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ADVANTAGES OF USING TWO-WAY ADJUSTABLE DAMPER TO IMPROVE SOLAR VEHICLE SUSPENSION PERFORMANCE

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Abstract - In this paper, two mathematical damper models are analyzed using quarter car model. Analysis is based on the solar vehicle build by students from Lodz University of Technology. First damper is characterized by symmetry between compression and rebound action, second one is described by Spencer model and reproduce two-way adjustable hydraulic device. It provides control over rebound and compression force, hence asymmetric characteristics can be created. The purpose of this paper is to present the possibilities of improving the vertical dynamics of a solar vehicle by using two-way adjustable damper. Quarter car models are forced by single excitation imitating road bump. The comparative analysis is made proving advantage of two-way adjustable damper for solar vehicle. The biggest advantage is significant reduction in vehicle settling time after hitting the bump.

Keywords: Quarter car model, Spencer model, passive suspension, solar vehicle, two-way adjustable hydraulic damper.

I. INTRODUCTION

Vibrations of vehicles influence their performance, safety and ride comfort. Main element that reduce effect of vibrations on vehicle dynamics is suspension. Properties of suspension system are mainly defined by tires, geometry (which means position and length of metal members and shock absorbers with respect to wheel and chassis), stiffness of the suspension and finally by the properties of a damper, what is the subject of this work [1]. A damper is a dissipative element that creates resistance force for a suspension system in vertical direction with respect to the road [2]. When a car hit a bump significant amount of force is trying to set suspension in motion. That motion is restricted by damper possessing piston that is ramming oil through bump and rebound valves. Hence, when a car spring is compressed, it does not rebound with all the accumulated elastic potential energy. Due to damper's motion the energy is dissipated in the form of heat inside the device. The primary function of the damper is to damp sprung and unsprung masses of the vehicle. The sprung mass consists of chassis and all the parts mounted to it, whereas unsprung mass includes components not supported by springs. Those are: part of suspension arms, brakes caliper, brake discs, wheel, in-wheel electric motor and tire. The second function of dampers is to control the rate of weight transfer during accelerating, cornering and braking. [1] For the purpose of engineering investigation, the most commonly used model of damper is a simple cylinder filled with oil, that generates force proportional to its velocity. However, nowadays, automotive industry provides more advanced dampers. In such a device value of compression and rebound force differs, due to the fact that much heavier sprung mass is mainly controlled by rebound force [3]. In this paper, two different hydraulic damper models are presented and compared. Examined suspension system, that includes the dampers, is from solar vehicle "Eagle Two", built as a student project at Lodz University of Technology. Its intended use is to participate in international races such as iLumen European Solar Challenge and Bridgestone World Solar Challenge. The vehicle is classified to cruiser class, defined by efficiency and practicality, hence it can be treated as a passenger car. Nevertheless, construction of "Eagle Two" differs from typical car available on the market. The main differences are significantly lower unsprung and sprung mass, which are 15 [kg] and 134 [kg] respectively in case of quarter of the car (including passengers). Such a mass combination also induce unusually high ration between them, equal to about 9. During the race "Eagle Two" has to cover the distance of 3000 km with constant speed on a straight road that lack corners. That is why, suspension requirements focus on vertical dynamics. To study the vehicle suspension system quarter car model is used. The model involves tire and suspension parameters taking into account its geometry. Quarter car models are forced by single excitation and their performance is evaluated. The purpose of this paper is to present the possibilities of improving the vertical dynamics of a solar vehicle by using two-way adjustable damper, that provides control over compression and rebound force. Analysis was carried out using Matlab software and authorial programs.

II. SYSTEM MODELING

In this paper, two quarter car models are analyzed. Both are two degrees of freedom systems, with two masses m_1 and m_2 that represents sprung and unsprung mass respectively. Unsprung mass is supported by tire, characterized by damping coefficient c_0 and vertical stiffness k_0. In each case between two masses there are spring, representing suspension vertical stiffness, denoted by k_r and a damper, that distinguish two models. Quarter car model 1 (QCM 1), presented in the Figure 1, represents linear system with hydraulic viscous damper that generate force proportional to its velocity. Quarter car model 2 (QCM 2) refers to Figure 2. It includes damper characterized by asymmetry in compression and rebound action and it's asymmetric characteristic is given through modified Bouc-Wen model introduced by Spencer, known also as a Spencer model [4,5]. Representation of such a damper is presented in the Figure 3, it consists of system of springs and dampers and a massless element.

