TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics and Mechanics
Vol. 56, Issue IV, November, 2013

HALF-CAR VERTICAL DYNAMICS USING CARSIM SOFTWARE

Dan N. DUMITRIU, Octavian Daniel MELINTE, Victor VLĂDĂREANU

Abstract: This paper presents half-car vertical dynamics results obtained using CARSIM software. A sinusoidal road profile is considered here for testing purposes. The presented results concern vertical displacements and accelerations, the pitch angle evolution, the damping and spring forces and the tire vertical forces, the suspension jounces/rebounds, the damper compression rate and damping law. These results are presented for the front and rear wheels of the car. Since a simplified half-car 2D model ("bicycle" model) is considered and the road profile is the same for the left and right wheels, there is no difference here between the motion of the left side of the car and its right side. Thus, only the pitch motion of the car is taken into account by the simplified 2D "bicycle" model, neglecting the roll motion and other lateral and longitudinal motions of the car. Further work will study the full car model, including lateral and longitudinal forces as well.
Key words: *CARSIM software, car vertical dynamics, jounce, rebound, pitch angle, damper force, spring force, compression rate.*

1. INTRODUCTION

The Institute of Solid Mechanics of the Romanian Academy has a strong tradition in vibrations of road and railway vehicles and concerning the study and optimization of suspensions behavior. The researches in this field have been started 35-40 years ago by Sireteanu et al. [1], being continued nowadays by Niculescu, Dumitriu, Sireteanu et al. [2-5]. Recently, a CARSIM software license has been purchased, in the framework of PN-II-PT-PCCA-2011-3.1-0190 research project, entitled "Reconfigurable Haptic Interfaces used in Dynamic Contact Reproduction - Theoretical and Experimental Developments".

The CARSIM simulations are aimed to complete the studies performed using an in-house car vertical dynamics simulator written in Matlab/Simulink. Our studies are focused on finding appropriate suspension shock absorbers to improve both wheel-road adherence and passengers comfort. In fact, A.-I. Niculescu has invented a new self-adjustable suspension shock absorber [2], with a line of holes laterally disposed, allowing a stepwise automatic change of the relative damping, according to the piston position.

Using the in-house Matlab/Simulink simulator, Niculescu, Dumitriu et al. [3] have firstly used a quarter-car model with 2 DOF (degrees of freedom), to simulate the vertical interaction between a rear car wheel and the road. Still using the in-house Matlab/Simulink simulator, the second step has been to consider a half-car 2D model for the vertical interaction between car and road. This 2D model is also called "bicycle" model and considers the pitch motion of the car [4] (but neglects the roll motion, which can be considered simultaneously only by a 3D model). This "bicycle" model has 4 DOF: the vertical displacement of the mass center of the sprung mass (bounce), the pitch angle, the vertical displacement of the front wheel center (front wheel hop) and the vertical displacement of the rear wheel center (rear wheel hop).

This paper uses CARSIM for "bicycle" model simulations. In fact, CARSIM simulates a complete 3D model, concerning not only the vertical dynamics, but also the lateral and longitudinal motions. But the considered case study, with the same sinusoidal road profile for both the left and right wheels, simplifies the problem to a 2D "bicycle" model.

2. CARSIM MODEL AND CAR VERTICAL DYNAMICS EQUATIONS

CARSIM software is a well-known 3D car dynamics simulator [6]. The simulations performed using CARSIM represent virtual experiments, which can be considered almost as accurate as real experiments, since CARSIM software is already validated by thousands of previous studies.

Fig. 1 shows the CARSIM model for a so-called "C-Class Hatchback" car, presented more in detail in the case study section.

CarSim 8.1.1 vehicle-suspension multibody model [6] is *"represented mathematically by 113 ordinary differential equations that describe the kinematical and dynamical behavior. This full model is composed of 32 bodies, has 16 multibody DOF, 41 multibody coordinates, 49 auxiliary coordinates, 16 multibody speeds, 7 auxiliary speeds, and has 127 active forces and 93 active moments".*

In this paper, due to the symmetry of the problem concerning the road profile, which is the same for both left and right wheels, the complete 3D model used by CARSIM can be simplified in a 2D "bicycle" model, as shown in Fig. 2. Only the vertical dynamics is studied here, neglecting the lateral and longitudinal motions and slips. Thus, the problem is simplified, since only the vertical behavior is studied, neglecting lateral and longitudinal motions and slips.

