Sastry et al. 2019. *Int. J. Vehicle Structures & Systems*, 11(1), 27-32
ISSN: 0975-3060 (Print), 0975-3540 (Online)
doi: 10.4273/ijvss.11.1.06

International Journal of
Vehicle Structures & Systems
Available online at www.maftree.org/eja

Analysis and Prediction of Performance of MR Damper at Different Currents and Control Strategies for Quarter Suspension System of a Roadway Vehicle

D.V.A. Rama Sastry[a, c], K.V.Ramana[a] and N. Mohan Rao[b]

[a]*Dept. of Mech. Engg., KoneruLakshmaiah Education Foundation, Vaddeswaram, Guntur, Andhra Pradesh, India*
[b]*Dept. of Mech. Engg., University College of Engg., JNTUK University, Kakinada, Andhra Pradesh, India*
[c]*Corresponding Author, Email: dvarsastry@kluniversity.in*

ABSTRACT:

Ride comfort and vehicle handling are the two major issues to be dealt in the design of suspension systems of automobiles. With passive systems offering contrariety on these two parameters, the alternative systems are being in study. Magnetorheological (MR) damper, a most feasible semi-active device, is one such alternative, which will offer the advantage of dealing with both these issues overcoming contrariety. In this study, the suspension system of a car using MR damper is analysed at 5 different currents viz., 0A, 0.25A, 0.5A, 0.75A, 1A, using 2DOF quarter car model and 4DOF half car models for ride comfort and handling and the comparisons of these are done with same suspension system equipped with regular passive damper. A MR damper is built-up using MR fluid consisting of carbonyl iron powder and silicone oil added with additive. Further, the characteristic of this damper is established by conducting experiments, which in turn is used to identify the parameters of Spencer model for MR damper. Using Spencer model of MR damper, at 5 different currents, the quarter car and half car models of vehicle suspension system are simulated by implementing a semi-active suspension system for analysing the resulting displacement and acceleration in the car body. The ride comfort and vehicle handling performance of each specific vehicle model with passive suspension system are compared with corresponding skyhook, ground hook and hybrid based semi-active suspension systems. The simulation and analysis are carried out using Matlab/Simulink.

KEYWORDS:

Magnetorheological dampers; Semi active suspension systems; Spencer model; Skyhook; Ground hook hybrid control

CITATION:

D.V.A.R. Sastry, K.V. Ramana and N.M. Rao. 2019. Analysis and Prediction of Performance of MR Damper at Different Currents and Control Strategies for Quarter Suspension System of a Roadway Vehicle, *Int. J. Vehicle Structures & Systems*, 11(1), 27-32. doi:10.4273/ijvss.11.1.06.

1. Introduction

Among various parameters that influence the performance of automobiles, ride comfort and vehicle handling are considered to be most crucial. The suspension system consisting of springs and the damper along with tires is responsible for these factors. Using passive suspension systems, one of these two needs to be compromised [1] and with usage of active suspension systems, the issues related to complexity, cost and stability will increase [2]. The emergence of semi-active suspension systems, especially magnetorheological (MR) damper, has led to many interesting studies in vibration control of vehicles [3]. MR damper is very much a hydraulic damper in construction, but with an electrical coil wound around the piston head and MR fluid which consists of suspensions of non-colloidal, multi-domain (0.05-10μm) and magnetically soft particles in organic or aqueous liquids[4]. MR fluid can change reversibly from free-flowing, linear viscous liquids to semi-solids having controllable yield strength under a magnetic field, which can be controlled using electric coil around piston head.

The apparent viscosity of MR fluid changes significantly (105-106 times) within a few milliseconds, when the magnetic field is applied [5]. There are various parametric models proposed to represent the behaviour of MR damper. The model proposed by Spencer [6, 7] modified Bouc-Wen model, is supposed to be most appropriate model among all the available models. In this paper, the suspension system of a car using MR damper is analysed at 5 different currents viz., 0A, 0.25A, 0.5A, 0.75A, 1A, using three different control strategies namely skyhook, ground hook and hybrid control strategies through 2DOF quarter car model for ride comfort and handling and the comparisons of these are done with same suspension system equipped with regular passive damper. In this study, lateral acceleration of sprung mass is considered to be the parameter that influences quality of ride and suspension travel and tyre displacement along with the lateral displacement of sprung mass are considered as parameters of study of vehicle handling [8].

