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Fuzzy Control of Seat Vibrations for Semi-Active Quarter Vehicle System Utilizing Magneto rheological Damper

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Abstract:–This paper presents an investigation into the effectiveness of controllable magnetorheological (MR) damper for a semi-acive vehicle model with passenger seat. Mathematical model has been experimentally developed for controller design using Choi et al. model. A quarter vehicle model has been employed for system performance evaluation via Matlab through numerical simulation. System behaviour related to passenger comfort and safety has been analysed without and with fuzzy logic control strategy in suspension system for passenger comfort and safety during on road varying driving conditions.

Keywords*:*–Magneto rheological damper,quarter vehicle model, semi-active suspension system,fuzzy controller

I. INTRODUCTION

The main function of suspension system in vehicle is to minimize/isolate road surface induced disturbances or vibrations for passenger ride comfort, safety, good vehicle handling and long life of vehicle components during vehicle traveling over rough, harsh and irregular road profiles. There are three types of vehicle suspensions known as passive, semi-active and active suspension systems [1]. Normally, conventional passive suspensions provide limited performance i.e. shows effectiveness in certain frequency range due to uncontrollable parts such as spring and damper system. On the contrary, active suspension system can deliver better performance over a wide range of frequency due to presence of electronically controlled parts in suspension, providing desired output based on closed loop feedback data.However, active suspensions have certain drawbacks such as high power requirement, huge setup cost and a large number of assembled electronic components which makes this technology restricted to be used in all vehicles.

Since 1970s, a promising technology known as semi-active suspension system in this field have attracted vehicle manufacturers due to deliverance of better results than passive suspension, less costly and reliable compared to active suspension system.Semi-active suspension based technology is dependent on controllable damper systems known as electro-rheological (ER) dampers and magneto-rheological dampers.But recent developments in the field of MR fluids have generated the logical reasons to choose it in controllable damper technology as compared to ER fluids [2-6].

The practical application of MR dampers in semi-active systems is hindered due to certain drawbacks such as inherent hysteretic and unpredictable non-linear dynamic behavior. Therefore, MR damper modeling is very crucial before its application in particular required field. In past, several models related to the performance and behavior of MR dampers have been put forward by researchers. These models include Bouc-Wen hysteresis model developed by Spencer et al. [7], neural network model put forward by Chang and Roschke [8],fuzzy model [9],nonlinear black box model [10],polynomial model [11], NARX model [12], and other approaches [13].

A lot of work has been done on semi-active quarter vehicle system using two degrees of freedom but present work is related to three degrees of freedom for vibration reduction of concerned system taking passenger seat into account. In present paper (a) a polynomial model based on Choi et al. technique is used (b) fuzzy logic controller is designed working on feedback data of quarter vehicle model.

II. MAGNETO-RHEOLOGICAL DAMPER MODELING

Choi et al. [11] proposed a polynomial model for curve fitting to experimental results related to the nonlinear characteristic of MR damper. In this proposed model, the divison of the MR damper generated hysteretic loop is considered into two parts i.e. the upper curve (negative acceleration) and the lower curve (positive acceleration) based on the test results of Y.Q. Ni [14] as shown in Fig.1. The following polynomial technique [Eqn. (1)-(3)] is adopted for expressing the damping force for the MR damper:

$$F_{MR} = \sum_{i=0}^{n} a_i v^i, \quad n=6 \qquad (1)$$

Where v is the damper piston velocity and a_i, i= 0,1…..,6 are coefficients to be determined from the curve fitting technique. The selection of mathematical value of n for hysteresis curve fitting is dependent on the experimental test results of MR damper. The coefficients a_i are linearly approximated with input current *I* as:

$$a_i = (b_i + c_i I), \quad i = 0,1,....6. \qquad (2)$$

Finally, the damping force can be presented as:

