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Simulation and Optimization of Semiactive Suspension Parameters Using Taguchi Method and Grey Relational Analysis

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Abstract: In present paper, a methodology is presented related to the optimization of semi-active quarter car model suspension parameters having three degrees of freedom, subjected to bump type of road excitation.Influence of primary suspension stiffness, primary suspension damping, secondary suspension stiffness and secondary suspension damping are studied on the passenger ride comfort, taking root mean square (RMS) values of passenger seat displacement and Semi-active quarter car model assembled with magneto-rheological (MR) shock absorber is selected for optimization of suspension parameters using Taguchi method in combination with Grey relational analysis. Confirmatory results with simulation run indicates that the optimized results of suspension parameters are helpful in achieving the best ride comfort to travelling passengers in terms of minimization of passenger seat displacement and settling time values.

Keywords:- Quarter car model, MR shock absorber, Passenger ride comfort, Taguchi method, Grey relational analysis,Parameter optimization

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I. INTRODUCTION

Passenger ride comfort is a major requirement in modern vehicles during its travelling period over different road profiles which need to be considered during design and development phase. Basically, road induced vibrations transmitted from vehicle tires to passenger seat are responsible for harmful effects on the passenger health as well on vehicle parts. Usually, passenger ride comfort is characterized by the seat acceleration, seat displacement and seat settling time response respectively. With the advancement in technology, suspension system concept has developed from passive to semi-active and active suspension type. In present scenario, passive suspension system is still used in vehicle as well as in seat suspensions and dominating the automotive sector due to its low cost and assembly of simple parts such as passive or uncontrollable shock absorber and conventional spring [1-2]. But its performance is poor in terms of passenger ride comfort and vehicle handling issues. While active suspension system can provide best ride comfort and road holding ability using the latest available technology, supplying required damping force from externally connected energy source but its cost and complicated sensors and actuators makes this concept applicable in limited vehicles [3-4]. Semi-active suspension system can deliver better performance than passive suspension and less costly as well as technically adaptable with magneto-rheological (MR) and electro-rheological (ER) shock absorbers compared to active type [5-6]. Feasibility study of electro-rheological and magneto-rheological shock absorbers in semi-active suspension system has been studied by manyresearchers [7-8]. MR shock absorbers poses many attractive characteristics in terms of requirement of very less power for its working, rapid response time of few milliseconds as well as not affected by temperature variations.

Since MR shock absorbers shows highly nonlinear dynamic and hysteretic nature during working, this makes the development of proper controller necessary for its utilization practically. Various parametric and non-parametric models have been developed for real use of MR shock absorbers which can match the dynamic behavior of these shock absorbers [9-13]. The used experimental results of MR shock absorber as well as fuzzy controller design in present research work can be found in [14]. In past, some studies have been performed related to the optimization of suspension system parameters. A.F. Naude et. al [15] developed vehicle simulation programmed for optimization of damper characteristics of 22 ton three axle vehicle. The leap-frog optimization algorithm for constrained problems (LFOPC) was integrated with multi-body dynamics simulation code (Vehsim2d) for optimization purpose. Anil Shirahatt et. al [16] applied genetic algorithm (GA) and compared with simulated annealing (SA) technique to select the passive and active suspension parameters for a full car model. A number of objectives were selected to fulfill passenger ride comfort and vehicle handling issues while the vehicle travels through sinusoidal road input. MSC ADAMS software was selected to perform simulation work under bump type of road displacement for passive quarter car model.. In literature, most of the available research work is related to the development of new control algorithms or comparative analysis of different control algorithm strategies to achieve better ride comfort and vehicle handling issues, taking advantages of MR shock absorbers using numerical simulation work. There is very little research work available in the direction of optimization of semi-active quarter car suspension parameters to enhance its performance capability to provide better ride comfort experience to travelling passengers. The aim of present paper is to optimize the suspension system parameters to achieve the best ride comfort for travelling passengers, taking the influence of shock absorber damping characteristics and spring characteristics in the quarter car model with three degrees of freedom. For simulation purpose, semi-active quarter car model assembled with MR shock absorber in primary suspension system is considered while secondary suspension system is assembled with passive shock absorber. Simulation results in terms of RMS displacement and settling time of passenger seat is used for optimization of suspension parameters using Taguchi method and Grey relational analysis.

II. SIMULATION OF SEMI-ACTIVE SUSPENSION WITH PID CONTROLLER

Figure 2.1 shows nonlinear semi-active quarter car model with three-degrees-of-freedom. This model is very useful for the analysis of vertical movement of assembled parts because of its design simplicity and rapid result generation capability. Three degrees of freedom of considered model includeThis nonlinear quarter car model can provide graphical data using simulation work and mathematical values can be calculated related to passenger seat displacement for analysis purpose. Mass (m_s= 320 kg) and un-sprung mass (m_u= 40 kg) respectively for simulation work while the Selected parameters for optimization purpose are given in Table 1.