2. Experimental setup and procedure

In order to conduct studies to identify the variation of damping force generated with variation in displacement and velocity of semi active damper, a MR damper with dimensions similar to existing car damper dimension is developed. MR damper consists of piston and cylinder arrangement with piston head assembly housing an electric coil. In this study, a coil consists of double wired parallel winding of a copper wire of 25 gauge for 200 turns, with a resistance of 3.5 ohms is used. To test the performance of the damper in terms of force with varying displacement and velocity, a damper test system, with 25kN capacity two column load frame, as shown in Fig. 1, is used. This test system consists of 15kN load cell, 15kN fatigue rated double acting, double ended actuator and is driven by 65 LPM hydraulic power pack system through SS digital servo controller in built with testing software. The experimental setup is used for testing of MR damper, at 5 different currents viz., 0A, 0.25A, 0.5A, 0.75A, 1A. Using data acquisition system connected to the system, the damping force data in variation to displacement caused by actuator motion as a sine wave with 0.1m amplitude, is acquired. The dimensions of MR damper are as given in Table 1.

Fig. 1: Experimental setup for testing MR damper

Table 1: Geometry of MR damper

Damper parameter	Dimension (mm)
Extended height	380
Compressed height	360
Stroke length	20
Damper tube length	300
Damper tube outer diameter	60
Damper tube inner diameter	50
Piston head diameter	48
Piston rod diameter	12

3. Modelling of MR damper using Spencer model

In this study, the Spencer's model, which is modified Bouc-Wen model, is considered to model MR damper is shown in Fig. 2. According to this Spencer's model, the damping force generated by the MR damper is given as

$$f_{MR} = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) = c_1(\dot{y}) + k_1(x - x_0) \quad (1)$$

$$\dot{z} = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y})$$

$$\dot{y} = \frac{1}{c_0 + c_1}\{\alpha z + c_0\dot{x} + k_0(x - y)\} \quad (2)$$

These equations are modelled in Matlab/Simulink and shown in Fig. 3. The values of various parameters mentioned in the above Eqns. are identified by considering the experimental data using parameter identification tool in Matlab/Simulink for 0A, 0.25A, 0.5A, 0.75A, 1A of current supply are shown in Table 2. The plots relating force generated by MR damper with time, displacement and velocity from the data obtained in experimental analysis are shown in Fig. 4 and that of MR damper Spencer model analysed in Matlab / Simulink are shown in the Fig. 5. It can be observed that the results obtained from Spencer model using Matlab / Simulink are comparable with experimental values and thus validates the Spencer model. Hence, the Spencer model is adopted to represent behaviour of MR damper for further analysing quarter car model in Simulink.

