Parametric Analysis of Magnetorheological Strut for Semiactive Suspension System Using Taguchi Method

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Abstract—**Magnetorheological (MR) strut is among the leading advanced applications of semi-active suspension systems. The damping force of MR damper is controlled by varying the viscosity of MR fluid. In this work, the viscosity of MR damper varies by changing the current from 0.5A to 0.7A. The design of experiments is taken into account in concert with the product/process development as one completely advanced tool. The parameters used for ride comfort optimization are sprung mass, spring stiffness, tire pressure, current, and cylinder material with two levels of each. Taguchi orthogonal array method is used to select the best results by parameter optimization with a minimum number of test runs. In this paper, from Taguchi L16 array and S/N ratio analysis, it is observed that the cylinder material with Al and CS for damper cylinder is a key parameter for performance measure of semi-active suspension system. From regression analysis, a linear mathematical model is developed for Al and CS as cylinder materials. The interaction of cylinder materials with all four parameters is plotted. The methodology implemented for measurement of acceleration as a ride comfort is as per IS 2631-1997. The more economical model of magnetorheological damper will motivate Indian auto industry to broader applications.**

Keywords-magnetorheological damper; parametric analysis; semiactive

I. INTRODUCTION

An effective automotive mechanical system has to give comfort and good road holding ability, once the vehicle is moving on any road disturbance. The vehicle body is supposed to have considerable damping or resistance to avoid massive oscillations. Comfort optimization is predicated on spring stiffness, damping and sprung mass. Normally, such system types are developed by experimental approach. The procedure for designing and modeling of a novel large-stroke MR damper is tested in [1] under impact load and it is observed that the inertia damping force could not be ignored like in the common MR damper due to large acceleration. 2D axisymmetric model was built up in [2] to investigate and analyze the MR damper qualities predicting the damping force characteristics. The Bingham model of MR damper was proposed and compared with experimental results for magnetic saturation. This work inferred that the obtained magnetic saturation model can show effect on current, amplitude and excitation frequency. The phenomenon of magnetic saturation is simulated in [3] and obtained results are compared with the experimental results. Optimization technique is used to maximize magnetic flux density which affects the force developed by damper [4]. The MR fluid structure and properties, damper description and parametric damper models which are connected in various ways with the actual behavior of the MR fluid were presented in [5]. Recommendations for the design of main-spring and shock absorber of motor vehicle suspensions were given in [6]. Indications acquired for the shock absorber allow us to obtain the damping coefficients in the compression and rebound strokes and to calculate the power dissipated during the vehicle oscillatory movement. An extensive work has been done on the transmissibility of vibration isolator in [7], where authors proposed the concept of output frequency response function in order to examine the force transmissibility of MDOF structures with a cubic non-linear viscous damping device. Control strategies can be divided into two main categories: active and semiactive. In the case of active systems the performance is superior and optimum transmissibility has no resonance. Semiactive systems provide reliability comparable to passive suspension systems [8]. In [9], it is observed that the vertical acceleration of body mass is substantially reduced by using a controlled MR damper.

Sensitivity analysis for leaf springs with different stiffness was done in [10] on roll bar of front suspension system by using Adams simulation software. Static test results were compared with the dynamic test ones. From the simulation results, it is observed that the parametric effect on suspension system is not satisfactory by using static analysis. The experimental results carried out in [11] regarded optimization of suspension system used for vehicle occupant seat for a quarter car model. The Taguchi method was implemented in order to reduce vibrations. From the simulation results it is observed that stiffness and damping preliminary values are the control variables of the suspension system. Authors in [12] studied the dynamic loads enforced on suspension components through bushings and joints. In order to predict the vehicle component life estimation, Taguchi method is implemented by minimizing the stress value of the lower control arm. The proposed in [13] robust optimization is based on Taguchi method and uses Adams software to model suspension. An experiment was designed based on the Taguchi method to achieve suspension Pareto solution set and the result illustrated that both suspension and robustness improved a lot after optimization. The design of car robustness needs various processes and a lot of time. In the current work, the semi active suspension parameters such as tire pressure, current, spring stiffness, sprung mass and most important, cylinder material for damper are considered to achieve good ride comfort (RC) [14]. This standard recommended the acceleration as RC measure for vehicle which is represented in Table I.