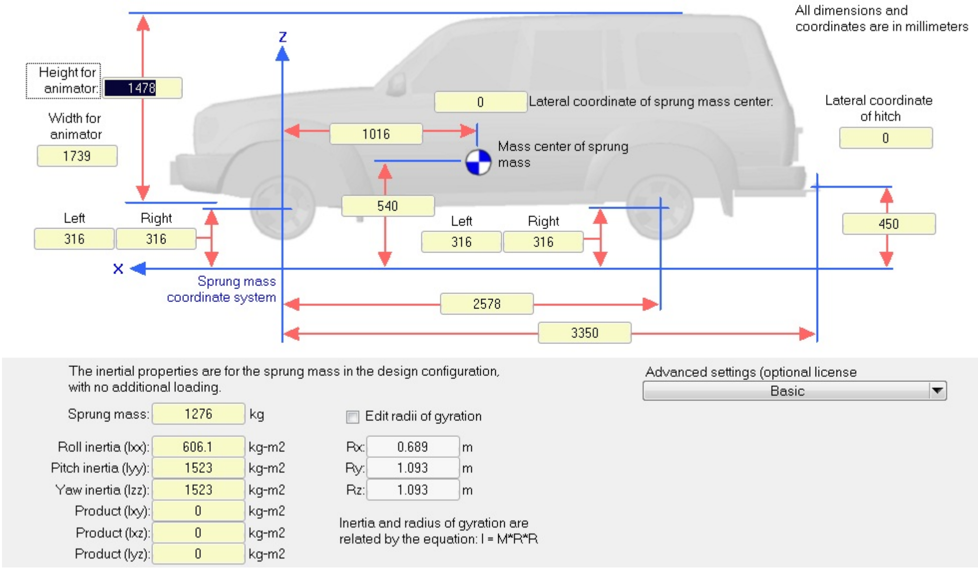

Fig. 1. CARSIM 3D model of a "C-Class Hatchback" car.

The "bicycle" model shown in Fig. 2 has 4 DOF: the vertical displacement z_{CG} of the mass center of the sprung mass (bounce), the pitch angle α, the vertical displacement z_3 of the front wheel center (front wheel hop) and the vertical displacement z_4 of the rear wheel center (rear wheel hop).

At time t, the vertical profile of the road (road roughness) corresponding to the front wheels is denoted by $z_{01}(t)$, being considered the same for the left and for the right front wheel, so that to obtain a 2D simulation when using the 3D CARSIM model. The road roughness corresponding to the rear wheel, both left and right, is denoted by $z_{02}(t)$.

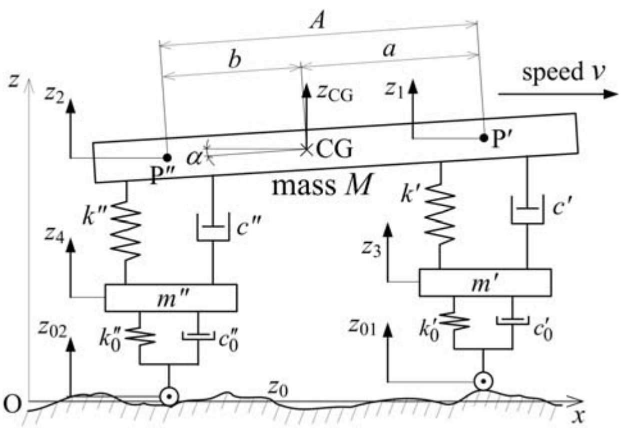

Fig. 2. Half-car 2D simplified "bicycle" model.

Obviously, the rear wheels encounter after $\Delta t \cong \frac{A\cos\alpha}{v}$ the same road profile already encountered by the front wheels, $z_{01}(t) = z_{02}\left(t + \Delta t\right)$.

