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Application of Magneto-Rheological Damper for Car Suspension Control

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Abstract: The MR damper is a control device that consists of a hydraulic cylinder filled with magnetically polarizable particles suspended in a liquid. MR dampers dissipate vibration by absorbing energy. Magnetorheological (MR) fluids dampers are very effective to control vibration, which use MR fluids to produce controllable damping force and provide both the reliability of passive systems and the facility of active control systems with small power supply. Due to their mechanical simplicity, high dynamic range, low power requirements, large force capacity and robustness, offer an attractive means of vibration protection. The objective of this study are understanding the characteristics of the MR damper to provide effective damping for the purpose of suspension isolation or suppression car body. In this study, fuzzy logic controller is used to control semiactive car suspension system.

Key words: Semiactive, suspension, MR damper, fuzzy controller

INTRODUCTION

One semi-active device that appears to be particularly promising for suspension protection is the MR damper. MR dampers use MR fluids to produce controllable dampers. The area of MR fluids deal with characterizing the properties of MR fluids. Lazareva *et al.* (1997) studied the properties of MR fluids that are based on barium and strontium ferrites and iron oxides. The fluids were prepared using various combinations of the materials and their properties, such as the MR effect, were studied. Ashour *et al.* (1996) studied the effects of components of the MR on sedimentation of the magnetic particles and initial viscosity. In another study, Ashour *et al.* (1996) studied the general composition of MR fluid along with the methods that are used to evaluate the performance of the fluids. Carlson *et al.* (1999) studied the advantages of MR over ER fluid devices in areas such as the yield strength, the required working volume of fluid and the required power. The operational modes of the MR fluid are presented along with the linear fluid damper, the rotary brake and the vibration damper. Kordonsky (1996) developed the concept of the MR converter (or valve) and applies the MR converter to create devices such as the MR linear damper, the MR actuator and the MR seal. Finally Bolter *et al.* (1997) examined the rules that should be applied when designing the magnetic circuit for MR devices that are working in the different modes of the MR fluid. Bolter also examined the use of permanent magnets in the design of the magnetic circuit to change the operational point of the MR device. When a magnetic field is applied to the fluid, particle chains form and the fluid becomes a semi-solid and exhibits viscoplastic behaviour similar to that of ER fluid. This controllable change of state with some desirable features such as high strength, good stability, broad operational temperature range and fast response time gives rise to isolation and suspension system applications. MR fluid dampers considered here are semi-active control devices that use MR fluids to produce controllable damping forces. MR fluid dampers considered here are semi-active control devices that use MR fluids to produce controllable damping forces. In particular, it has been found that (MR) fluids can be quite promising for vibration reduction. One such study is an experimental investigation by Ivers and Miller (1989).

The main object of this paper is to verify the ability of the MR damper to reduce suspension over a wide range and implementation of fuzzy controller in semiactive MR damper. The results reported herein indicate that this semi-active control system is quite effective for suspension control.

MECHANICAL MODEL OF THE MR DAMPER

The mathematical model proposed by Spencer *et al.* (1996a, b) is adopted in this study. The hysteretic behaviour in the damper was described by the Bouc-Wen model. The mechanical realization of the MR damper is shown in Fig. 1. The equations governing the force f_{MR} predicted by this model are:

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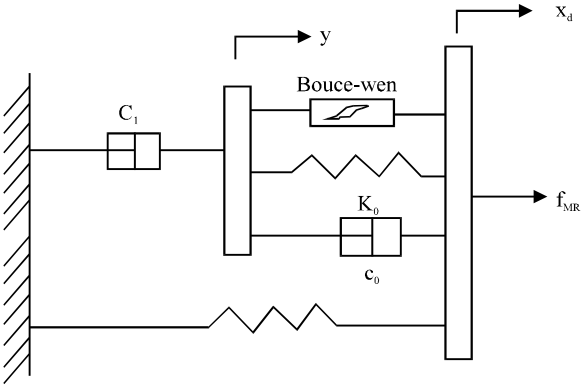

