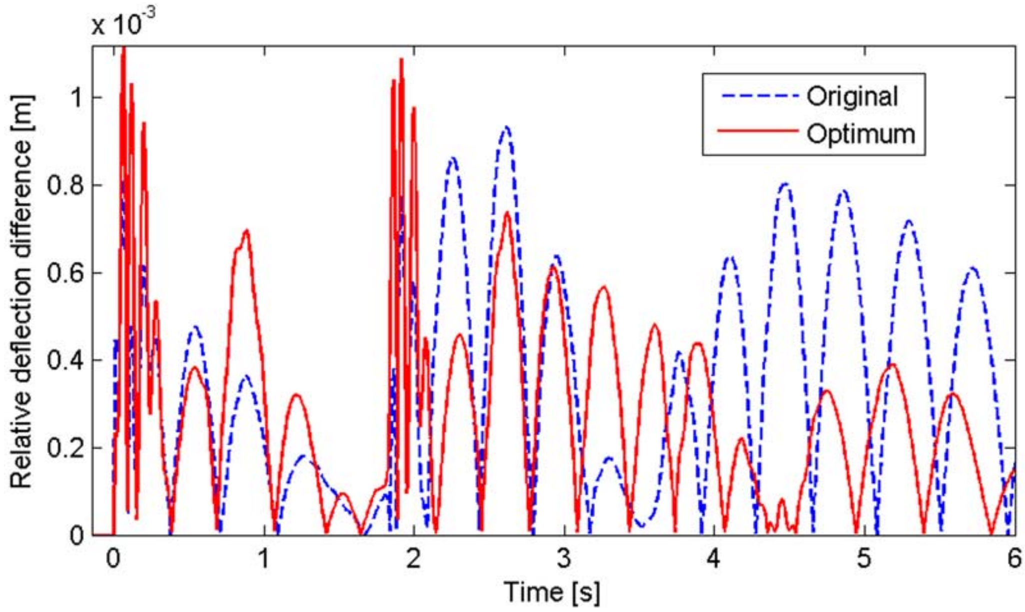


Fig. 10. Differences of time histories of relative deflections of the right front air spring of the fully loaded bus and of the bus of the reference load (comparison of the original and the optimally tuned force-velocity characteristics)

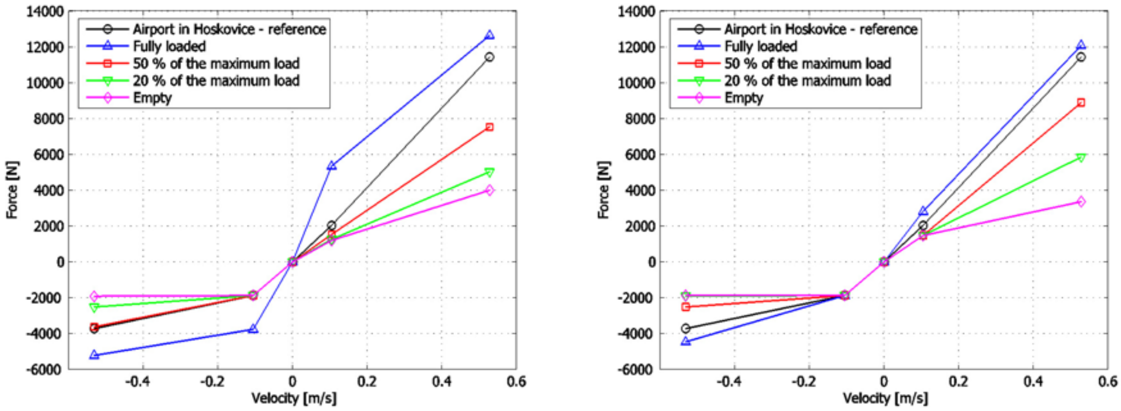


Fig. 11. The originally designed [12, 14] and the verified force-velocity characteristics of the APCSA of the front axle of the SOR C 12 intercity bus