The model contains two levels of elastic and damping elements: one level between the wheels and the road, characterized by the stiffness coefficients k_0' and k_0'' of the tires and the damping coefficients c_0' and c_0'' of the tires; the second level between the wheels and the body (vehicle suspension), characterized by the spring rates of suspension k' and k'' and the damping coefficients c' and c'' of the shock absorbers. Here $'$ corresponds to front wheels, while $''$ corresponds to rear wheels.

The simplified 2D "bicycle" model for studying the car/road vertical interaction implies the following geometrical and inertial characteristics:

- the distance a between the mass center CG of the sprung mass M and the point P′ located on the vertical axis passing through the front wheel center;
- the distance b between the mass center CG of the sprung mass M and the point P″ located on the vertical axis passing through the rear wheel center;
- the car wheelbase A (obviously $A=a+b$);
- the front unsprung mass m', i.e., the mass of one front wheel plus half of the mass of the front axle;
- the rear unsprung mass m'', i.e., the mass of one rear wheel plus half of the mass of the rear axle;
- the mass M of the car body (sprung mass M), which normally takes values between M_{empty} (unloaded car case, including only seat+driver and fuel masses) and M_{full} (maximum admissible car loading case);
- the moment of inertia $I_\alpha = I_{yy}$ of the sprung mass M with respect to the transversal y axis passing through the mass center CG of the sprung mass.

The vertical dynamics equations of the simplified 2D "bicycle" model are written using Newton-Euler formulations. By neglecting the aerodynamic forces, one obtains the following two dynamics equations of the sprung mass [1,7] (one in terms of forces and the other in terms of moments with respect to the mass center CG):

$$\begin{cases} M\ddot{z}_{\text{CG}} = -F_c' - F_c'' - F_e' - F_e'' + F_{e,\text{bumper}}' + F_{e,\text{bumper}}'' \\ I_\alpha \ddot{\alpha} = aF_c' - bF_c'' + aF_e' - bF'' - aF_{e,\text{bumper}}' + bF_{e,\text{bumper}}'' \end{cases} \quad (1)$$

where F_c' and F_c'' are the front and rear damping forces given by the shock absorbers, usually depending on the damper compression rates $v_{13} = \dot{z}_1 - \dot{z}_3$ and $v_{24} = \dot{z}_2 - \dot{z}_4$, as follows: $F_c' = c'(\dot{z}_1 - \dot{z}_3)^2$, $F_c'' = c''(\dot{z}_2 - \dot{z}_4)^2$. Concerning the spring forces $F_e' = k'\Delta z_{13}$ and $F_e'' = k''\Delta z_{24}$, they depend on the spring compressions $\Delta z_{13} = z_1 - z_3$ and $\Delta z_{24} = z_2 - z_4$, where the vertical displacements z_1 and z_3 of points P′ and P″ can be expressed as functions of z_{CG} and α, as follows: $z_1 = z_{\text{CG}} + a\sin\alpha$, $z_2 = z_{\text{CG}} - b\sin\alpha$. Here Δz_{13} and Δz_{24} denote the additional spring compression with respect to the static equilibrium position (in which the springs are already pre-compressed to support the weight of the car). Finally, $F_{e,\text{bumper}}'$ and $F_{e,\text{bumper}}''$ represent the elastic striking forces when the piston hits either the rebound bumper ($F_{e,\text{bumper}} < 0$ case) or the compression bumper ($F_{e,\text{bumper}} > 0$ case), as detailed in [4].

For the "bicycle" model, the two dynamic equations of the front and rear wheels are [1,7]:

$$\begin{cases} m'\ddot{z}_3 = F_c' + F_e' - F_w' - F_{e,\text{bumper}}' \\ m''\ddot{z}_4 = F_c'' + F_e'' - F_w'' - F_{e,\text{bumper}}'' \end{cases} \quad (2)$$

where $F_w' = k_0'(z_3 - z_{01}) + c_0'(\dot{z}_3 - \dot{z}_{01})$ and $F_c'' = k_0''(z_4 - z_{02}) + c_0''(\dot{z}_4 - \dot{z}_{02})$ are the front and respectively rear tire vertical forces, comprising the elastic and also the damping force of the tire.