Fig. 1: Mechanical model of the MR damper

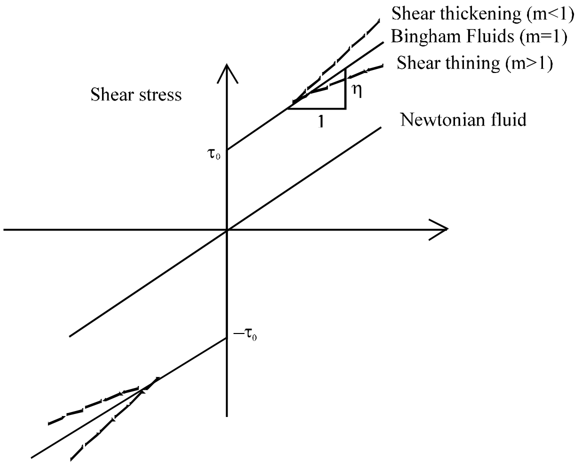

Fig. 2: Visco-plasticity models of MR fluids

$$f_{MR} = c_1\dot{y} + k_1(x_d - x_0) \tag{1}$$

$$\dot{z} = -\gamma|\dot{x}_d - \dot{y}|z|z|^{n-1} - \beta(\dot{x}_d - \dot{y})|z|^n + A(\dot{x}_d - \dot{y}) \tag{2}$$

$$\dot{y} = \frac{1}{c_0 + c_1}\{\alpha z + c_0\dot{x}_d + k_0(x_d - y)\} \tag{3}$$

Where, z is an evolutionary variable that accounts for the history dependence of the response. The model parameters depend on the voltage v to the current driver as follows:

$$\alpha = \alpha_a + \alpha_b u,\ c_1 = c_{1a} + c_{1b}u,\ c_0 = c_{0a} + c_{0b}u \tag{4}$$

where, u is given as the output of the first-order filter

$$\dot{u} = \eta(u\text{-}v) \tag{5}$$

It is necessary to model the dynamics involved in reaching rheological equilibrium and in driving the electromagnet in the MR damper Eq. 5 is necessary to model the dynamics involved in reaching rheological equilibrium and in driving the electromagnet in the MR damper. there are a total of 14 parameters c_{oa}, C_{ob}, k_0, c_{1a}, c_{1b}, k_1, x_0, c_{0a} c_{0b}, k_0, $c1_b$, c_{1a}, k_1, x_0, to characterize the MR damper. A simple Bingham visco-plasticity model (Phillips, 1969) (Fig. 1), is effective at describing the essential field-dependent fluid characteristics. In this model, the total shear stress is given by:

$$\tau = \tau_0(H)\operatorname{sgn}(\dot{\gamma}) + \eta\dot{\gamma} \tag{6}$$

Where, τ_0 = yield stress caused by the applied field; H = magnitude of the applied magnetic field; γ = shear strain rate and η = field-independent plastic viscosity, defined as the slope of the measured post-yield shear stress versus shear strain rate.

It can be mentioned that the fluid post-yield viscosity is assumed to be a constant in the Binghammodel. Because MR fluids exhibit shearing thinning effect which is shown in Fig. 2, the Herschel-Bulkley visco-plasticity model (Herschel and Bukely, 1926) can be employed to accommodate this effect. In this model, the constant post-yield plastic viscosity in the Bingham model is replaced with a power law model dependent on shear strain rate. Therefore, where m,k = fluid parameters and m, k>0. Comparing Eq. 6 with Eq. 7, the equivalent plastic viscosity of the Herschel-Bulkley model is:

$$\eta_e = k|\dot{\gamma}|^{\frac{1}{m}-1} \tag{7}$$

Equation 7 indicates that the equivalent plastic viscosity η_e decreases as the shear strain rate $\dot{\gamma}$ increases when m>1 (shear thinning). Furthermore, this model can also be used to describe the fluid shear thickening effect when m<1. The Herschel-Bulkley model reduces to the Bingham model when m = 1, therefore η = K. Based on Bouc-Wen model, MR damper model RD-1005-3 (Lord corporation USA) is practical type damper. In this study, data for MR damper are obtained according to seven current range (0, 0.25, 0.5, 0.75, 1.0, 1.5 and 2.0 A). The responses of the MR damper subject to a 1 Hz sinusoidal signal are shown in Fig. 3 for seven constant current applied to the damper. The force-displacement loops progress along a clockwise path with the increase of time while the force-velocity loops (Fig. 3) progress along a counterclockwise path. Also, it can be seen that, as the current increases, the corresponding damping force increases. Figure 3 provide the measured MR damper force-velocity behaviors and comparisons with theoretical results. Due to the plastic viscous force, a larger damping force is seen at high velocity.