TABLE I. COMFORT REACTIONS TO VIBRATION ENVIRONMENT

Acceleration (m/s^2)	Level
Less than 0.315	Not Uncomfortable
0.315 to 0.63	A little Uncomfortable
0.5 to 1	Fairly Uncomfortable
0.8 to 1.6	Uncomfortable
1.25 to 2.5	Very Uncomfortable
Greater than 2	Extremely Uncomfortable

II. DAMPER FABRICATION

The MR damper damping force is calculated for 250kg and designed accordingly. For calculation of the damping force, the mathematical model suggested by the Bingham plastic model and magnetic circuit shown in Figure 1 is used in which the damping force F_D is divided into an induced yield stress, F_{τ} and viscous components $F\eta$.

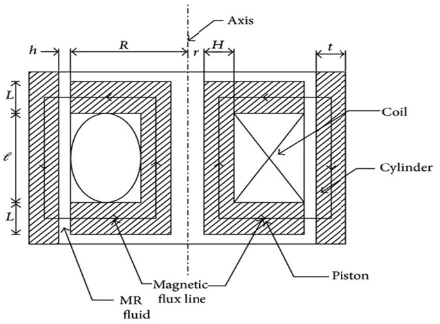

Fig. 1. Magnetic circuit design of MR damper

A. Damping Force Calculations

The damping force F_D is divided into a yield stress induced F_{τ} and viscous component F_{η} as in (1) and (2).

$$F_D=F_{\tau}+F_{\eta} \qquad (1)$$

$$=\left[\left\{\left(2.07+\frac{12Q\eta}{12Q\eta+0.4wh^2\tau y}\right)\frac{\tau y L A_p}{h}\right\}+\left\{\left(1+\frac{whv}{2Q}\right)\frac{12\eta Q L_t A_p}{wh^3}\right\}\right. \qquad (2)$$

where, $Q= A_p \times v$, $A_p=\frac{\pi}{4}(D^2 - d_o^2)$, $w = \pi\left(\frac{h}{2}+D+\frac{h}{2}\right)$

The calculations are obtained by considering the piston and cylinder gap as 1.2mm and velocity as 10 kmph. Table II shows the dimensions of the MR damper and in Figure 2 we can see the fabricated damper.

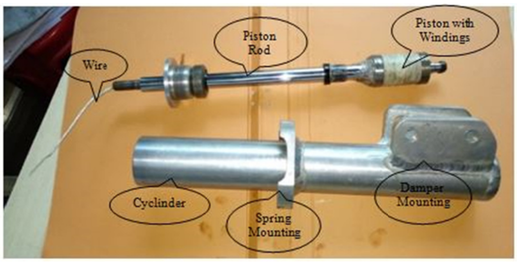

Fig. 2. Fabricated MR damper

TABLE II. DIMENSIONS OF FABRICATED MR DAMPER

Parameter	Notations	Dimensions(mm)
Piston rod and coil width radial distance	H	5
Cylinder thickness	t	3
Length of Pole	L	9
Piston and cylinder clearance	h	1.5
Piston radius	R	18.03
Distance among the poles	l	42
Radius of piston rod	r	9

III. EXPERIMENTAL PROGRAM FOR MR DAMPER

In order to study the suspension effects and study RC and road holding, the Quarter Car Model experimental setup is used. Test set up has arrangements for varying sprung mass to test the suspension on different loading conditions. Sprung mass is connected to the vertical column by linear bearing to minimize friction. Double wishbone suspension system (compatible for McPherson type of suspension) is used for testing. Figure 3 demonstrates the experimental setup. The setup is provided with a cam exciter which is designed according to constant wave form and powered by a PMDC motor. It contains instruments like data acquisition hardware, accelerometer, a loaded pc, MR damper, power supply for the pc and connecting cables for the DC current controller and accelerometer. The model is tested for measurement of acceleration of wishbone and on sprung mass.

Fig. 3. Experimental setup of quarter car model with MR damper with CS cyclinder

IV. EXPERIMENT DESIGN

The experiment design is taken into account in concert with the product/process development as one completely advanced tool. The experiment design takes into consideration wide-ranging applications in the development of product/process. There are the two approaches of DOE.

A. Full Factorial Design

In full factorial experimental approach, two (at least) or more factors are used in a feasible level and the required units take all probable combinations of all levels of these factors. For 9 factors with 2 levels for each, 512 runs are required for a full factorial design. In this method, each parametric effect on response variables and the interaction between factors is studied.