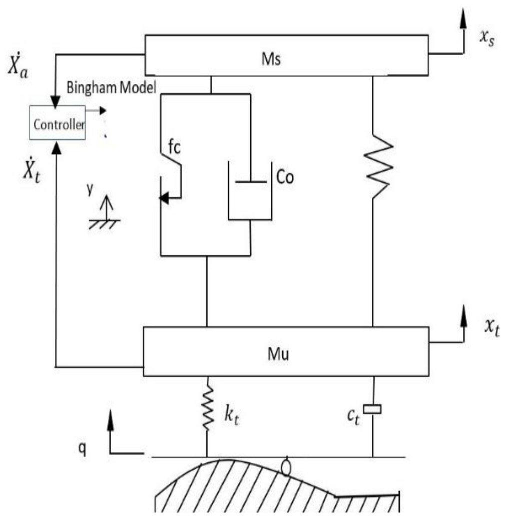


Fig.2.1 Semi-Active suspension design

For the controller, (z_s) and (z_t) represents absolute displacement of sprung mass and un-sprung mass respectively. Controller generates the current $z_s$in the MR damper and changes the force F of semi active suspension system [10]. The motion equations of the car body and wheel of this model areas follows

$$m_s\ddot{z}_u + c_s(\dot{z}_u - \dot{z}_s) + k_s(z_u - z_s) + c_u\dot{z}_u + k_u z_u = -U_c + k_u r + c_u\dot{r} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Table 1. Quarter Car Model Parameters [10]

Parameters	**Values**
Sprung Mass (Ms)	**145 kg**
Un-sprung Mass(Mu)	**30 kg**
Spring Stiffness(Ks)	**26000 N/m**
Damping Coefficient(Cs)	**1200 Ns/m**
Tyre Stiffness(Kt)	**198850 N/m**
Un-sprung Mass coeff.(Cu)	**0**
Damping Coeff. Of Bingham Model(Co)	**320 Ns/m**
Offset force(Fo)	**0**
Frictional Force(Fc)	**210 N**
Stiffness of elastic Component(Ko)	**300 N/m**
Form Factor (d)	**10**

Fig.2.2 Sprung mass Acceleration of Semi-active suspension with PID and without PID vs. Time (sec)