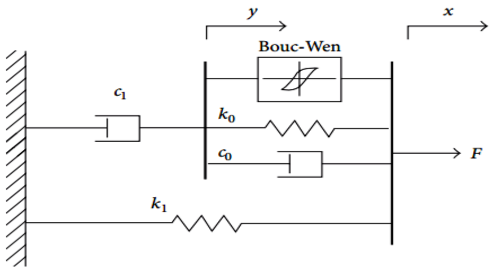

Fig. 2: Spencer model of MR damper

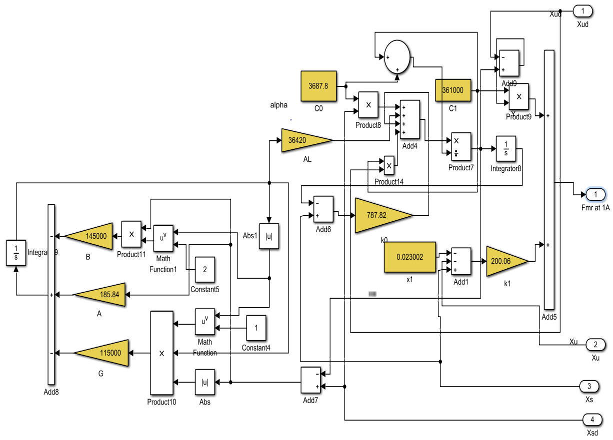

Fig. 3: Simulink modelling of phenomenological Spencer model of MR damper

Table 2: Spencer damper model parameters

Para-meters	0A	0.25A	0.5A	0.75A	1A
A	841.18	158.91	110.17	220.76	107.18
α (N/m)	3785.5	14832	48410	29502	65992
β (m^{-1})	6.34×10^{7}	16111	3.62×10^{5}	1.87×10^{5}	3.03×10^{5}
C_0(Ns/m)	3101.5	2847.2	3651.3	3397.2	3999.2
C_1(Ns/m)	23395	1.94×10^{5}	4.17×10^{5}	$4.24E\times10^{5}$	3.68×10^{5}
γ (m^{-1})	4346.8	1.99×10^{5}	2.08×10^{5}	66035	1.94×10^{5}
K_0 (N/m)	332.42	28.104	66.422	113.28	273.95
K_1 (N/m)	175.71	16.451	31.08	4.9029	36.22
X_0(N/m)	0.016	0.15	0.14	0.73	0.12
N	2	2	2	2	2

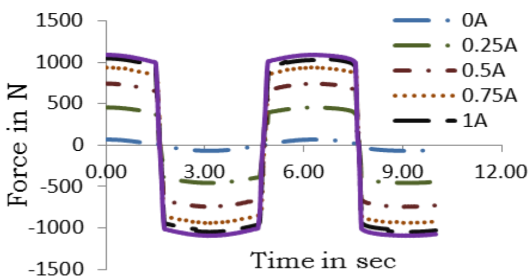

Fig. 4(a): Force Vs Time plots obtained from experimental analysis

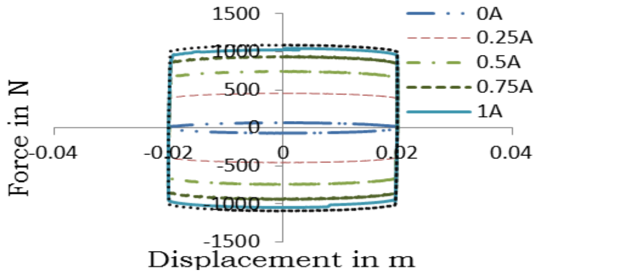

Fig. 4(b): Force Vs Displacement plots obtained from experimental analysis

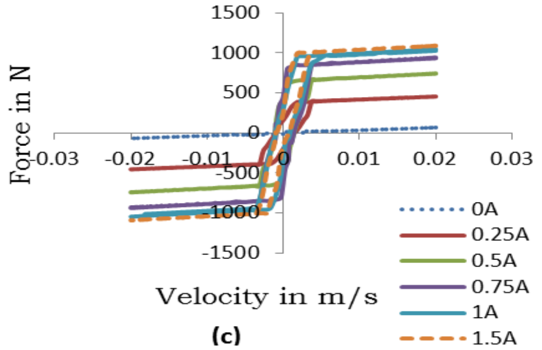

Fig. 4(c): Force Vs Velocity plots obtained from experimental analysis of MR damper

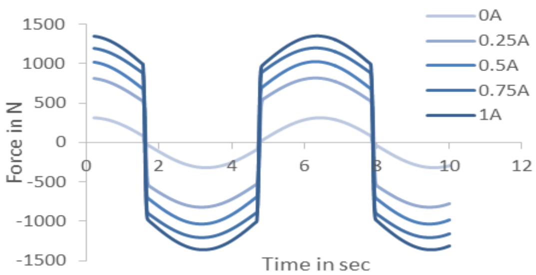

Fig. 5(a): Force Vs Time plots obtained from analysis of Spencer model for Matlab/Simulink