B. Taguchi Method

The major shortcoming of full factorial design is that the number of experiments to be carried out is large which means more laborious work on a large number of parameters. To avoid this troublesome work, Taguchi recommended a specially intended method called orthogonal array to learn the whole parameter effect with lesser quantity of experiments.

C. Selection of Control Factors

It is observed that spring stiffness and electric current need to be appropriately considered under positive range of sprung mass and road conditions. For exceedingly rigid suspension the vehicle system will be vastly stable but acceleration of occupant body will be high and comfort will be low. For a smaller amount of hard suspension, passenger comfort will increase but vehicle stability decreases. The selected parameters for suspension are described in Table III.

TABLE III. TAGUCHI PARAMETER TABLE

Parameter	Unit	Levels	Level 1	Level 2
Tire Pressure	Kgf/cm^2 (PSI)	2	34	40
Spring Stiffness	N/mm	2	14000	8000
Damper Cyclider Material	---	2	Al (+1)	Structural Carbon Steel (-1)
Sprung Mass	Kg	2	72	97
Current	(A)	2	0.5	0.7

D. Orthogonal Arrays

Taguchi developed the orthogonal array method to study systems whose performance is affected by different factors, in a more convenient and rapid way. This method can be used to select the best results by optimization of parameters with a minimum number of test runs. Application of Taguchi method can achieve the best results out of various tests by selecting the optimum combination of different factors. Final product quality can be improved in terms of process optimization, product design and system analysis. To study a sufficient number of experiments with a large number of variables, Taguchi recommended the orthogonal array method for experimental design. The conclusions made after a sufficient number of experiments are usable over the whole experimental area covered by control factors and their ranges. Orthogonal array method was discovered before Taguchi implemented it for DOE. In this method, the columns of tabulated sets are orthogonal and consequently linear graphs are plotted to fit the specific project applications. In the current study, five parameters, tire pressure, spring stiffness, damper cylinder material, sprung mass and electric current, each one with two levels are used. Table IV defines the L16 array. The number following the "L" indicates the number of runs in the design, and 16 means the array requires 16 runs (2^5), which indicates that the design estimates up to 5 main parameters at 2 levels each.

TABLE IV. TAGUCHI L16 ORTHOGONAL ARRAY

Run	Air Pressure	Spring Stiffness	Cylinder Material	Sprung Mass	Current
1	34	14000	1	72	0.5
2	34	14000	1	97	0.7
3	34	14000	-1	72	0.7
4	34	14000	-1	97	0.5
5	34	8000	1	72	0.7
6	34	8000	1	97	0.5
7	34	8000	-1	72	0.5
8	34	8000	-1	97	0.7
9	40	14000	1	72	0.7
10	40	14000	1	97	0.5
11	40	14000	-1	72	0.5
12	40	14000	-1	97	0.7
13	40	8000	1	72	0.5
14	40	8000	1	97	0.7
15	40	8000	-1	72	0.7
16	40	8000	-1	97	0.5

E. Analysis of S/N Ratio

To measure the performance characteristics, Taguchi recommends the use of the loss function that is deviating from the desired target value. The value of this loss function is further transformed into signal-to-noise (S/N) ratio or SNR. The preferred parameter settings are determined through SNR analysis where the optimized parameters are considered those that maximize the appropriate SNR [15-17]. To analyze SNR three types of performance characteristics are considered.

1) The Smaller the Better (for making the system response as small as possible)

$$SN_S = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad (3)$$

2) The Nominal the Best (for reducing variability around a target)

$$SN_T = 10\log\left(\frac{\bar{y}^2}{s^2}\right) \qquad (4)$$

3) The Larger the Better (for making the system response as large as possible):

$$SN_L = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \qquad (5)$$

Lower values of passenger seat displacement and displacement settling time are the prime requirements to achieve passenger RC and safety, thus in present work, SNR with lower-is-better characteristic is selected. Table V represents the L16 orthogonal array with acceleration as output.