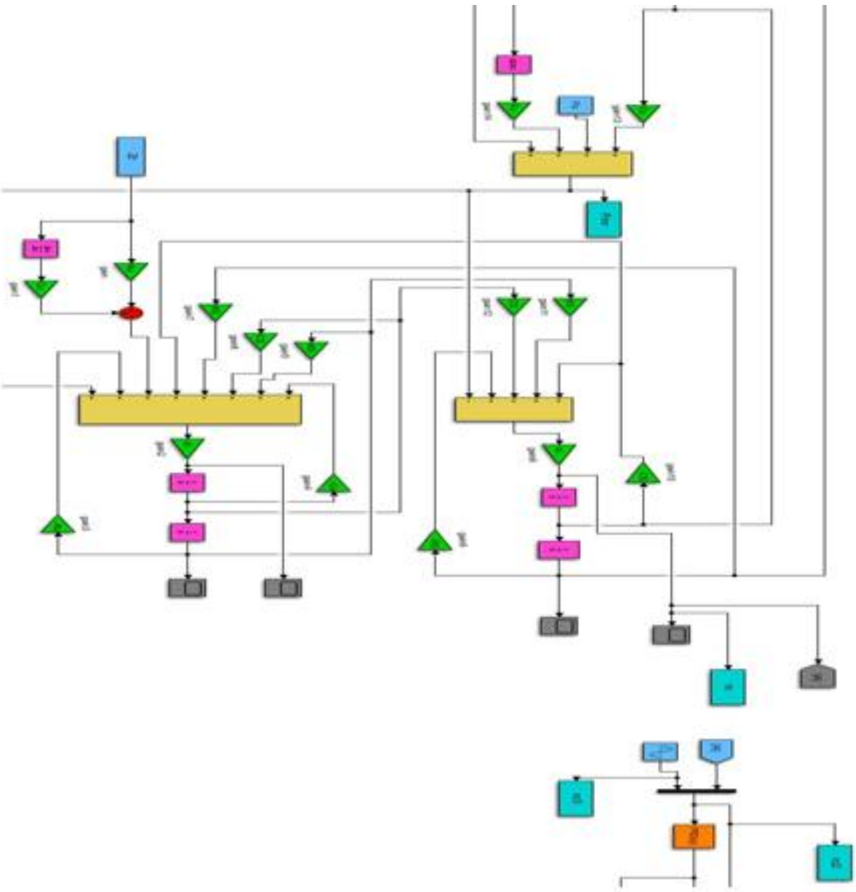


Fig.2.2 Simulink Model of Semi-Active Suspension with PID Controller

2.1 MR Damper Characteristics

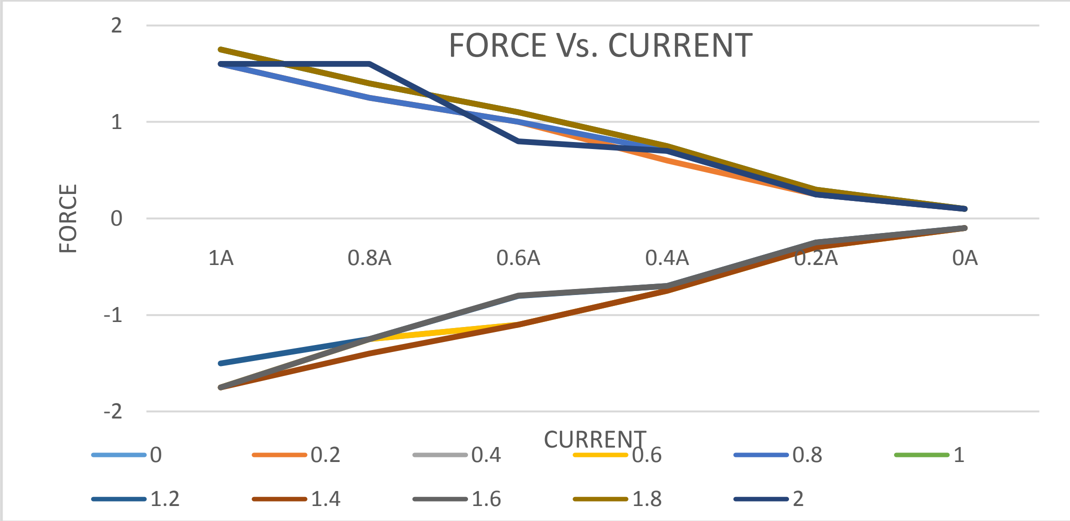


Fig. 2.1.1 MR Damper Characteristic[1]

Table No. 10.2.1.1 MR Damper Characteristics

Amp	Time										
	0	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2
1A	1.75	1.6	-1.75	-1.75	1.6	1.75	-1.5	-1.75	-1.75	1.75	1.6
0.8A	1.4	1.25	-1.25	-1.25	1.25	1.4	-1.25	-1.4	-1.25	1.4	1.6
0.6A	1.1	1	-1.1	-1.1	1	1.1	-0.8	-1.1	-0.8	1.1	0.8
0.4A	0.75	0.6	-0.75	-0.75	0.7	0.75	-0.7	-0.75	-0.7	0.75	0.7
0.2A	0.3	0.25	-0.3	-0.3	0.25	0.3	-0.25	-0.3	-0.25	0.3	0.3
0A	0.1	0.1	-0.1	-0.1	0.1	0.1	-0.1	-0.1	-0.1	0.1	0.1

III. TAGUCHI METHOD FOR SUSPENSION SYSTEM PARAMETER OPTIMIZATION

Taguchi developed the orthogonal array method to study the systems in a more convenient and rapid way, whose performance is affected by different factors when the system study become more complicated with the increase in the number of factors. This method can be used to select best results by optimization of parameters with a minimum number of test runs. Application of Taguchi method can support significantly to achieve the best results out of various tests by selection of optimum combination of different factors. Final product quality can be improved ranging from industrial products to service sector in terms of process optimization, product design and system analysis [19-22]. The steps followed for suspension parameter optimization using Taguchi method in present study related to minimization of RMS passenger seat displacement(PSD) and settling time (ST) values are as follows:

1. Suspension system parameters selection.
2. Level assignment to each suspension parameter.
3. Taguchi orthogonal array selection.
4. Simulation work using quarter car model.
5. Calculation of RMS passenger seat displacement and settling time values.
6. Calculation of S/N ratios using obtained RMS PSD and ST values.
7. Final Experimental / Simulation work, taking obtained suspension parameter values

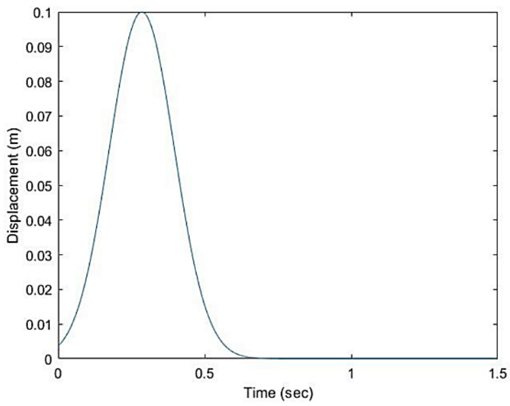
Simulation results are used to determine the corresponding values in terms of signal-to-noise (S/N) ratio for each run. It projects the performance of each test run depending on the obtained S/N ratio. Basically, three types of S/N ratios are used in Taguchi method such as: lower is better (LB), higher is better (HB) and nominal is best (NB). Since the lower values of passenger seat displacement and displacement settling time are prime requirement to achieve passenger ride comfort and safety, thus in present work, S/N ratio with a lower is better

Table No. 3.1 Input Parameters and levels.