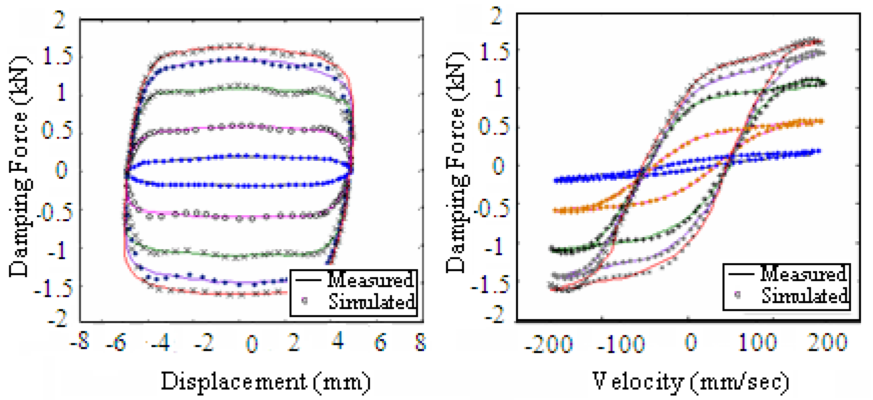
$$F_{MR} = \sum_{i=0}^{n} (b_i + c_i I) v^i, \quad n=6 \qquad (3)$$

The values of coefficients b_i and c_i are shown in Table 1 and obtained from the fitness of the experimental data. The polynomial curve fitting technique generated curve as well as experimental hysteresis curve shows good agreement with each other as shown in Fig. 1. The control current (I) for MR damper is determined when the piston travelling velocity (v) and the desired damping force (F_{MR}) is known by the proposed control strategy as follows [Eqn. (4)]:

$$I = \frac{F_{MR} - \sum_{i=0}^{6} b_i v^i}{\sum_{i=0}^{6} c_i v^i} \qquad (4)$$

Table 1
Coefficients b_i and c_i of polynomial model

Positive acceleration				Negative acceleration			
Coeff.	Value	Coeff.	Value	Coeff.	Value	Coeff.	Value
b_0	-84.14	c_0	-1003.96	b_0	90.011	c_0	957.56
b_1	2.8679	c_1	13.0495	b_1	3.0128	c_1	11.734
b_2	0.0174	c_2	0.1580	b_2	-0.0219	c_2	-0.1380
b_3	-9.86e-05	c_3	-2.97e-06	b_3	-1.20e-04	c_3	1.562e-04
b_4	-1.49e-06	c_4	-8.18e-06	b_4	-1.63e-06	c_4	6.46e-06
b_5	1.89e-09	c_5	-6.15e-09	b_5	2.61e-09	c_5	-1.06e-08
b_6	3.79e-11	c_6	1.39e-10	b_6	-3.69e-11	c_6	-9.74e-11



(a) Damping Force vs. Displacement (b) Damping Force vs. Velocity

Fig. 1: Experimental vs polynomial model results (5 Hz, ±5mm) of MR damper

III. QUARTER VEHICLE MODEL WITH PASSENGER SEAT

Quarter-car model of the complete vehicle system having 3 degrees of freedom is shown in Fig. 2. For research purpose the adopted model is highly used for suspension system design, analysis and effectiveness calculation due to its simplicity and ability to provide comparable and desired results. The major difference between the passive and semi-active quarter car model is dependent on the selection or assembly of damper part i.e. it is non-controllable in first case but externally controllable in second case. Present model is formed by assembling driver seat, sprung mass, un-sprung mass, spring-damper combination and wheel part.

The equations of motion for the present model in mathematical form can be derived by using Newton's second law of motion as follows [Eqn. (5) - (7)]:

$$m_p\ddot{x}_p + k_p(x_p - x_s) + c_p(\dot{x}_p - \dot{x}_s) = 0 \quad (5)$$

$$m_s\ddot{x}_s - k_p(x_p - x_s) - c_p(\dot{x}_p - \dot{x}_s) + k_s(x_s - x_{us}) + c_s(\dot{x}_s - \dot{x}_{us}) + F_{MR} = 0 \quad (6)$$

$$m_{us}\ddot{x}_{us} - k_s(x_s - x_{us}) - c_s(\dot{x}_s - \dot{x}_{us}) + k_t(x_{us} - x_r) - F_{MR} = 0 \quad (7)$$