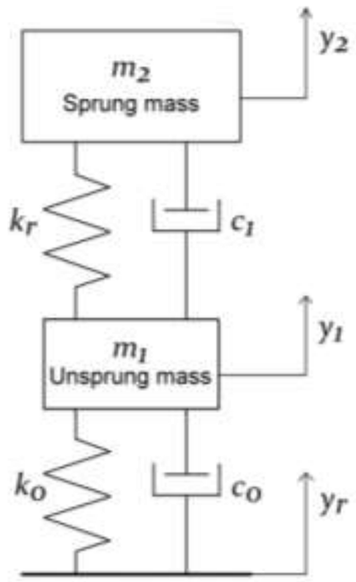

Figure 1 Quarter car model 1

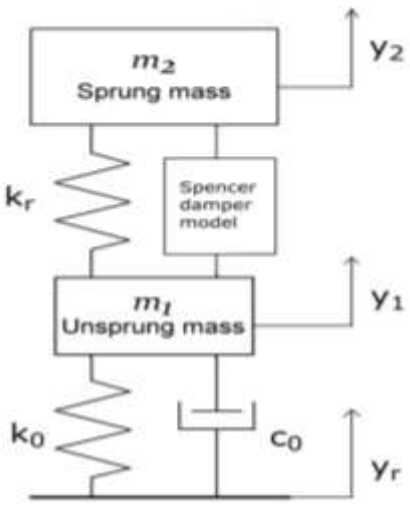

Figure 2 Quarter car model 2

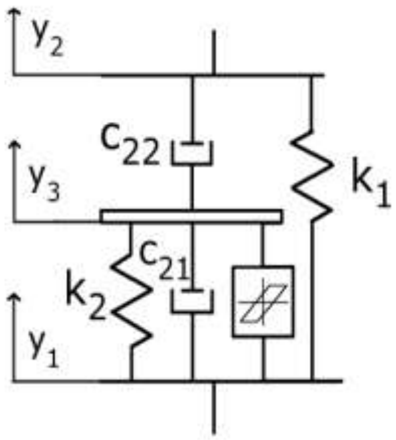

Figure 3 Spencer damper model

Equations of motion for model 1 were derived using Lagrange equations of second kind. Hence the final equations have a following form:

$$m_1\ddot{y_1} = -k_r(y_1 - y_2) - k_0(y_1 - y_r) - c_1(\dot{y_1} - \dot{y_2}) - c_0(\dot{y_1} - y_r) - m_1 g \quad (1)$$

$$m_2\ddot{y_2} = -k_2(y_2 - y_1) - c_1(\dot{x_2} - \dot{x_1}) - m_2 g \quad (2)$$

Motion of masses in model 2 are described by equations 3 and 4. Force generated by hydraulic damper, designated by F, is found by solving equations 5, 7 and 8 that accounts several parameters describing Spencer model (A_0, β_0, γ_0, α_0, k_1, k_2, c_{21}, c_{22}). Hydraulic damper described by Spencer damper model was initially introduced and analyzed in details by Łuczko [5].
Quarter car model 2 is described by set of following equations:

$$m_1\ddot{y_1} = -c_0(\dot{y_1} - \dot{y_0}) - k_0(y_1 - y_0) + k_r(y_2 - y_1) + F - m_1 g \quad (3)$$

$$m_2\ddot{y_2} = -k_r(y_2 - y_1) - F - m_2 g \quad (4)$$

$$F = F_0(1 + \varepsilon \mathrm{sgn} F_0) \quad (5)$$

$$F_0 = c_{22}(\dot{y_2} - \dot{y_3}) + k_2(y_2 - y_1) \quad (6)$$

$$c_{21}(\dot{y_3} - \dot{y_1}) + k_1(y_3 - y_1) + \alpha z_0 = c_{22}(\dot{y_2} - \dot{y_3}) \quad (7)$$