Symbol	Suspension Parameter	Levels		
		level 1	level 2	level 3
A	Bump height (m)	0.05	0.075	0.1
B	Tire Stiffness (N/m)	198850	210210	231360
C	spring stiffness (N/m)	26000	28000	30000
D	Damping Coff. (N.m/s)	1200	1400	1600

3.1 SELECTION OF SUSPENSION PARAMETERS AND ORTHOGONAL ARRAY

In this study, primary suspension MR shock absorber damping, spring stiffness as well as secondary suspension shock absorber damping and spring stiffness are selected as parameters for optimization purpose as shown in Table 1 while the bump type of road excitation responsible for vibration generation is shown in Figure 2. The orthogonal array (L27) selected to determine the optimum suspension parameters are shown in Table 2. Each suspension parameter is written in a column whereas the total combination of all four suspension parameters is having nine independent rows. Therefore, total nine simulation runs are required in present work to study the combination of entire suspension parameters influence using L27 orthogonal array.



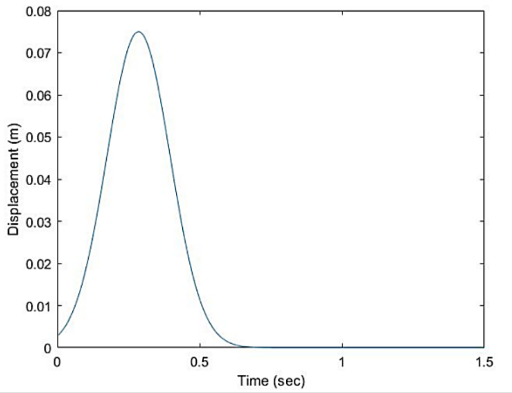


Fig. 3.1.1 Bump Height 0.1m Fig. 3.1.2 Bump Height 0.075m

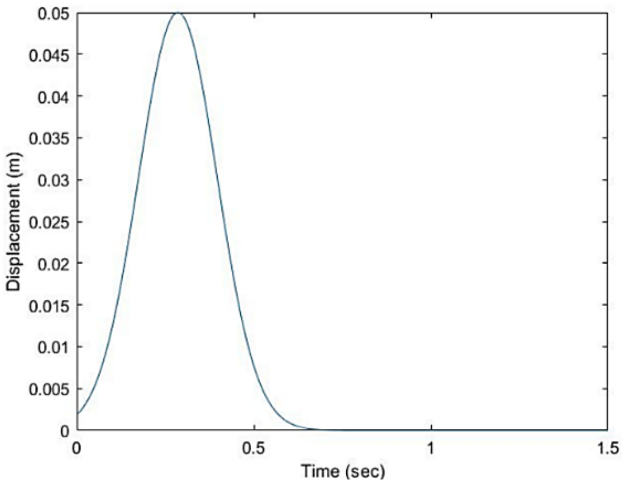


Fig**. 3.1.3** Bump Height 0.05m.

3.2.TAGUCHI ORTHOGONAL ARRAY L27 TABLE

Table 12.2.1.1 Taguchi orthogonal array

Run number	A	B	C	D
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	2
5	1	2	2	3
6	1	2	3	1
7	1	3	1	3
8	1	3	2	1
9	1	3	3	2
10	2	1	1	1
11	2	1	2	2
12	2	1	3	3
13	2	2	1	2
14	2	2	2	3
15	2	2	3	1
16	2	3	1	3
17	2	3	2	1
18	2	3	3	2
19	3	1	1	1
20	3	1	2	2
21	3	1	3	3
22	3	2	1	2
23	3	2	2	3
24	3	2	3	1
25	3	3	1	3
26	3	3	2	1
27	3	3	3	2

3.3 ANALYSIS OF SIGNAL- TO-NOISE (S/N) RATIO

Since, improvement in the quality of results are related to minimization of passenger seat acceleration thus the equation used for the mathematical calculation of S/N ratio is "lower is better" as per objective for requirement. The calculated mean S/N ratio for ride comfort for semi-active quarter car system is Table as obtained by performing 27 simulation runs.