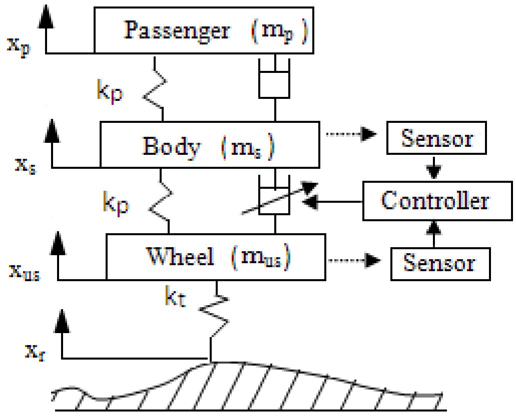


Fig. 2: Quarter vehicle model with passenger

Where quarter vehicle sprung mass, unsprung mass and seat mass including passenger mass are represented by m_s, m_{us} and m_p respectively, whereas k_p and c_p are the stiffness and damping values of the spring and damper parts under the passenger seat while k_s and k_t are the suspension spring constant and stiffness of wheel part; c_s is suspension basal damping coefficient; the vertical displacement of passenger seat x_p, vertical displacement of sprung mass x_s,vertical displacement of the wheel base x_{us} and x_r represents variation in road profile.

IV. FORMULATION OF FUZZY LOGIC CONTROLLER

Fuzzy controllers are widely used in many industries such as automotive, automatic transmissions, ABS and cruise control systems. Fuzzy control system operates on the human readable rules in the form of fuzzy logic implications, representing a human's heuristic knowledge. Fuzzy Logic Control (FLC) systems have been successfully used and practically implemented to many industrial and research work [17]. Fuzzy control systems are suitable for semi-active suspension systems having complicated nonlinear dynamics including tires, MR damper (as it is nearly impossible to set-up an accurate and acceptable mathematical model related to MR damper performance due to complex behavior of the magneto-rheological fluid in MR damper) and spring etc. and many control criteria for suspension operation with two criteria on top priority: vehicle handling and passengers comfort. Fig. 3 shows the application of Fuzzy Logic Controller in semi-active quarter vehicle model with MR damper.

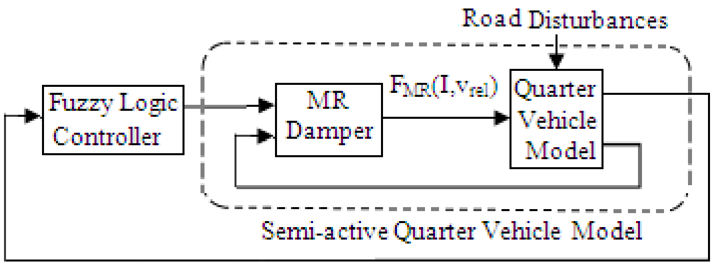


Fig. 3: Block diagram of Semi-active FLC control for vehicle system with MR damper

In present work Mamdani method is selected in fuzzy inference system whereas "max-min" inference method is selected as aggregation operator, being mostly used and simplest method. For defuzzification stage, "centroid" method is employed where "center of mass" of the output generates a numerical value i.e. transformation of linguistic variables to crisp values. The labels used for linguistic variables in Table 2 are mentioned as: NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PL (Positive Large) while implemented fuzzy membership functions are shown in Fig. 4 to achieve maximum passenger ride comfort including driving safety and vehicle handling.