TABLE V. TAGUCHI L16 ARRAY WITH ACCELERATION AND SN RATIO

Run	**Air Pressure**	**Spring Stiffness**	**Cylinder Material**	**Sprung Mass**	**Current**	**Acceleration (RC)**	**SNR**
1	34	14000	1	72	0.5	0.7250	2.79324
2	34	14000	1	97	0.7	0.6820	3.32431
3	34	14000	-1	72	0.7	1.1150	-0.94550
4	34	14000	-1	97	0.5	0.8852	1.05917
5	34	8000	1	72	0.7	0.9980	0.01739
6	34	8000	1	97	0.5	0.9250	0.67717
7	34	8000	-1	72	0.5	1.2500	-1.93820
8	34	8000	-1	97	0.7	0.9960	0.03481
9	40	14000	1	72	0.7	0.6520	3.71505
10	40	14000	1	97	0.5	0.8250	1.67092
11	40	14000	-1	72	0.5	0.8524	1.38713
12	40	14000	-1	97	0.7	0.7920	2.02550
13	40	8000	1	72	0.5	0.5240	5.61337
14	40	8000	1	97	0.7	0.9152	0.76968
15	40	8000	-1	72	0.7	1.2100	-1.65571
16	40	8000	-1	97	0.5	1.1600	-1.28916

F. Optimum Level Prediction

The results obtained are depicted in Table VI. It is observed that cylinder material ranks first and Figure 4 shows the optimum parameter level. From Table VI it is observed that cylinder material performs ranks first and from the main effect plot of SN Ratios (Figure 4), **P34K8000CM-1M97I0.7** shows optimum level of parameter.

TABLE VI. SNR RESPONSE TABLES

Level	**Air Pressure**	**Spring Stiffness**	**Cylinder Material**	**Sprung Mass**	**Current**
1	0.6278	0.2787	-0.1652	1.1233	1.2467
2	1.5296	1.8787	2.3226	1.0341	0.9107
Delta	0.9018	1.6001	2.4879	0.0893	0.3360
Rank	3	2	1	5	4

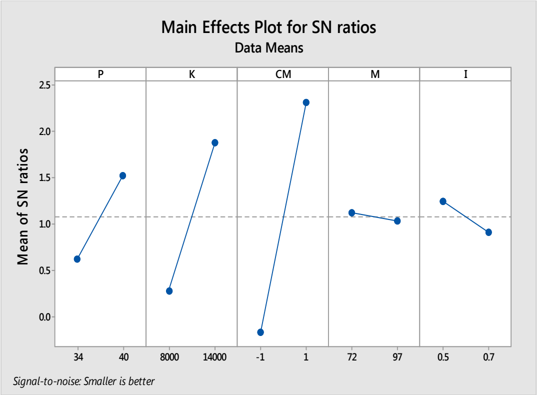

Fig. 4. Main effect plot for SNR

V. SNR INTERACTION PLOT

Taguchi designs conventionally focus on the main effects, but it is important to test the supposed interactions. In order to determine the effect of one on another parameter with respect to its response, Taguchi uses a method known as interaction plot. To study the interaction plot, the interpretation of Table VII is considered. According to SNR response table, ranks are established. From Table VI, cylinder material takes first rank. In order to check the cylinder material's effect on the other four parameters, its interaction plot with tire pressure, spring stiffness, sprung mass and current is plotted. Table VII represents the interpretation of interaction lines. The regression equation (6) is generated from regression analysis.

$$RC\_1 = 1.718 - 0.0134P - 0.000030K \\ - 0.1259CM - 0.00073M + 0.134I \quad (6)$$

TABLE VII. INTERPRETATION OF INTERACTION LINES

Position of Interaction Lines	**Interpretation**
Parallel	No interaction between two factors
Not Parallel	Interaction between two factors

VI. CONCLUSION

Taguchi L16 array and SNR analysis show the cylinder material with Al and CS for damper cylinder is a key parameter for performance measure of semi active suspension with MR damper. It is observed that damper cylinder material is a key parameter to design the MR damper. From the interaction plot, it is concluded that cylinder material interacts more with spring stiffness and tire pressure compared to sprung mass and current. The low price model developed will have wide range of applications to Indian auto industry.

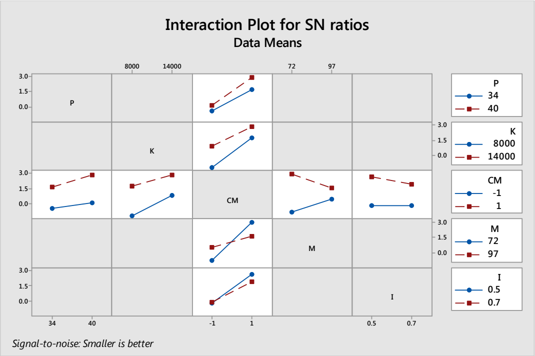

Fig. 5. Interaction plot for SN ratios

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