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Research Article

Optimization of Seat Displacement and Settling Time of Quarter Car Model Vehicle Dynamic System Subjected to Speed Bump

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Abstract

This paper presents an optimum concept to design passenger-friendly vehicle suspension system with the help of Taguchi Approach. A quarter car suspension systems is used as an illustrative example of vehicle model to demonstrate the concept and process of optimization. The numerical analysis is carried out in MATLAB/Simulink by varying the stiffness of shock absorber, damping co-efficient of shock absorber, stiffness of seat and damping co-efficient of seat. The values of suspension parameters have been obtained by using the Taguchi design of experimental method. The implication of input parameters on seat displacement (D_S) and settling time (S_T) has been investigated by using analysis of variation. The optimum system parameters are predicted using Taguchi analysis and verified by the confirmation analysis carried out by using MSC ADAMS.

Keywords*: Quarter car model, Taguchi Method, Optimization, Vehicle dynamic system*

1. Introduction

The vibration of vehicle and seat leads to driver fatigue, and decreases driver safety and operation stability of vehicle. Hence development of improved suspension system toachieve high ride quality is one of the important ride challenges in automotive industry. Therefore the goal of vehicle suspension system is to decrease the acceleration of car body as well as the passenger seat. In reality, some of the vehicle parameters are with uncertainties, so that it is an important issue to deal with vehicle suspension subjected to uncertain parameters in engineering application. The vehicle suspension system is responsible for driving comfort and safety as the suspension carries the vehicle-body and transmits all forces between body and road.It is well known that the ride characteristics of passenger vehicles can be characterized by considering the so-called “quarter-car” model (R. Kalidas *et al*. February 2013). Physical models for the investigation of vertical dynamics of suspension systems are most commonly built on the quarter-car model. In this paper, suspension parameters is been optimized. As the MSC ADAMS is a Multidynamic Simulation Software, so it gives real result as compared to MATLAB/ Simulink (S. J. Chikhale *et al*.). The optimum results obtained is confirmed by validating result against MSC ADAMS. Tires and suspensions are considered in three DoF quarter car model as shown in Fig 1

Where,
M_1 = Unsprung mass
M_2 = Sprung mass
M_3 = Mass of the driver
K_1 = Stiffness of tire
K_2 = Coefficient of damping of shock absorber
C_2 = Stiffness of shock absorber
K_3 = Stiffness of seat spring
C_3 = Coefficient of damping of seat damper
$X_1 = Vertical\ displacement\ of\ unsprung\ mass$
$X_2 = Vertical\ displacement\ of\ sprung\ mass$
$X_3 = Vertical\ displacement\ of\ seat$
$w = Road\ excitation$

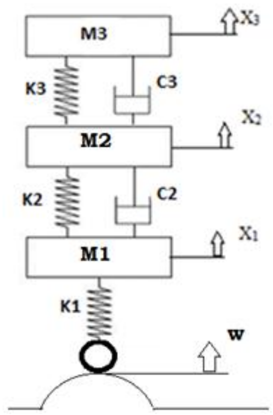

Fig.1 Quarter Car Mathematical Model

The equations of motion can be obtained using the Newton's second law for each of the three masses are in motion and Newton's third law of their interaction . These will be:

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$$M_1\ddot{X}_1 = -K_1(X_1 - w) + K_2(X_2 - X_1) + C_2(\dot{X}_2 - \dot{X}_1) \quad (1)$$

$$M_2\ddot{X}_2 = K_3(X_3 - X_2) + C_3(\dot{X}_3 - \dot{X}_2) - K_2(X_2 - X_1) - C_2(\dot{X}_2 - \dot{X}_1) \quad (2)$$

$$M_3\ddot{X}_3 = -K_3(X_3 - X_2) - C_3(\dot{X}_3 - \dot{X}_2) \quad (3)$$

2. MATLAB/Simulink Model

The experiment is simulated using MATLAB/Simulink software. Here a quarter car suspension model is been considered, added to it seat's cushioning effect is included. The mathematical modeling of quarter car model with seat suspension is shown in Fig 2. The shown quarter car model is made to run over a speed bump. The vertical displacement of seat (D_S) and settling time (S_T) of seat is taken as objective parameters. The stiffness of shock absorber (K_2), damping co-efficient of shock absorber (C_2), stiffness of seat (K_3) and damping co-efficient of seat (C_3) is taken as input parameters. The values of input parameters is been varied and its effect on objective parameter is studied. The model is made to run on the test road. The experimental parameter is given in the Table 1. The design of experiments is planned by using L27 orthogonal array with 4 factors at 3 levels.

Table 1 Experimental Parameters

Parameter	Symbol	Value
Sprung mass	M_S	625 Kg
Mass of driver	M_D	80 Kg
Stiffness of seat spring	A	60 N/mm
Coefficient of damping of seat damper	B	5 Ns/mm
Stiffness of damping of shock absorber	C	2 N/mm
Coefficient of damping of shock absorber	D	0.2 Ns/mm
Stiffness of tire	K_t	100000 N/mm
Unsprung mass	M_{US}	35 Kg

Table 2 Taguchi Quarter Car Level Table

Parameter	Unit	Level	Level 1	Level 2	Level 3
Stiffness of shock absorber	Ns/mm	3	60	220	500
Damping co-efficient of shock absorber	Ns/mm	3	5	10	15
Stiffness of seat	Ns/mm	3	2	6	10
Damping co-efficient of seat	Ns/mm	3	0.2	0.5	0.8

The vertical displacement of the seat is calculated from the output reading from the MATLAb/Simulink software during travelling over bump with the settling displacement. The above is demonstrated in the Fig. 3, while the settling time is calculated by measuring the time for stabilization of seat after crossing the speed bump. The above is demonstrated in the Fig. 3. The graph for tire displacement is shown in the Fig. 4.