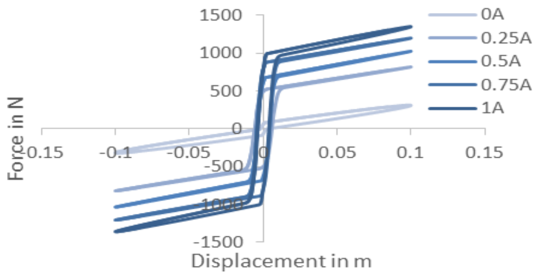

Fig. 5(b): Force Vs Displacement plots obtained from analysis of Spencer Model for Matlab/Simulink

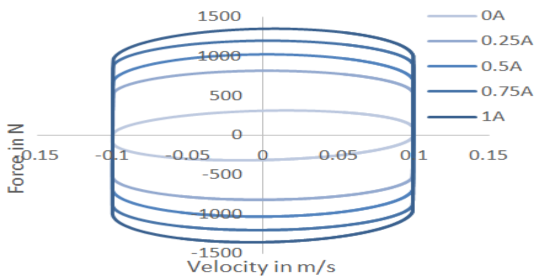

Fig. 5(c): Force Vs Velocity plots obtained from analysis of Spencer model for Matlab/Simulink

4. Modelling and analysis of passive quarter car

Fig. 6 represents the quarter car model for passive suspension system. The Eqns. of motion for this model are given as,

$$m_s\ddot{x}_s = -[k_s(x_s - x_u) + c_s(\dot{x}_s - \dot{x}_u)] \quad (3)$$

$$m_u\ddot{x}_u = -\{-[k_s(x_s - x_u) + c_s(\dot{x}_s - \dot{x}_u)] + [k_s(x_u - q) + c_t(\dot{x}_u - \dot{q})]\} \quad (4)$$

For this study, the vehicle considered is Hyundai i20 with curb weight of 1180kg and gross total weight of 1580kg, of which 180kg is the weight of total unsprung mass leading to 45kg at each wheel. Therefore 1500kg is considered as total sprung mass, of which 60% acts on rear side leading to 450kg on each rear wheel. Using the parameters of suspension systems as mentioned in Table 3, the passive suspension system of quarter car is analysed to identify the displacement and acceleration of the sprung mass. Modelling is carried out in Matlab/Simulink and shown in Fig. 7.

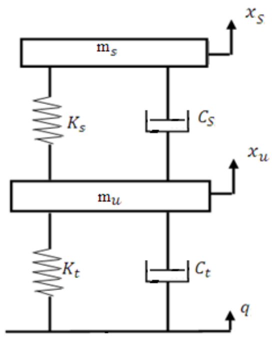

Fig. 6: Quarter car model for passive suspension system

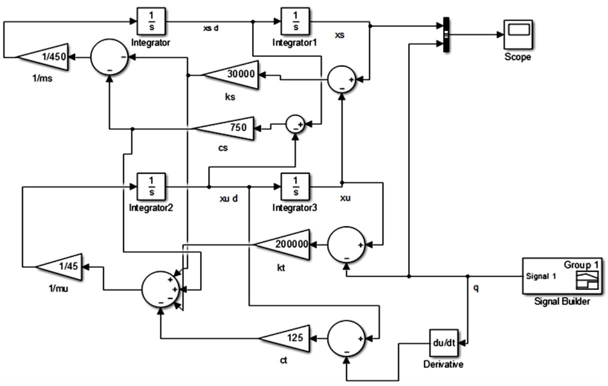

Fig. 7:Matlab/Simulink model of quarter passive suspension system

Table 3: Parameters of quarter passive suspension system

System parameter	Value
Sprung mass (m_x)	450kg
Unsprung mass (m_u)	45kg
Suspension stiffness(k_s)	300N/cm
Damping coefficient (c_s)	7.50Ns/cm
Tire Suspension stiffness(k_t)	2000N/cm
Tire Damping coefficient (c_t)	1.25Ns/cm