$$\dot{z_0} = A_0\dot{y} - \gamma_0\dot{y_1}|z_0|^n - \beta_0|\dot{y}||z_0|^{n-1}z_0 \quad (8)$$

$$y = y_3 - y_1 \quad (9)$$

For the further investigation following values of parameters common for both models are assumed: $m_1 = 15$ [kg], $m_2 = 134$ [kg], $k_0 = 200000$ [N/m] $k_r = 38000$ [N/m], $c_0 = 0$. Additionally, several extra parameters for Spencer damper model are determined, basing on literature and series of performed initial simulations: $A_0 = 80000\,[-]$, $\beta_0 = \gamma_0 = 1000\,[m^{-2}]$, $\alpha_0 = 100\,[N/m]$, $n = 2\,[-]$, $\varepsilon = 0.2\,[-]$, $k_1 = 0.02 * k_r\,[N/m]$, $k_2 = 0.01 * k_r\,[N/m]$

Both system are subjected to the same single excitation, given by equation:

$$y_r(t) = \frac{ht^a}{t^a + t_1{}^a} - \frac{ht^a}{t^a + (t_1+t_2)^a} \qquad (10)$$

Where:

h - define bumph height.

t_1 - position of the bump in time.

t_2- determine how fast the car goes through the bump.

a - determine bump steepness.

Single excitation was imitating road bump. Presented function provides control over the bump height and its duration in time. Assuming the width of the bumps 1 meter, velocity of the car is expressed by equation:

$$\text{Carvelocity} = \frac{s}{t_2} = \frac{1}{t_2} \qquad (11)$$

Simulations were performed with following values of excitation function coefficients: $h = 20$ [mm], $t_1 = 0.3$ [s], $t_2 = 0.05$ [s], $a = 60\,[-]$.

III. RESULTS AND DISCUSSION

System response for both quarter car models is presented in the Figures 4-6. Influence of viscous damping coefficient on settling time and maximum displacement amplitude (designated by A_{max}) for sprung mass is investigated. A_{max} is measured straightforward, by reading its value for the highest peak from the graph. Considering settling time, the system is said to be stable while the vibration amplitude is below 5e-05 [m].

According to Figure 4, in case of a model consisting of simple damper with linear characteristic between compression and rebound force, increasing damping coefficient generate reduction in settling time, what is favourable for transient manoeuvres and handling, however maximum displacement amplitude is significantly increased, what negatively influence ride comfort. In case of such a damper it is impossible to reduce both settling time and vertical travel of vehicle. Since the compression force mainly influence upward movement of the car and it should be minimized in order not to lift the car when it hit the bump. Whereas rebound force has an impact on downward movement of the car and it ought to be high enough to control mass of the car moving down after hitting the bump. Comparing all three curves for quarter car model 1 (Figure 4) damping coefficient equal to about 720 [Ns/m] generates amount of damping optimal for a solar vehicle. This value provides satisfying ride comfort and sufficient level of vehicle control [6]. According to Table 1 there is a difference of 60% in car displacement amplitude between optimal (720 [Ns/m]) and critical (2700 [Ns/m]) value of damping.

In case of quarter car model 2 consisting of Spencer damper model, increasing parameter c_{22} responsible for rebound force results in significant settling time reduction, at the same time the change of maximum displacement amplitude is minimized, what can be observed

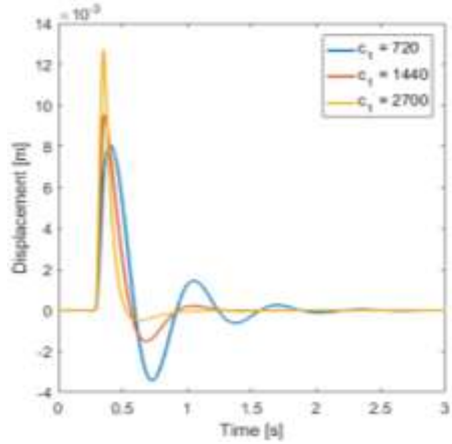

Figure 4 System response for quarter car model 1 for different values of c1. Blue line for c1=720, red line for c1=1440, yellow line for c1=2700.