3.4 Analysis of S/N ratio

Table 12.4.1 Taguchi orthogonal array with Actual Values

Run number	Parameter				Peak Accl.	S/N Ratio
	A	B	C	D	(m/S^2)	
1	0.05	198850	26000	1200	0.4358	7.214255
2	0.05	198850	28000	1400	0.4338	7.254209
3	0.05	198850	30000	1600	0.4328	7.274255
4	0.05	210210	26000	1400	0.4283	7.365039
5	0.05	210210	28000	1600	0.4266	7.399583
6	0.05	210210	30000	1200	0.4496	6.943474
7	0.05	231360	26000	1600	0.4205	7.52468
8	0.05	231360	28000	1200	0.4432	7.068005
9	0.05	231360	30000	1400	0.4396	7.138846
10	0.075	198850	26000	1200	0.6158	4.211206
11	0.075	198850	28000	1400	0.6712	3.462961
12	0.075	198850	30000	1600	0.6657	3.534429
13	0.075	210210	26000	1400	0.6611	3.594657
14	0.075	210210	28000	1600	0.6595	3.615704
15	0.075	210210	30000	1200	0.6949	3.161554
16	0.075	231360	26000	1600	0.6504	3.736389

17	0.075	231360	28000	1200	0.6858	3.27605
18	0.075	231360	30000	1400	0.6789	3.363884
19	0.1	198850	26000	1200	0.9164	0.758298
20	0.1	198850	28000	1400	0.9081	0.837326
21	0.1	198850	30000	1600	0.9003	0.912255
22	0.1	210210	26000	1400	0.8978	0.936408
23	0.1	210210	28000	1600	0.8913	0.999522
24	0.1	210210	30000	1200	0.9394	0.542989
25	0.1	231360	26000	1600	0.8798	1.112321
26	0.1	231360	28000	1200	0.9296	0.634078
27	0.1	231360	30000	1400	0.9156	0.765884

The calculated mean S/N ratios for selected suspension parameters related to semi-active quarter car model with two degrees of freedom for defined levels i.e. from Level 1 to Level 3 in terms of mean peak acceleration. S/N plots for mean peak acceleration presented in Figure 12.4.1 and Figure 12.4.2 respectively, helpful in selection of optimum combination of suspension parameters as A1B3C1D3 having smallest S/N ratios for individual suspension parameters.

3.5 Taguchi Parameter Results

Table no. Taguchi Parameters and Ranks.

Level	A	B	C	D
1	7.2425	3.9399	4.0504	3.7567
2	3.5508	3.8399	3.8386	3.8577
3	0.8332	3.8467	3.7375	4.0121
Delta	6.4093	0.1000	0.3129	0.2555
Rank	1	4	2	3

Fig. 3.5.1 Main Effects of Plot for Means

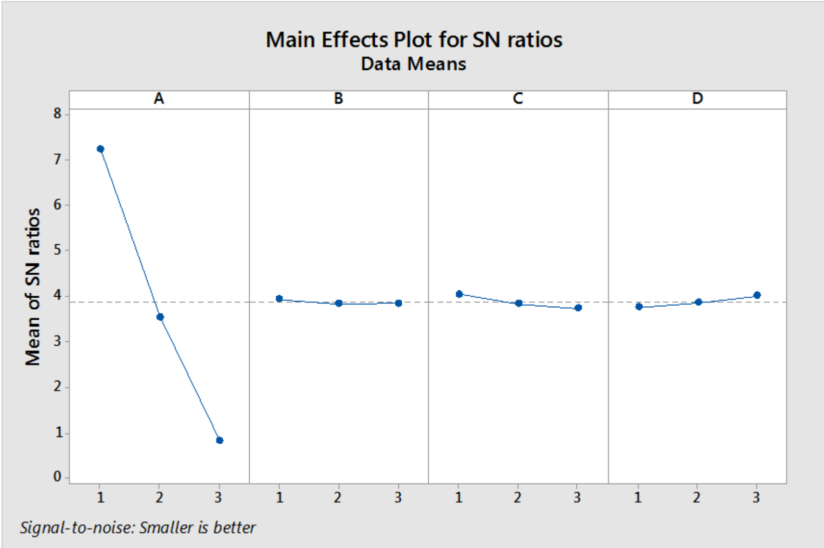


Fig. 3.5.2 Main Effects of Plot for SN Ratios

3.6 Result summary

Taguchi method was used to optimize Peak acceleration (Ride comfort) individually. The optimal setting found for both the desired results is A1B3C1D3 with the optimal values of 0.4205(m/s^2) for Ride comfort. Application of ANOVA technique shows that there

Are mainly three suspension parameters such as bump height (A) and primary suspension stiffness (B) and (C) for damping coefficient responsible for high contribution in achieving the lower values of Peak acceleration.

IV. GREY RELATIONAL ANALYSIS FOR SUSPENSION SYSTEM PARAMETER OPTIMIZATION

4.1 GRA procedure adopted

Grey relational analysis technique is based on the concept of multi-objective optimization of considered parameters for getting best combination of input parameters by taking the experimental results.[24] The procedure adopted to optimize the passenger Ride comfort using grey relational analysis (GRA) is as mentioned below:

1. Conversion of simulation data into S/N values.
2. Normalize the S/N values.
3. Calculation work related to Grey relational generating and grey relational coefficient.
4. Calculation of grey relational grade by taking the average values of the considered performance results.
5. Experimental result analysis using grey relational grade.
6. Selection of optimum levels of suspension system parameters.
7. Simulation run for the verification of optimal suspension system parameters.