Fig.8 represents the quarter car model for semi-active suspension system. The equations of motion for this model are given as

$$m_s\ddot{x}_s = -[k_s(x_s - x_u) + f_{MR})] \quad (5)$$

$$m_u\ddot{x}_u = -[[k_s(x_s - x_u) + f_{MR}] + [k_t(x_u - q) + C_t(\dot{x}_u - \dot{q})]] \quad (6)$$

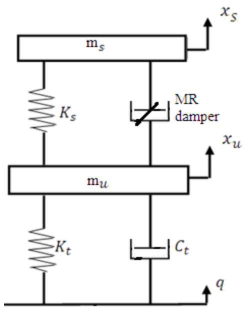

Fig. 8: Quarter car model for semi-active suspension system

A good controller design is to be provided for the better ride and handling. In this study, the skyhook controller, the ground hook controller and the hybrid controller were adopted and applied to roadway vehicle to investigate ride comfort and vehicle handling performance based on lateral vibration control. The skyhook control law was proposed in 1973 by Karnopp [9] and is intended to control sprung mass. The control law turns off the action of damper when the direction of the damper velocity and direction of the desired damper force are not consistent with each other. In other words, only an upwards force will be induced from the damper, only when the sprung mass is being pulled down,. The skyhook controller varies the damper force such that the damper force is equal to,

$$F_{mr} = C_{sky}\dot{x}_s \quad \text{if } \dot{x}_s(\dot{x}_s - \dot{x}_u) > 0 \tag{7}$$

$$F_{mr} = 0 \quad \text{if} \dot{x}_s(\dot{x}_s - \dot{x}_u) < 0 \tag{8}$$

Where, F_{mr} = Desired damping force(N), $\dot{x}_s$= Sprung-mass velocity(m/s), $\dot{x}_u$=Unsprung mass velocity(m/s), C_{sky}= Skyhook gain(N/m/s). Similarly, in case of the ground-hook controller, which is intended to control unsprung mass, the damper force is given as,

$$F_{mr} = C_{grd}\dot{x}_s \quad \text{if } -\dot{x}_u(\dot{x}_s - \dot{x}_u) > 0 \tag{9}$$

$$F_{mr} = 0 \quad \text{if } -\dot{x}_u(\dot{x}_s - \dot{x}_u) < 0 \tag{10}$$

Where, C_{grd} is the groundhook gain (N/m/s). It has been shown in various earlier studies [10] that the original skyhook controller can significantly reduce the transmissibility of the sprung mass, and the ground-hook controller can substantially reduce the unsprung mass transmissibility.

On the other hand, hybrid control strategy is an alternative semi-active control policy that combines the concepts of skyhook and ground hook control to combine the advantages of both [11]. With hybrid control, the system can be set up to function as a skyhook or ground hook controlled system, or a combination of both. In hybrid control strategy, the damper force is given as follows,

$$F_{mr} = C(\alpha\sigma_{sky} + (1-\alpha)\,\sigma_{grd}) \tag{11}$$

$$\sigma_{sky} = \dot{x}_s \quad \text{if} \quad \dot{x}_s(\dot{x}_s - \dot{x}_u) > 0$$

$$\sigma_{sky} = 0 \quad \text{if} \quad \dot{x}_s(\dot{x}_s - \dot{x}_u) < 0$$

$$\sigma_{grd} = \dot{x}_u \quad \text{if} \quad -\dot{x}_u(\dot{x}_s - \dot{x}_u) > 0$$

$$\sigma_{grd} = 0 \quad \text{if} \quad -\dot{x}_u(\dot{x}_s - \dot{x}_u) < 0$$

As discussed earlier, in this study the performance of MR damper is predicted in all three cases of skyhook, ground hook and hybrid control with α=0.85. Using the parameters of suspension systems as mentioned in Tables 2 and 3, the semi-active suspension system of quarter car is analysed to identify the displacement and acceleration of the sprung mass at 5 different currents considered. Modelling of skyhook control is carried out in Matlab/Simulink and shown in Fig. 9 and that of hybrid control is shown in Fig. 10.