The second order differential equations of motion (1) and (2) can be easily transformed in a system of 8 first order explicit ordinary differential equations, which can be integrated using the 4th-order Runge-Kutta method.

3. CASE STUDY AND RESULTS

The CARSIM simulations presented here concern a simple sinusoidal road profile, with an amplitude of 0.03 m (3 cm) and a frequency of 3 Hz: $z_0(t) = z_{01}(t) = 0.03\sin(2\pi\cdot 3\cdot t)$ [m]. The purpose of such testing simulations is to acquire a correct knowledge of CARSIM software use and to draw possible interesting conclusions. As already mentioned, a symmetrical problem is considered here, i.e., the road profile for the left wheels is the same with the one for the right wheels. Thus, the "bicycle" model applies.

The following geometrical, inertial and elastic characteristics are considered in this case study:

- $a = 1.016$ [m], wheelbase $A = 2.578$ [m], $b = A - a = 1.562$ [m];
- sprung mass $M = 1.276$ [t];
- pitch inertia $I_\alpha = 1.523$ [$t\cdot m^2$];
- front unsprung mass $m' = 31.5$ [kg];
- rear unsprung mass $m'' = 30$ [kg];
- spring rates $k' = k'' = 30.57$ [kN/m] of front and rear suspensions;
- stiffness coefficients of the tires $k_0' = k_0'' = 228$ [kN/m].

The simulations are performed for a constant car speed of $v = 60$ [km/h].

The results of the CARSIM vertical dynamics simulation for the case study above are summarized in Figs. 3-11. Fig. 3 shows the vertical displacements of the mass center of the sprung mass and of the front and rear wheels, as well as the considered sinusoidal road profile. Fig. 4 shows the derived accelerations of the sprung mass and of the front and rear wheels. The motion of the car is described also by the pitch angle and its rate (Figs. 5 and 6).

Figure 7 shows the front vertical forces: the front tire vertical force, the front suspension damping force and spring force. According to the first equation (2), their difference must be approximately equal to $m'\ddot{z}_3$. This verification has been performed and is shown in Figure 7.

The rear forces and the same verification between $m''\ddot{z}_4$ versus the difference of forces as indicated by the right term of the second equation (2) are shown in Figure 8.

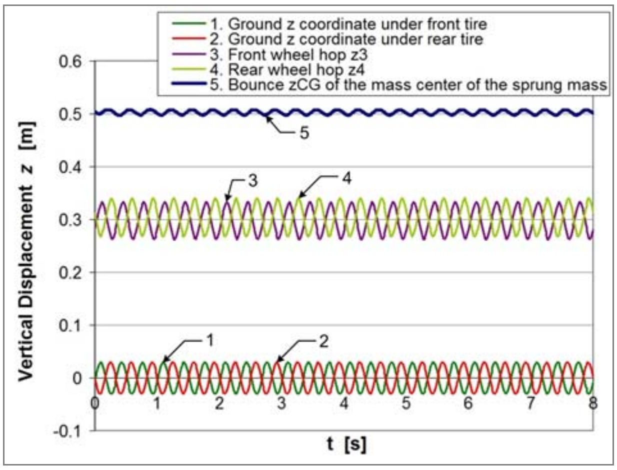

Fig. 3. Vertical displacements [mm].

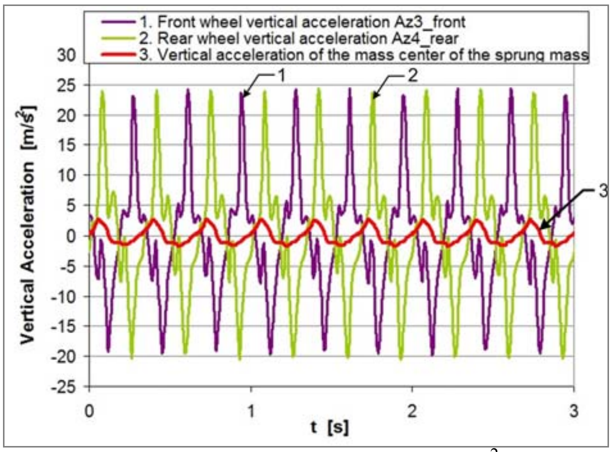

Fig. 4. Vertical accelerations [mm/s^2].