4.2 CALCULATION OF GREY RELATIONAL COEFFICIENT AND GRADE

At initial stage, data pre-processing is performed for normalization of the simulation results in term of S/N ratios for Peak acceleration within the range of zero to one, this procedure is also known as grey relational generating [23-24]. In present case, the method selected for greyrelation computation is based on “the smaller the better” type taking the values of S/N ratios and can be represented as below. There are 3 main steps in GRA. The first step is data pre-processing. Data pre-processing is usually required when the range or unit in one data sequence is different from others or the sequence scatter range is too large. Data pre-processing is a method of transferring the original data sequence to a comparable sequence. Therefore, data must be normalized, scaled and polarized first into a comparable sequence before proceed to other steps.The processing is called generation of grey relation or standard processing.There are two process involves in this step; data representative and data normalization. First represent the original data series (X) as reference (x0) and comparative series (xi) . In this paper, reference series, (x0) represent the China’s crop yield and comparative series (xi) represent the ten affecting factors that influent the production of China’s crop.[25]Then implement the data normalization. There are a few formulas of data pre-processing available for the GRA such as equation 1,2,3 and 4 . The determination of which formula to be employed for data normalization is based on the characteristics of a data sequences, for example:

If the expectancy is the higher-the-better, then it can be expressed by

$x^{*}(k) = \frac{x_i^0(k) - min x_i^0(k)}{max\ x_i^0(k) - min\ x_i^0(k)}$……………………………………………………….…..1

If the expectancy is the lower-the-better, then it can be expressed by

$x^{*}(k) = \frac{max\ x_i^0(k) - x_i^0(k)}{max\ x_i^0(k) - min\ x_i^0(k)}$……………………………………………………......….2

Where
i = 1,…m; k = 1,...n.
mis number of experimental data items,nis the number of parameters;
x_i^0 (k)is the original sequence,
x_i^* (k) is the sequences after data pre-processing,
Min $x_i^0$and max $x_i^0$are the smallest and thelargest value of x_i^0(k)
In this study, Equation 1 is employed, since output of this study has the characteristic of the "smaller is better", means that if the value of grey relational grade is higher, than there is a strong relationship between comparative and reference series. The range of data is adjusted so as to fall within [0,1] range.
The second step is to locate the grey relational coefficient by using Eq. 3

$\varepsilon_i(k) = \frac{\Delta min + \zeta \Delta max\ (k)}{\Delta_{0,i}(k) + \zeta \Delta max}$……………………………………………………………..….3

Where,
$\Delta_{0,i}$= deviation sequences of the reference sequence and comparability sequence
$\Delta_{0,j}$ = $\| x_0^*(k) - x_i^*(k) \|$
Δmin = min min $\| x_0^*(k) - x_j^*(k) \|$,
Δmax = max max $\| x_0^*(k) - x_j^*(k) \|$,
$x_0^*(k)$= the reference sequence and
$x_i^*(k)$= the comparative sequence

ζ is known as identification coefficient with ζ€ [0,1], which can be adjusted to help make better distinction between normalization reference series and normalized comparative series. Normally ζ=0.5 is used because its offers moderate distinguishing effect and stability. Furthermore, based on mathematic proof, the value change of ζwill only change the magnitude of the relational coefficient but it won't change the rank of the grey relational grade. From the calculation, the values of Δmin and Δmax are respectively 0 and 1. Then replace these values in Equation 3 and we obtained. [24]

$\varepsilon_i(k) = \frac{0 + \zeta(1)}{\Delta_{0,i}(k) + \zeta(1)}$…………………………………………………………………….4

$\varepsilon_i(k) = \frac{0.5}{\Delta_{0,i}(k) + 0.5}$……………………………………………………………………..5

After the grey relational coefficient is derived, grey relational grade (GRG) is calculated by averaging the value of the grey relational coefficients. [10,11,12]. GRG is defined as the numerical measure of the relevancy between two systems or two sequences such as the reference sequence and the comparability sequence. The existing GRG between two series is always distributed between 0 and 1. Grey relational grade can be calculated using formula below

$\gamma_i = \left(\frac{1}{n}\right) \sum_{k=1}^{n} \varepsilon\ (k)$ ……………………………………………...……………6

Where γ_i represents GRG; the level of correlationbetween the reference sequence and thecomparability sequence. In this study, GRG is usedto indicate the degree influence that thecomparability sequence (10 affecting factors) couldexert over the reference sequence (China's cropyield). Therefore, if a particular comparabilitysequence is more important than the othercomparability sequences to the reference sequence, than the GRG for that comparability sequences and reference sequence will be higher than other GRG