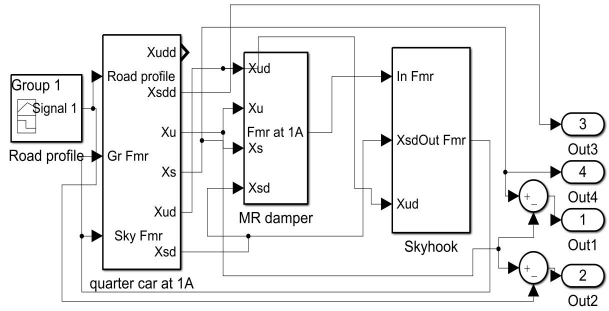

Fig. 9: Matlab/Simulink quarter car model of skyhook controlled semi-active suspension system

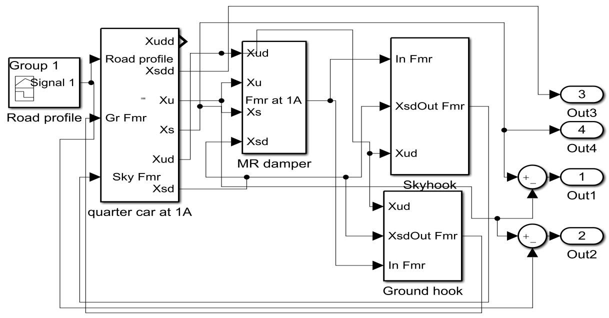

Fig. 10: Matlab/Simulink quarter car model of hybrid controlled semi-active suspension system

The comparison of 2- DOF quarter car passive and semi-active suspension systems at 0A to 1A using hybrid control strategy in terms of variation of lateral displacement of sprung mass, acceleration of sprung mass, tyre displacement and suspension travel with respect to time are shown in Figs.11 to 14 respectively. The road profile is considered as a bump of 0.1m height as shown in Fig.12. The simulation based analysis of the same for all the cases is also conducted using skyhook and ground hook control strategies. The peak (maximum) values for all four parameters indicating ride comfort and vehicle modelling for all cases using three different control strategies along with percentage reduction achieved in comparison of passive system are shown in Table 4. The positive values of percentage reduction represent reduction and negative values represent increase of value. As the goal is to improve ride comfort and vehicle handling, greater the percentage reduction better it is.

To understand the overall relative comparison among various control strategies, an average of all four parameters is also been shown in last column. It can be clearly observed that at any current input, the performance of damper is better using hybrid control strategy and the performance is also improving as current input is increasing from 0A to 1A. With the usage of hybrid control, an overall percentage improvement of 9.55, 15.05, 20.51, 23.27, and 23.9 is predicted from simulation-based analysis over passive suspension system. Between skyhook and ground hook, it is observed that performance of skyhook is better. It is to note that all best percentage reductions are not at 1A, with best acceleration and tyre displacement reduction were observed at 0.75A and best suspension travel was reduction at 0.5A for the considered system.

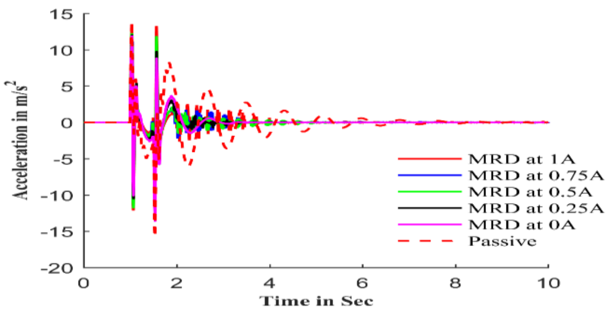

Fig. 11: Comparison of acceleration of sprung mass for passive and semi-active suspension model