Table 2
Fuzzy Logic control rules

Vs \ Vrel	NL	NS	ZE	PS	PL
NL	PL	PM	PS	ZE	ZE
NS	PM	PS	ZE	ZE	ZE
ZE	PM	PS	ZE	NS	NM
PS	ZE	ZE	ZE	NS	NM
PL	ZE	ZE	NS	NM	NL

Fig. (a): Tabular Form

Rule	Application of Rules
1	If Vs NL and Vrel is NL THEN C is PL
2	If Vs NL and Vrel is NS THEN C is PM
—	— — — — — — — — — — —
—	— — — — — — — — — — —
24	If Vs PL and Vrel is PS THEN C is NM
25	If Vs PL and Vrel is PL THEN C is NL

Fig. (b): IF THEN Form

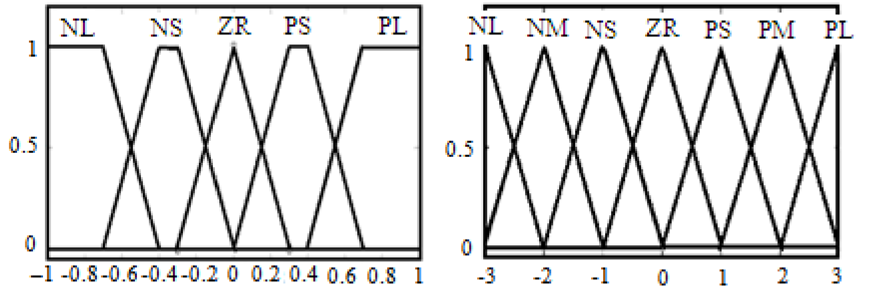


Fig (a): Input membership functions Fig. (b): Output membersip functions

Fig. 4: Fuzzy membership functions

V. SIMULATION WORK AND RESULTS

In this section, performance evaluation of the passive system and semi-active quarter vehicle model with MR damper assembled between sprung and unsprung mass and working on the feedback data provided by FLC is done. The selected values for quarter vehicle model for simulation work are as follows:

m_p=50 kg , c_p=1000 N-s/m, k_p=40 kN/m, m_s=350 kg,
c_s=1000 N-s/m, k_s=60 kN/m, m_u=40 kg, k_t= 180 kN/m

The performance of the designed system is evaluated under two types of road conditions i.e. bump input and step input. The road input signals and the responses of the passenger system for both the road excitations with passive and semi-active quarter vehicle model are shown in Fig. 5 and Fig. 6. Here, Fig. 5(b) and Fig. 6(b) provide simulation results for driver seat acceleration while Fig. 5(c) and Fig. 6(c) provide simulation results for driver seat displacement in time domain for both passive as well as semi-active system.