In this study, simulation has been done by using this model at Pilot Lab in Faculty of Engineering,

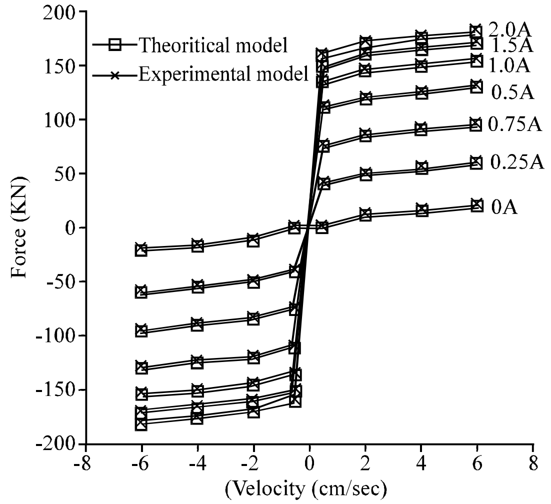

Fig. 3: Measured force-velocity relationships for MR damper

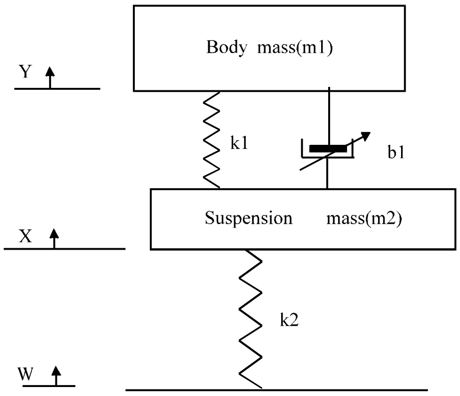

Fig. 4: Modeling of quarter-car suspension system

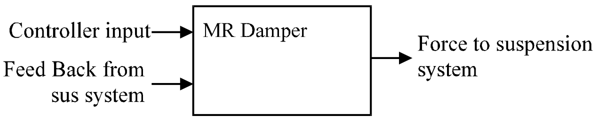

Fig. 5: Simplified block diagram for MR damper

University Malaya 2005. Detail damper parameter are listed in Table 3.

Semiactive car suspension systems: A semiactive damper suspension system varies the damping force in real time depending on the dynamics of the controlled masses. The effect of semiactive control on suspension performance has also been studied on a two degree of freedom system (two mass) system, such as the one depicted in Fig. 4. This model is the quarter car model (one of the four wheels) which is used to simplify the problem to a one-dimensional spring-damper system.

The motion equations of the car body and the wheel are as follows:

$$m1\ddot{y} = -k1(y - x) - \tilde{b}1(\dot{y} - \dot{x}) \tag{8}$$

$$m2\ddot{x} = k1(y - x) - k2(\dot{x} - \dot{w}) \tag{9}$$

Suspension parameters used in quarter-car model are as follows.

Parameter		Value
Sprung mass (m_1)	=	325 kg
Unsprung mass (m^2)	=	55 kg
Suspension stiffness (K1)	=	42,000 N m^{-1}
Tire stiffness (K2)	=	180,000 N m^{-1}

Damper coefficient of MR damper $(\tilde{b}1)$ which is controlled variable.

The semiactive system utilizes a feedback loop to control the damping force at any time. The feedback is usually taken as the velocities/displacement of the bodies that the suspension controls. A controller can then use the feedback data to calculate the desired damper control force, which must be converted into a control signal that will adjust the damper simplified schematic diagram of combined unit is shown in Fig. 5.

The signal that is sent to the damper changes the damper's resistance to velocity and therefore changes the damper force. Finally, the feedback loop is completed as the changing damper force alters the acceleration of the controlled bodies and the feedback variables in ways that would not have occurred had a passive system been used. If the system works as desired, then the semiactive system dynamics will be more favorable than the passive system dynamics. In studying dynamic systems, whether semiactive or not, the terminology sprung and unsprung bodies (masses) are often used in dynamics literature to refer to the two bodies of a two degree of freedom dynamic model (Fig. 4.) Here, the sprung body is represented by m1 and the unsprung body by m2. The bodies are connected together by a spring and the unsprung body is connected to a movable base. A movement of this base is called a base excitation of the dynamic system. Block diagram for semiactive suspension system using fuzzy has been seen in Fig 7.