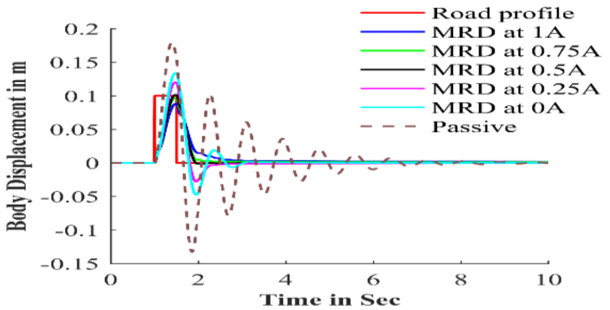

Fig. 12: Comparison of lateral displacement of sprung mass for passive and semi-active suspension model

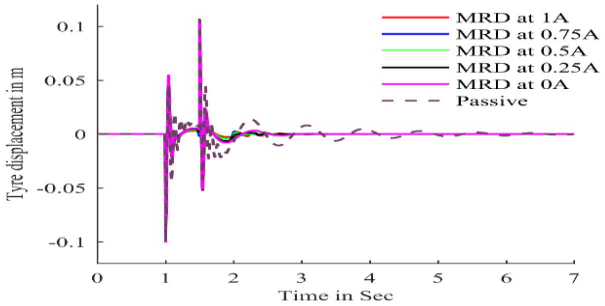

Fig. 13: Comparison of tyre displacement of sprung mass for passive and semi-active suspension model

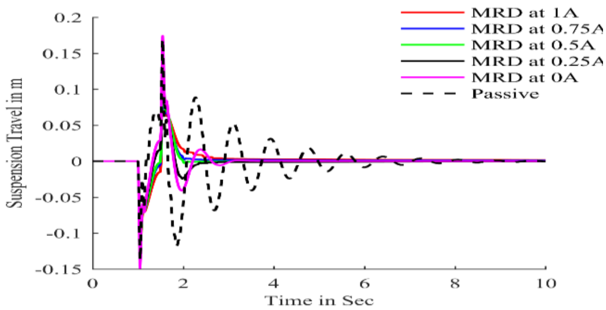

Fig. 14: Comparison of suspension travel of sprung mass for passive and semi-active suspension model

Table 4: Comparison of different parameters analysed for passive and semi active systems

Suspension	Control	Peak acc.	% reduc.	Peak disp.	% reduc.	Peak tyre disp.	% reduc.	Peak susp. travel	% reduc.	Avr. of all % reduc.
Passive	-	-15.76	-	0.18	-	0.11	-	0.17	-	-
MRD at 0A	Hybrid control at α=0.85	-13.58	13.79	0.13	25.30	0.10	2.27	0.17	-3.15	9.55
	Skyhook control (α=1)	-16.41	-3.80	0.13	27.74	0.10	1.47	0.19	-11.85	3.39
	Ground hook control (α=0)	-24.38	-54.18	0.19	-8.52	0.11	-0.06	0.12	26.55	-9.05
MRD at 0.25A	Hybrid control at α=0.85	-12.89	18.18	0.12	33.08	0.10	4.55	0.16	4.40	15.05
	Skyhook control (α=1)	-15.30	3.25	0.11	37.21	0.10	2.25	0.18	-4.48	9.56
	Ground hook control (α=0)	-24.70	-56.16	0.18	-2.29	0.11	1.13	0.12	31.97	-6.34
MRD at 0.5A	Hybrid control at α=0.85	-12.83	18.54	0.10	43.40	0.10	5.44	0.14	14.66	20.51
	Skyhook control (α=1)	-18.29	-15.62	0.09	48.80	0.10	3.36	0.16	5.19	10.43
	Ground hook control (α=0)	-26.44	-67.19	0.17	3.11	0.10	2.90	0.09	45.95	-3.81
MRD at 0.75A	Hybrid control at α=0.85	-12.26	22.20	0.10	46.00	0.10	7.79	0.14	17.11	23.27
	Skyhook control (α=1)	-22.23	-40.60	0.09	51.74	0.10	3.51	0.16	7.12	5.44
	Ground hook control (α=0)	-26.00	-64.42	0.17	7.34	0.10	3.25	0.09	45.52	-2.08
MRD at 1A	Hybrid control at α=0.85	-12.73	19.20	0.09	50.89	0.10	4.34	0.14	21.18	23.90
	Skyhook control (α=1)	-36.58	-131.29	0.08	56.67	0.10	3.95	0.15	11.46	-14.80
	Ground hook control (α=0)	-27.23	-72.21	0.20	-11.05	0.10	1.84	0.12	29.31	-13.02