Table 4.2.1 Grey Relational analysis

Run No.	Peak Accl	Normalized S/N Ratio	Deviation Sequence Peak Accl	Grey Relation Coefficient Peak Accl	Grey Relation Grade GRD	Rank
1	0.4358	0.9705	0.0295	0.9443	0.9443	6
2	0.4338	0.9744	0.0256	0.9512	0.9512	5
3	0.4328	0.9763	0.0237	0.9547	0.9547	4
4	0.4283	0.9850	0.0150	0.9708	0.9708	3
5	0.4266	0.9882	0.0118	0.9770	0.9770	2
6	0.4496	0.9439	0.0561	0.8992	0.8992	9

7	0.4205	1.0000	0.0000	1.0000	1.0000	1
8	0.4432	0.9563	0.0437	0.9195	0.9195	8
9	0.4396	0.9632	0.0368	0.9314	0.9314	7
10	0.6158	0.6236	0.3764	0.5705	0.5705	10
11	0.6712	0.5169	0.4831	0.5086	0.5086	15
12	0.6657	0.5275	0.4725	0.5141	0.5141	14
13	0.6611	0.5363	0.4637	0.5188	0.5188	13
14	0.6595	0.5394	0.4606	0.5205	0.5205	12
15	0.6949	0.4712	0.5288	0.4860	0.4860	18
16	0.6504	0.5569	0.4431	0.5302	0.5302	11
17	0.6858	0.4887	0.5113	0.4944	0.4944	17
18	0.6789	0.5020	0.4980	0.5010	0.5010	16
19	0.9164	0.0443	0.9557	0.3435	0.3435	25
20	0.9081	0.0603	0.9397	0.3473	0.3473	23
21	0.9003	0.0754	0.9246	0.3510	0.3510	22
22	0.8978	0.0802	0.9198	0.3522	0.3522	21
23	0.8913	0.0927	0.9073	0.3553	0.3553	20
24	0.9394	0.0000	1.0000	0.3333	0.3333	27
25	0.8798	0.1149	0.8851	0.3610	0.3610	19
26	0.9296	0.0189	0.9811	0.3376	0.3376	26
27	0.9156	0.0459	0.9541	0.3438	0.3438	24

Figure shows the linear graph for the variation of grey relational grade for different combinations of nine simulation runs. Basically, larger value of grey relational grade is desired since it favours the selection of suspension parameters to achieve the optimum / best results. The mean values of grey relational grade related to suspension parameters are calculated for each level as listed in Table13.2.1. Figure shows that both the desired characteristics/ results of quarter car simulation response are significantly dependent on the selected suspension parameters. It can be seen from Table that trial No. 7 has the maximum value of grey relational grade providing the best multiple performance characteristics

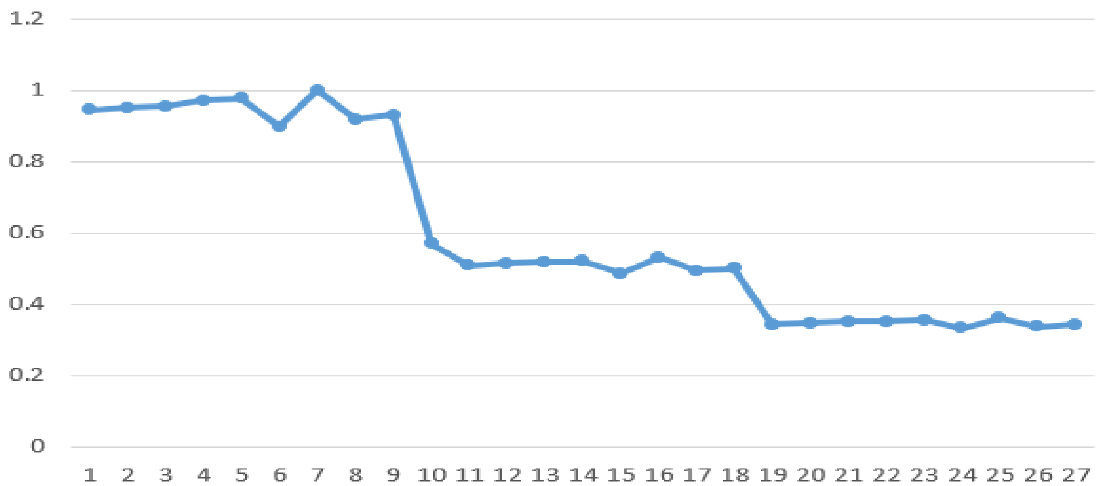


Fig.4.2.1 Number of test vs. GRG relational grade

4.3 Confirmation Test

Simulation analysis is performed, under the combinations of optimum values of suspension parameter namely A1B3C1D3 and achieved ride comfort is 0.4205. In the initial design A1B1C1D1 ride comfort achieved is 0.4205(m/s^2).