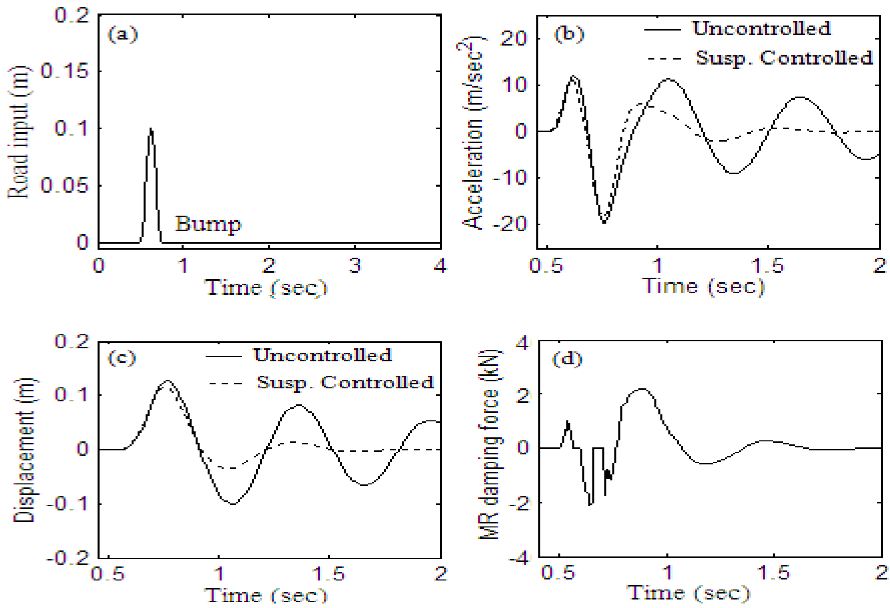


Fig. 5: System responses under bump input

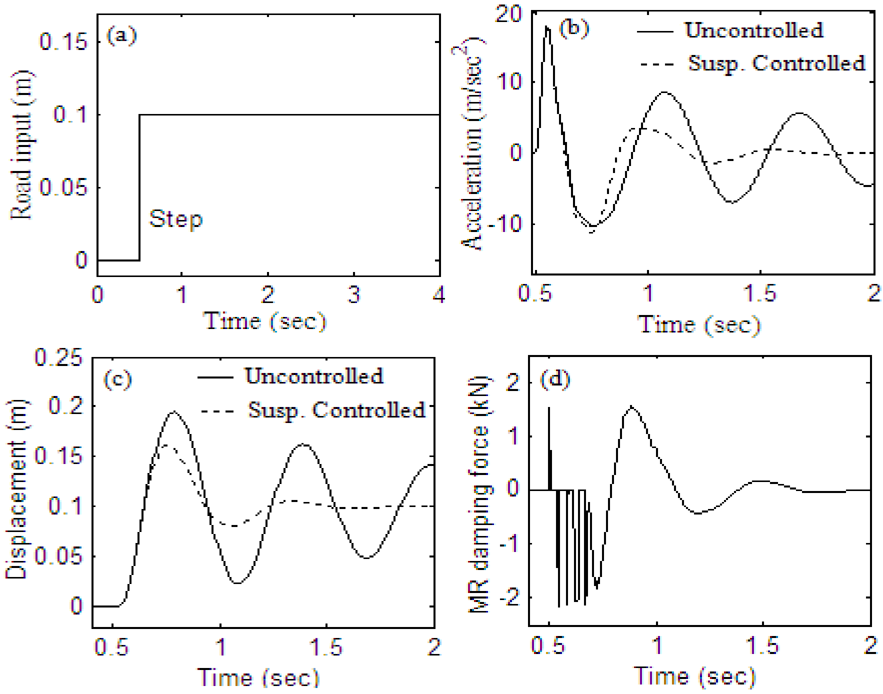


Fig. 6: System responses under step input

The following criterion was applied for performance index calculation in terms of acceleration and displacement parameters to evaluate & compare the output responses of semi-active and passive vehicle system using root mean square (RMS) percentage reduction value, defined by:

$$\text{Improvement } (\%) = \left| \frac{\text{Semi-active RMS value} - \text{Passive RMS value}}{\text{Passive RMS value}} \right| \text{x } 100$$

The root-mean-square (RMS) values of the simulation results for step road input are calculated for ride comfort evaluation and presented in Table 3. It can be observed that the suspension controlled semi-active system with MR damper provides good performance in terms of passenger seat acceleration, sprung mass acceleration, passenger seat displacement and relative passenger seat displacement as compared to uncontrolled passive system.

Table 3
Performance comparison (RMS) for step input

Parameter	Uncontrolled	Suspension Controlled	Improvement (in %)
$\ddot{x}_p$	4.0205	2.8609	-28.84*
$\ddot{x}_s$	3.6375	2.6248	-27.84
x_p	0.0998	0.0949	-4.91
$x_p - x_s$	0.0047	0.0031	-34.04

* Negative numbers represent response improvement

VI. CONCLUSIONS

In this study, a polynomial model has been proposed based on Choi et al. methodology using experimental data, which makes it feasible to use MR damper in vehicle suspension system. Simulation results show that the fuzzy logic controlled quarter vehicle suspension system has achieved better performance as compared to uncontrolled system in terms of reduction of passenger seat acceleration (-28.84%), sprung mass acceleration (-27.84%), passenger seat displacement (-4.91%) and relative passenger seat displacement (-34.04%) in terms of RMS values. It can be concluded that the performance of the quarter vehicle suspension system can be improved by application of MR damper in combination with Fuzzy Logic Controller in terms of passenger's ride comfort, safety and vehicle handling during on road varying driving conditions.

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