Implementation of fuzzy controller in semi-active suspension systems: The fuzzy logic controller used in the semi-active suspension has two inputs: body velocity $\dot{y}$ and difference between body velocity and suspension

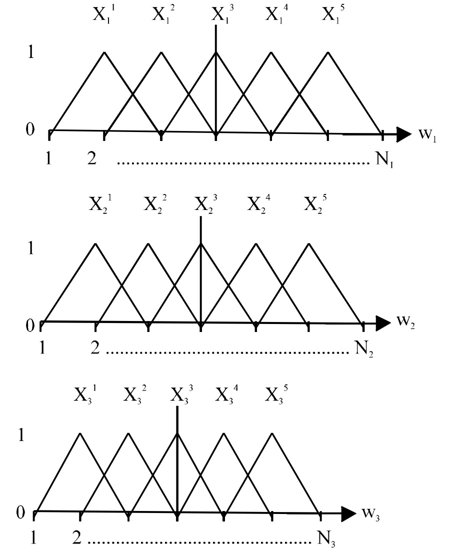

Fig. 6: Membership function for scalar components w_I

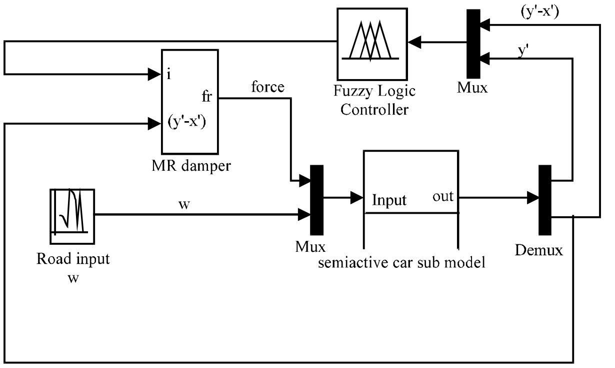

Fig. 7: Block diagram representation of the fuzzy control system

velocity $(\dot{y}-\dot{x})$. The control system itself consists of three stages : fuzzification, fuzzy inference machine and defuzzification.

A standard Fuzzy-Logic (FL) system takes an input w, fuzzifies it using prescribed Membership Functions (MF), goes to a table-lookup rule-base to determine associated output values, then defuzzifies the output values into a single `crisp' value u. A paradigm of FL for control design is given in (Lewis and Liu, 1996). Given an integer N define the set $\bar{N} \equiv \{1, 2..., N\}$. For each component wj of the input vector $w = [w_1 \quad w_n]^T$ the Mfs are selected, often chosen triangular as shown in Fig. 6. Letting Nj represent the number of MF for component wj, the MF $X_j^{i_j}(w_j)$; $i_j \in \bar{N}_j$ is denoted as $X_j^1, X_j^2, X_j^{N_j}$ or generally In this study the rule-base consist of R rules. In multivariable control applications, where $w \in R^n$, $u \in R^n$ the rules often have a special form, given for the ρth as IF [(w_1 is $X_1^{i_{1p}}$) and (w_2 is $X_2^{i_{2p}}$) and [(w_n is $X_n^{i_{np}}$)] THEN [(u_i is θ_{ip})]. The

Table 1: Look up table fuzzy input-output action

ẏ

PB					▩	▩	▩
PM					▦	▦	▦
PS					▨	▨	▨
ZO							
NS	▥	▥	▥				
NM	▤	▤	▤				
NB	▒	▒	▒				
	NB	NM	NS	ZO	PS	PM	PB

$(\dot{y}-\dot{x})$

Table 2: Controller action represented by carious shade

shade	▩	▦	▨		▥	▤	▒
Controller action %	+100	+50	25	0	-25	-50	-100

θ_{ip} component u_i and rule ρ. The degree of membership associated with rule ρ is $\mu_j^{i_{j\rho}}(w_j)$, $j \in \bar{n}$. We use product inferencing to define the participation factor of $w \in R^n$ for the ρth rule as:

$$\mu_{i_{1\rho},i_{2\rho},\dots,i_{n\rho}}(w) = \mu_1^{i_{1\rho}}(w_1)\mu_2^{i_{2\rho}}(w_2)\dots\mu_n^{i_{n\rho}}(w_n)$$