4.3 Grey Relation Rank & Table

Table 4.3.1 Grey Relational analysis rank

Parameter	Level			Max-Min	Rank
	1	2	3		
A	0.9498	0.5160	0.3472	0.6026	1
B	0.6095	0.6015	0.6021	0.0074	4
C	0.6213	0.6013	0.5905	0.0307	2
D	0.5920	0.6028	0.6182	0.0262	3

V. CONCLUSION

We have studied passive suspension and semi-active suspension and it can be concluded as per literature usually suspension system is used in vehicle and damped the vibration from road profile. However passive suspensions have long settling time. When car are moving in bumpy road, passive suspension driver cannot react in effective time. As a result, the usual suspension system cannot damped the excitation with small time interval.in order to remove this problem the properties of suspension system should be variable in nature. This task will be done by MR dampers in semi active suspension system as a actuator to suspension system. A number of research works have been carried out to compare negative suspension and semi-active suspension. Their dynamic and observable characteristics are compared with the results. There is improved performance in reference to performance standards such as peak overshot time, settling time, wheel deflection, suspension deflection, wheel position the body accelerates. In turn the art of improving the performance of the vehicle will increase the condition and ensure stability and this raises the level of passenger comfort. It has also been shown that the semi-active suspension system that uses the PID controller is superior to the passive suspension when exposed to any outside input (external stirring) in terms of wheel deflection, suspension deflection, body position response as well as body acceleration and wheel acceleration. Therefore, the use of the semi-active suspension system is the best passive suspension system from the perspective of vehicle handling as well as ride comfort and safety.

In this study, the effect of a MR Damper for suspension control was investigated. The characteristics of the MR damper are studied here. 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 semi-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 work 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 damper increase vehicle stability and to control suspension.The percentage variation in maximum sprung mass acceleration of semi-active suspension system based on Bingham model is 18.75% from passive suspension system. Also the percentage variation in maximum sprung mass acceleration of semi-active suspension with PID controller is 53.85% from semi-active suspension system and 62.5% from passive suspension system

Characteristics graph represents vertical sprung mass acceleration vs excitation bump frequency in RPM.The sprung mass acceleration is categorized in accordance to ISO 2631 standard as shown in given table 4.

Table.5.1ISO 2631-1:1997 Ride Comfort Chart [12]

Sprung mass acceleration	Ride Condition
Less than 0.315 m/s^2	Not comfortable
0.315 m/s^2 to 0.63 m/s^2	A little uncomfortable
0.5 m/s^2 to 1 m/s^2	Fairly uncomfortable
0.8 m/s^2 to 1.6 m/s^2	Uncomfortable
1.25 m/s^2 to 2.5 m/s^2	Very uncomfortable
Greater than 2 m/s^2	Extremely uncomfortable

The passive suspension system, semi-active suspension system with PID and MR damper (Bingham Model) is simulated. From the simulation results it is observed that the sprung mass peak acceleration for Passive is 0.8m/s^2, and semi-active suspension is 0.65m/s^2 and semi-active suspension with PID controller is 0.3m/s^2. The simulation results shows that semi-active suspension system with PID Bingham model gives lower value of maximum sprung mass acceleration for road excitation. Hence suspension model with semi-active suspension with PID controller provides good passenger comfort and vehicle stability than passive suspension system.

Hence, the semi-active suspension system gives the ride comfort as non- uncomfortable i.e. under the comfort level as per IS 2631 standard. In present work, optimization of primary as well as secondary suspension parameters of quarter car model having three degrees of freedom is studied using Taguchi and Grey Relational

Analysis separately using simulation results. Based on the optimized results in terms of Peak acceleration (Ride comfort) following conclusions can be made from the study:

1. Taguchi method was used to optimize Peak acceleration (Ride comfort) individually. The optimal setting found for both the desired results is A1B3C1D3 with the optimal values of 0.4205 for Ride comfort. Application of ANOVA technique shows that there
Are mainly three suspension parameters such as bump height (A) and primary suspension stiffness (B) and (C) for damping coefficient responsible for high contribution in achieving the lower values of Peak acceleration.
2. GRA method was helpful in achieving the optimum combination of suspension parameters for multiple suspension characteristics based on the steps followed in this method in terms of normalization of S/N ratios, weighted grey relational coefficients and grey relational grade respectively. Using ANOVA technique based on grey relational grade data, primary bump height (A) and primary suspension stiffness (B) and (C) for damping coefficient responsible for high contribution in achieving the lower values of Peak acceleration.
3. It can be concluded that using Taguchi and GRA method for simultaneous optimization of suspension parameters, the optimum combination of suspension parameters was found to be A1B3C1D3 in both the cases. Thus the results and procedures adopted for optimization of suspension parameters will be useful for automotive manufacturers in selection of best possible combination of suspension parameters to achieve desired ride comfort and safety to travelling passengers.

Table.5.2 Comparison of ranks between Taguchi and Grey relational analysis

parameter	Rank	
	Taguchi Method	Grey relational analysis
A	1	1
B	4	4
C	2	2
D	3	3

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