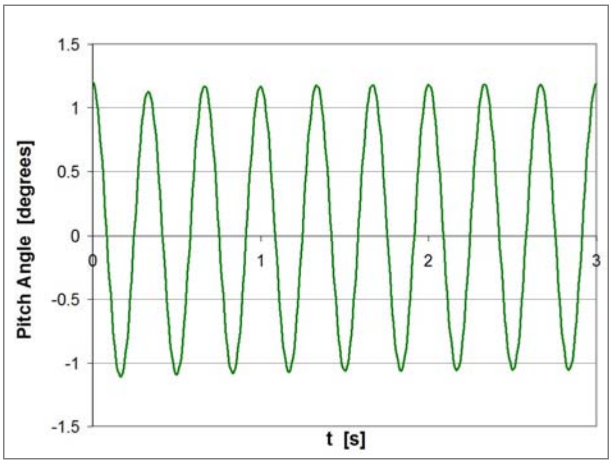

Fig. 5. Pitch angle [º].

In order to be able to represent the damping law, Figure 9 shows the suspension jounces and the tire compressions, while Figure 10 shows the damper compression rates.

By representing in Figure 11 the damping forces (the ones already shown in Figs. 7 and 8) as function of the damper compression rates, the verification concerning the damping law is performed successfully. Thus, no abnormalities were found during this case study.

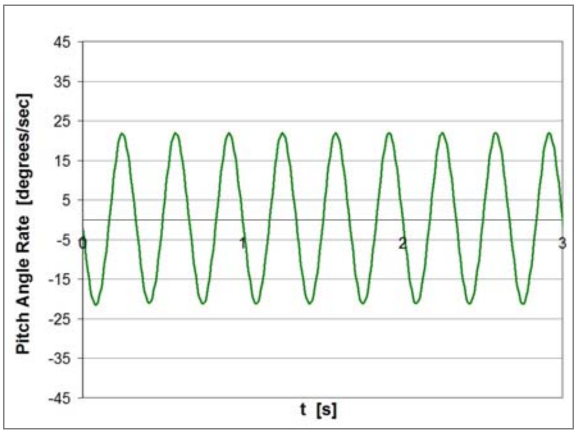

Fig. 6. Pitch angle rate [º/s].

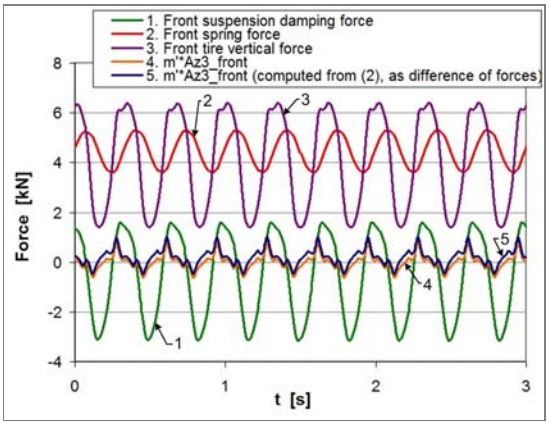

Fig. 7. Front vertical forces [kN].

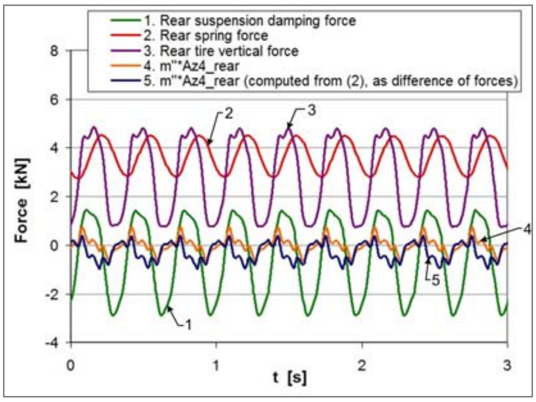

Fig. 8. Rear vertical forces [kN].