Centroid defuzzification is used to obtained the output u_i, given as:

$$u_i = \frac{\sum_{\rho=1}^{R} \theta_{i\rho}\,\mu_{i_{1\rho},i_{2\rho},\dots,i_{n\rho}}(w)}{\sum_{\rho=1}^{R} \mu_{i_{1\rho},i_{2\rho},\dots,i_{n\rho}}(w)} \tag{10}$$

$$i = 1,2,..,m,$$

Where, θ_{ip} is the control representative value for rule ρ. This is the equation of the outputs u_i of the FL system in terms of the input $w \in R^n$. It is known as the Fuzzy Associative Memory (FAM) function or the reasoning surface.

Typical Fuzzy Logic controller composed of three basic parts; input signal fuzzification, a fuzzy engine and defuzzification that generates continuous signals for actuators such as control valves. The fuzzification block transforms the continuous input signal into linguistic fuzzy variables. The fuzzy engine carries out rule inference through linguistic rules. The defuzzification block converts the inferred control action back to a continuous signal that interpolates between simultaneously fired rules. Fuzzy-logic provides a non-linear relationship induced by membership functions, rules and defuzzification. These features make fuzzy logic promising for process control where conventional control technologies do a poor job and where human experience exists.

Table 3: Parameters for the MR model

Para-meter	Value	Para-meter	Value
c_{0a}	784 N s m^{-1}	α_a	12 441 N m^{-1}
c_{0b}	1803 N s V^{-1} m^{-1}	α_b	38 430 N V^{-1} m^{-1}
k_0	3610 N m^{-1}	γ	136 320 m^{-2}
c_{1a}	14649 N s m^{-1}	μ	2059 020 m^{-2}
c_{1b}	34622 N s V^{-1} m^{-1}	A	58
k_1	840 N m^{-1}	n	2
x_0	0.0245 m	η	190 s^{-1}

Para-meter	Value
Sprung Mass (m1) =	325 kg
Unsprung Mass (m2) =	55 kg
Suspension Stiffness (K1) =	42,000 N/m
Tire Stiffness (K2) =	180,000 N/m
Sprung Mass (m1) =	325 kg
Unsprung Mass (m2)	55 kg
Suspension Stiffness (K1)	42,000 N m^{-1}
Damper coefficient of MR damper ($\tilde{b}$)	Control variable

Table 1 and 2 represent the fuzzy controller action strategy for suspension system

In present study, velocity of sprung mass $\dot{y}$ and difference between sprung mass velocity and unsprung mass velocity $(\dot{y}-\dot{x})$ are used as fuzzy controller inputs and the fuzzy output is the MR damper input (coil current) as seen in Fig. 7 (membership functions are seen in Fig. 6. The universe of discourse of the input and output variables are selected based on the results of simulation for different conditions. Triangle memberships for the input and output variables with seven values, are used for each variable. They are Negative Big [NB], Negative medium [NM], Negative small [NS], Zero [ZE], PositiveSmall [PS], PositiveMedium [PM] and Positive Big [PB], respectively.

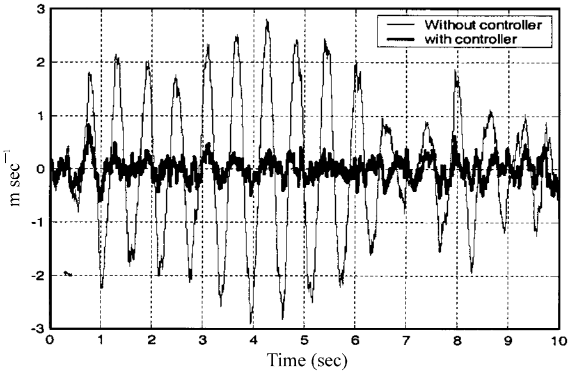

Fig. 8: Velocity responses of suspension system using fuzzy controller for random number disturbances