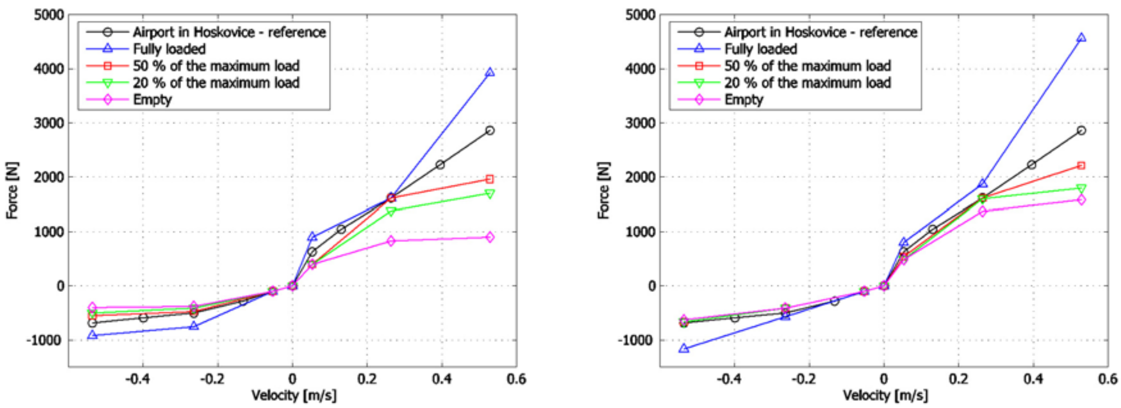


Fig. 12. The originally designed [12, 14] and the verified force-velocity characteristics of the APCSA of the rear axle of the SOR C 12 intercity bus

model of the bus of the reference vehicle weight was chosen. Simulations of running over an obstacle with all the wheels were originally (i.e. for the design of the APCSA) chosen (symmetric kinematic excitation of wheels). Verification of the suitability of the designed force-velocity characteristics of the APCSA is performed on the basis of the simulations of general kinematic excitation of wheels at driving on the artificially created test track according to the ŠKODA VÝZKUM road vehicles testing methodology (e.g. [19]). The test track consists of three standardized artificial obstacles spaced out on the smooth road surface 20 meters apart. The first obstacle of the artificially created test track is run over only with right wheels, the second one with both and the third one only with left wheels at bus speed 40 km/h.

The values of the damping forces in the selected points of the force-velocity characteristics of the non-controlled shock absorbers were the design parameters of the optimization problem. The correlation coefficient between the dynamic responses of the vehicle under the reference load (the bus loaded to 71.5 % of the maximum load) and the vehicle under the other loads was used as a suitable criterion for the evaluation of the responses similarity.

The designed force-velocity characteristics of the APCSA, when comparing the time histories of the relative deflections of the axles' air springs determined during the simulations of running over the obstacle (symmetric excitation of wheels) and determined during the simulations of driving on artificially created test track (general excitation of wheels), are similar. Though it seems to be evident that the approach to the design of force-velocity characteristics of the APCSA at the general kinematic excitation of wheels is the most correct, "higher-quality" (from the point of view of the real APCSA function) characteristics at acting only the symmetric kinematic excitation of wheels were determined. The range of the force-velocity characteristics determined at acting only the symmetric kinematic excitation of wheels is larger (except for rebound field of rear APCSA of the loaded bus at the rear shock absorber relative velocity 0.5 m/s) and thus it offers more possibilities at shock absorbers adjustment for the given operational conditions. This fact follows from the verification of force-velocity characteristics determined at acting only the asymmetric kinematic excitation of wheels, during which the force-velocity characteristics in a smaller range of magnitudes of forces [17] were obtained. At acting general kinematic excitation of wheels the influence of the symmetric excitation is "suppressed" by the asymmetric excitation and consequently the determined characteristics have a narrower range of magnitudes of forces. Evaluation of results at the general kinematic excitation of wheels is also more demanding and time consuming at these simulations. From these points of view the originally used characteristics' determination only at the symmetric excitation of the wheels seems to be more suitable.

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