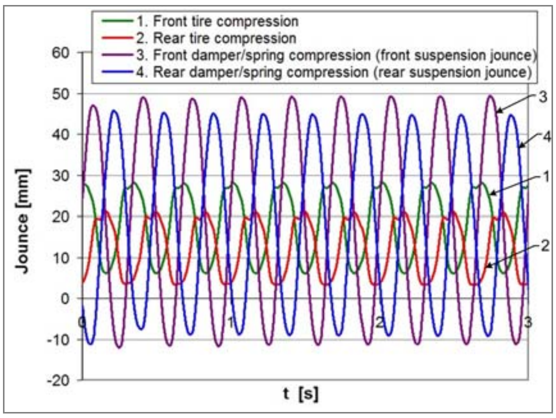

Fig. 9. Suspension and tire jounces [mm].

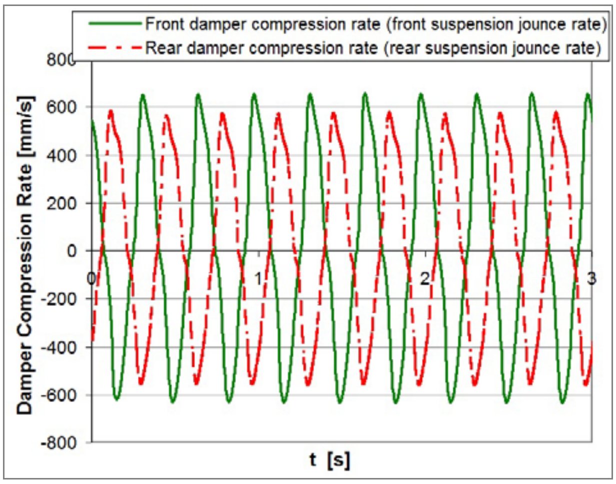

Fig. 10. Damper compression rates [mm/s].

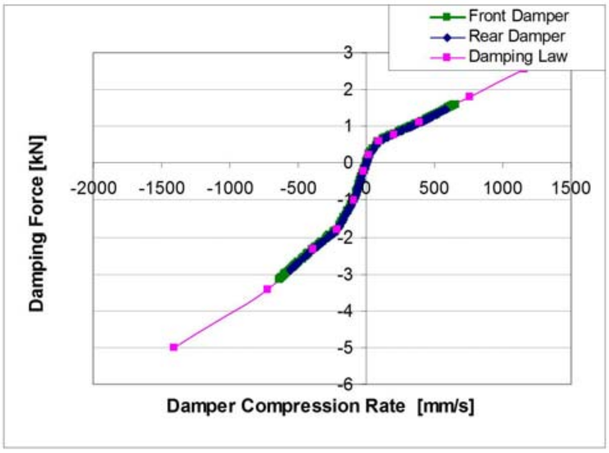

Fig. 11. Considered damping law and verification.

4. CONCLUSION AND FUTURE WORK

This paper presents a case study for the vertical car dynamics, neglecting other lateral and longitudinal motions. The simulations are performed using CARSIM software, but an in-house simulator written in Matlab/Simulink is also available. The links between CARSIM and the in-house simulator are shown in this paper by means of the dynamics equations of the simplified "bicycle" model.

Further work will concern the testing using CARSIM of the performances of a new shock absorber [2] already tested using the in-house simulator [3-5]. Different driving and road scenarios will also be considered as further case studies, in order to realize a road response simulator, designed as a haptic interface that includes real-time wheel/road dynamic contact simulation in its control system.

ACKNOWLDGEMENT:
The authors gratefully acknowledge the financial support of the National Authority for Scientific Research ANCS/UEFISCDI through the PN-II-PT-PCCA-2011-3.1-0190 project, contract no. 149/2012.