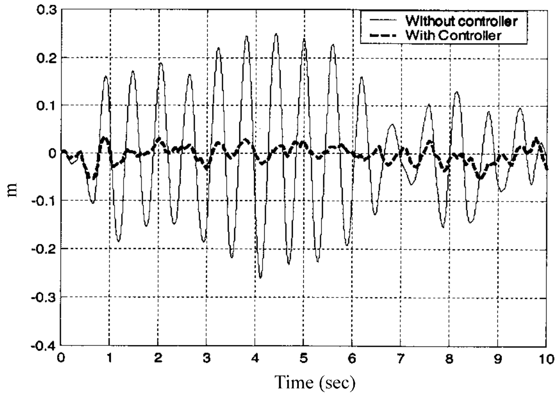

Fig. 9: Displacement responses of suspension system using fuzzy controller for random number disturbances

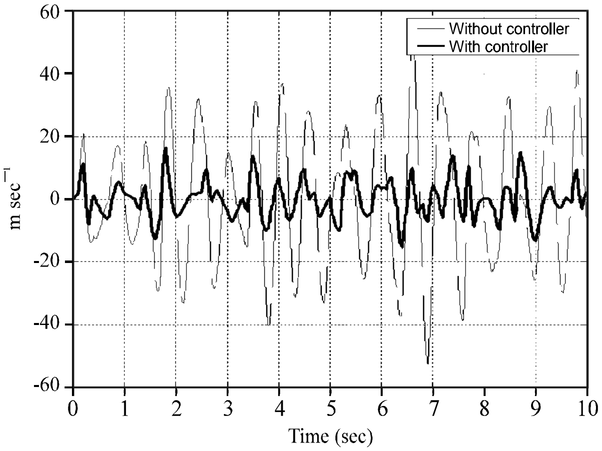

Fig. 10: Velocity responses of suspension system using fuzzy controller for BLWN disturbances

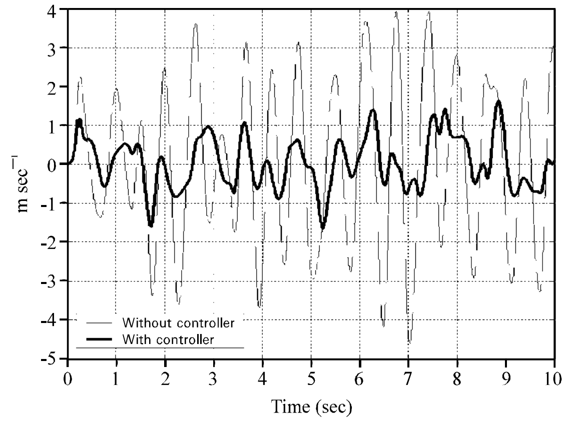

Fig. 11: Displacement responses of suspension system using fuzzy controller for BLWN disturbances

RESULTS AND DISCUSSION

In order to evaluate ride performance of the vehicle, Random number disturbance and Bandlimited-white-noise(BLWN) type disturbances are undertaken and its result is presented in Fig. 8 to 11. As clearly observed from Figures, the body displacement and body velocity is reduced the input disturbances more significantly than passive damper in all cases. From this result, we may reduced greatly by applying the control field to the MR absorber model. It can be mentioned that the without controller responses are obtained in the absence of the magnetic field and this result is equivalent to the performance of the conventional passive damper. The control simulation studies as shown in Fig. 8 to 11 show the output response with the fuzzy controller for the random numbers disturbance and BLWN disturbances, respectively. The result shows that fuzzy controller can expect that ride comfort can be improved by employing fuzzy controller in MR damper model.

CONCLUSIONS

In this study, the effect of a MR Damper for suspension control was investigated. The characteristics of the MR damper are studied here. The damping coefficient of the MR damper in terms of input current, displacement amplitude and frequency are examined. Compared with passive damper, the results of this study show that the semi-active controlled MR damper well suited for suspension suppression without the sacrifice of worse isolation for higher frequencies of interest. The steady state analysis indicate that MR dampers are effective in lowering the RMS acceleration at most locations than passive stock dampers. In this study, the new semi-active suspension control system is proposed to achieve both ride comfort and good handling. This aim was achieved with respect to the results of the simulation; the results of the active suspension system based on the fuzzy logic controller also show the improved stability of the one-quarter-car model. The results presented in this research are quite self-explanatory justifying that the semi-active MR suspension system can be effectively employed to the passenger vehicle with improved both ride comfort and steering stability. This would encourage that the use of the MR increase vehicle stability and to control suspension.

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