5. Conclusion

In this paper, the performance of MR damper based semi active suspension system, in terms of ride comfort and vehicle handling, is predicted and is compared with that of passive system at 0A, 0.25A, 0.5A, 0.75A, 1A using skyhook, ground hook and hybrid control strategies. It can be concluded that hybrid control give better results and performance with simultaneous improvement in both ride comfort and vehicle handling over pure skyhook or ground hook control strategies. Even though the performance of damper is improving as current input is increasing, best acceleration and tyre displacement reduction were observed at 0.75A and best suspension travel reduction was 0.5A for the considered system. Hence, the best current to be supplied always depends on the road conditions.

REFERENCES:

[1] D. Ryba. 1974. Improvements in dynamic characteristics of automobile suspension systems part 1. Two-mass systems, *Vehicle System Dynamics*, 3(1), 17-46. https://doi.org/10.1080/00423117408968445.

[2] R. Rajalakshmi, S. Rajeshkumar, J. Thiyagarajan, A. Vinothkumar. 2017. Evaluation of human exposure to vibration subjected to active suspension actuators, *Int. J. Vehicle Structures & Systems*, 9(2), 68-71. https://doi.org/10.4273/ijvss.9.2.01.

[3] J. Wang and G. Meng. 2001. Magnetorheological fluid devices: principles, characteristics and applications in mechanical engineering, *IMAHE, J. Materials: Design & Applications, Part L*, 215(3), 165-174. https://doi.org/10.1243/1464420011545012.

[4] R. Turczyn and M. Kciuk. 2008. Preparation and study of model magnetorheological fluids, *J. Achievements in Materials and Manuf. Engg.*, 27(2), 131-134.

[5] M. Jolly, J.W. Bender and J.D. Carlson. 1998. Properties and applications of commercial magnetorheological fluids, *Proc. SPIE 5th Annual Int. Symp. Smart Structures and Materials*, San Diego.

[6] Jr.B.F. Spencer, S. Dyke, M. Sain and J. Carlson. 1997. Phenomenological model for magnetorheological dampers, *J. Engg. Mech.*, 1-23.

[7] D.V.A.R. Sastry, K.V. Ramana, N.M. Rao, P. Pruthvi and D.U.V. Santhosh. 2016. Analysis of MR damper for quarter and half car suspension systems of a roadway vehicle, *Int. J. Vehicle Structures & Systems*, 9(1), 17-22.http://dx.doi.org/10.4273/ijvss.9.1.04.

[8] V.K. Grag and R.V. Dukkipati. 1984.*Dynamics of Railway Vehicle Systems*, Academic Press Inc.

[9] D. Karnopp, J. Crosby and R. Harwood. 1973. *Vibration Control using Semi-Active Force Generators*, Lord Library of Technical Articles, LL-7004.

[10] S.B. Choi, W. Li, M. Yu, H. Du, J. Fu and P.X. Do. 2016. State of the art of control schemes for smart systems featuring magneto-rheological materials, *Smart Mater. Struct.*, 25. https://doi.org/10.1088/0964-1726/25/4/043001.

[11] S.M. Savaresi and C. Spelta. 2007. Mixed sky-hook and approaching the filtering limits of a semi-active suspension,*J. Dyn. Syst. Meas. Control*, 129, 382-392. https://doi.org/10.1115/1.2745846.