REFERENCES

[1] Sireteanu, T., Gündisch, O., Părăian, S., *Random vibrations of road vehicles (in Romanian: Vibrațiile aleatoare ale automobilelor)*, 1981, Editura Tehnică, Bucharest.
[2] Niculescu, A.-I., *The self-adjustable shock absorber, with self-correcting damping characteristic*, European Patent EP1190184, 2005 (Romanian Patent OSIM RO 118546/2004: *Amortizor autocorector, cu caracteristică disipativă autocorectoare*).
[3] Niculescu, A.-I., Dumitriu, D., Sireteanu, T., Alexandru, C., *The new self-adjustable shock absorber-VZN*, Proceedings of the 31st FISITA World Automotive Congress, Yokohama, Japan, October 22-27, 2006.
[4] Niculescu, A.I., Dumitriu, D., Sireteanu, T., *Half-Car 2D Model Simulation of the Self-Adjustable VZN Shock Absorber Suspension Behavior*, Proceedings of the 9th WSEAS International Conference on Acoustics & Music: Theory & Applications (AMTA'08) , pp. 35-40, ISSN 1790-5095 / ISBN 978-960-6766-74-9, Bucharest, June 24-26, 2008, WSEAS Press, http://www.wseas.us/e-library/conferences/2008/bucharest/amta/04amta.pdf.
[5] Dumitriu, D., *Car vertical dynamics 3D simulator using a 7 DOF model*, Acta Technica Napocensis, Series: Applied Mathematics and Mechanics, vol. 55, no. III, pp. 647-650, 2012, ISSN 1221-5872.
[6] Mechanical Simulation Corporation, *CARSIM*, http://www.carsim.com/
[7] Demić, M., Diligenski, Đ., Demić, I., Demić, M., *A method of vehicle active suspension design*, Forschung im Ingenieurwesen (Engineering Research), vol. 70, no. 3, pp. 145-158, September 2006, Springer, ISSN 0015-7899.

Dinamica verticală a modelului bicicletă al autovehiculului folosind programul CARSIM

Rezumat: Lucrarea prezintă rezultate folosind programul CARSIM ale dinamicii verticale ale modelului "bicicletă" al unui autovehicul. Simulările au fost efectuate pentru un profil sinusoidal al drumului. Rezultatele privesc deplasările verticale ale caroseriei şi ale roților, evoluția unghiului de tangaj al caroseriei, forțele de amortizare şi din arcurile suspensiei, forțele verticale la nivelul roților, cursele pistoanelor din amortizoare şi vitezele pistoanelor, pentru a putea reprezenta/verifica curbele de amortizare. Rezultatele prezentate se referă atât la roțile din față cât şi la cele din spate. Folosindu-se un model "bicicletă" simplificat, mărimile considerate/rezultate sunt identice pentru roțile din stânga şi cele din dreapta. Modelul "bicicletă" consideră doar mişcarea de tangaj a caroseriei, nu şi pe cea de ruliu sau alte mişcări laterale şi longitudinale. Simulări viitoare vor considera un model mai complet al dinamicii autovehiculului, considerând şi forțele laterale şi longitudinale.

Dan DUMITRIU, PhD. in Mechanics, Scientific Researcher 3rd degree (CS3), Institute of Solid Mechanics of the Romanian Academy, 15 Ctin Mille, 10141 Bucharest, www.imsar.ro, Department of Deformable Media and Ultrasonics, E-mail: dumitri04@yahoo.com, dumitriu@imsar.bu.edu.ro, Phone: +(40)721397848.
Octavian Daniel MELINTE, PhD Student and Scientific Researcher at the Institute of Solid Mechanics of the Romanian Academy, 15 Ctin Mille, 10141 Bucharest, www.imsar.ro, Department of Robotics and Mechatronics, E-mail: octavian.melinte@yahoo.com
Victor VLĂDĂREANU, PhD Student at University "Politehnica" Bucharest, Researcher in the framework of the PN-II-PT-PCCA-2011-3.1-0190 project at the Institute of Solid Mechanics of the Romanian Academy, E-mail: vladareanuv@gmail.com