Table 1 Max displacement amplitude and settling time for Quarter car model 1 and different values of c1

c_1 [Ns/m]	720	1440	2700
A_{max} [m]	0.0081	0.0094	0.0131
Settling time [s]	1.849	0.933	0.703

in the Figure 5 and in the Table 2. Parameter c_{21} was set to value of 720[Ns/m] that corresponds to viscous damping coefficient of simpler model. One can see that for value of c_{22}=2700 [Ns/m] maximum amplitude equals one received from optimal damping from car model 1 but settling time is reduced over three times.

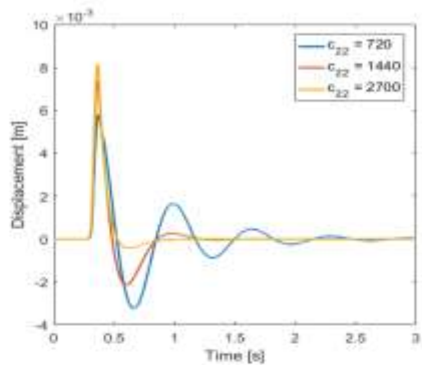

Figure 5 System response for Quarter car model 2 for different values of c22. Blue line for c22=720, red line for c22=1440, yellow line for c22=2700

Table 2 Max. displacement amplitude and settling time for Quarter car model 2 and different values of c22

c_{22} [Ns/m]	720	1440	2700
A_{max} [m]	0.0055	0.0075	0.0082
Settling time[s]	2.113	0.862	0.596

Figure 6 presents comparison of system response for model 1 and model 2, for the chosen values of damping coefficients. For the quarter car model 1, value c_1=720 [Ns/m] is presented as it is optimal for that type of passenger car. Damping coefficient c_{21} responsible mainly for compression in model 2 is set to 720 [Ns/m]. Value of c_{22} was set to 1440 [Ns/m].

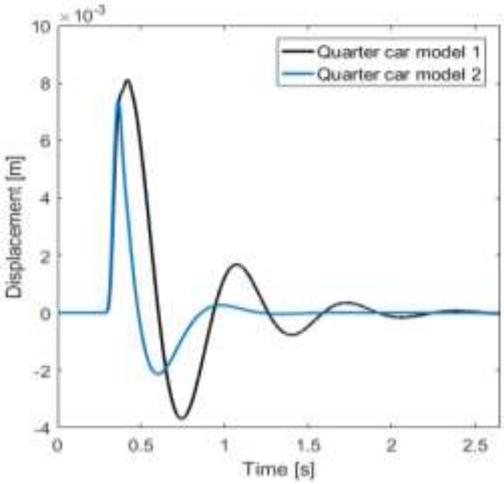

Figure 6 System response for both quarter models, for following parameters values: c1-720 Ns/m, c21-720 Ns/m, c22-1440 Ns/m. Quarter car model 1 - black line, quarter car model 2 - blue line

Spencer damper model reveal desired reduction in settling time, at the same time producing significantly lower value of maximum displacement amplitude what was not possible for simpler damper model used in quarter car model 1.

Table 3 Comparison of Max. displacement amplitude and settling time for two quarter car models

	QCM 1	QCM 2	Improvement [%]
A_{max} [m]	0.0081	0.0075	7.4
Settling time [s]	2	0.75	62.5

IV. CONCLUSION

Two different quarter car models representing solar vehicle Eagle Two are analyzed and forced with single excitation representing road bump. The performance of the suspension system is based on maximum sprung mass displacement and settling time. Quarter car model 1, including damper characterized by linear relation between compression and rebound force, produces significant raise of maximum displacement amplitude as a cost of settling time reduction. Contrary, quarter car model 2 generates great reduction in settling time, at the same time producing lower value of maximum displacement amplitude in comparison to model 1. According to obtained results, settling time is reduced by 64.5% and A_{max} by 7.4 %. Therefore, two-way adjustable damper can enhance the performance of the solar vehicle by improving vibration absorption.

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