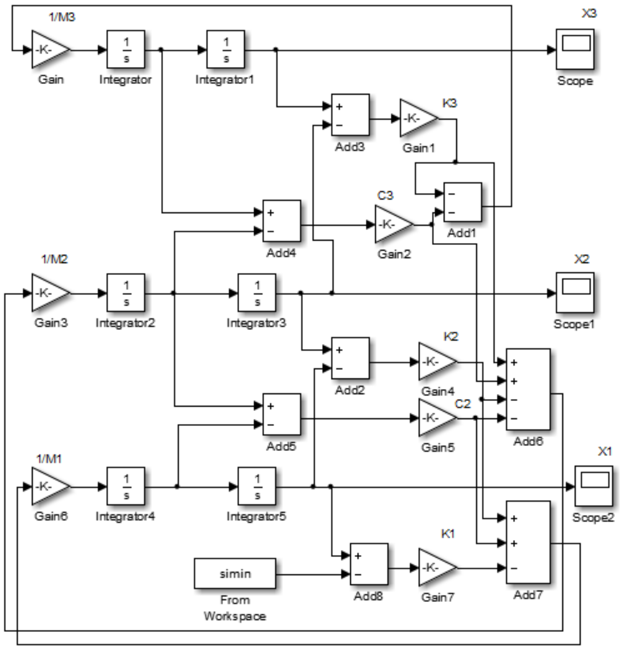

Fig. 2 MATLAB Representation of Equation (1), (2) and (3).

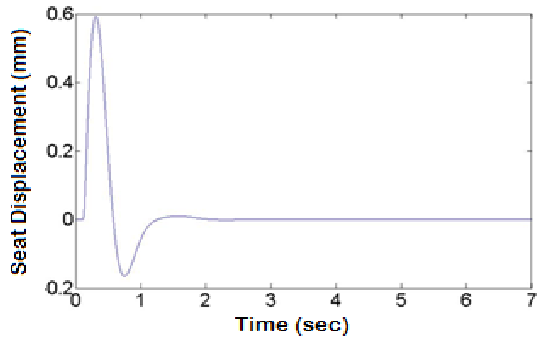

Fig. 3 Demonstration of Graph foe seat displacement and settling Time

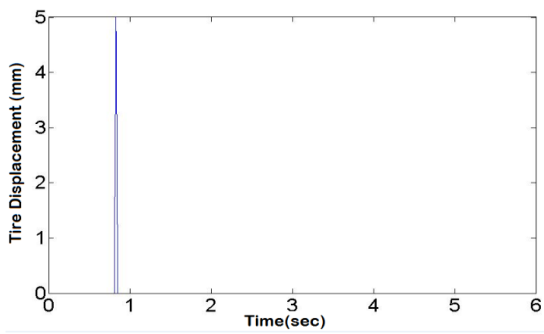

Fig.4 Input Tire Displacement

3. Exploratory Experiments

One Variable at a Time (OVAT) is initially used for studying the vertical displacement of seat (DS) and

Table 3 Experimental Design using L27orthogonal Array

Run	K_3	C_3	K_2	C_2	Displacement (mm)	Time for stabilization of seat (sec)	S/N ratio of displacement (db)	S/N ratio of time for stabilization of seat (db)
1	60	5	2	0.2	0.55	5.2	5.193	-14.320
2	60	5	2	0.5	0.59	2.1	4.583	-6.444
3	60	5	2	0.8	0.64	2.1	3.876	-6.444
4	60	10	6	0.2	0.82	4.3	1.724	-12.669
5	60	10	6	0.5	0.768	2.1	2.293	-6.444
6	60	10	6	0.8	0.79	1.9	2.047	-5.575
7	60	15	10	0.2	1.1	4.1	-0.828	-12.256
8	60	15	10	0.5	0.94	2.1	0.537	-6.444
9	60	15	10	0.8	0.93	1.6	0.630	-4.082
10	220	5	6	0.2	1.14	5.2	-1.138	-14.320
11	220	5	6	0.5	1.11	1.92	-0.906	-5.666
12	220	5	6	0.8	1.16	1.6	-1.289	-4.082
13	220	10	10	0.2	1.34	4.9	-2.542	-13.804
14	220	10	10	0.5	1.2	2.4	-1.584	-7.604
15	220	10	10	0.8	1.2	1.6	-1.584	-4.082
16	220	15	2	0.2	0.5	4.7	6.021	-13.442
17	220	15	2	0.5	0.673	2.07	3.440	-6.319
18	220	15	2	0.8	0.83	1.6	1.618	-4.082
19	500	5	10	0.2	1.5	4.8	-3.522	-13.625
20	500	5	10	0.5	1.52	2.3	-3.637	-7.235
21	500	5	10	0.8	1.6	1.2	-4.082	-1.584
22	500	10	2	0.2	0.55	4.6	5.193	-13.255
23	500	10	2	0.5	0.84	2.2	1.514	-6.848
24	500	10	2	0.8	1.13	1.6	-1.062	-4.082
25	500	15	6	0.2	0.94	4.9	0.537	-13.804
26	500	15	6	0.5	1.02	1.82	-0.172	-5.201
27	500	15	6	0.8	1.16	1.2	-1.289	-1.584

settling time (ST). Here one variable at a time is varied and its effects on DS and ST are studied while keeping all other variables at fixed value. For each input parameter, six different levels of experiment have been done and single run is performed for each level. Though OVAT analysis doesn't provide clear picture of the phenomena over the entire range of input parameters, it accentuates some important characteristics. The range value levels for later stage experiments are decided by using this OVAT analysis.

4. Design of Experiments based on Taguchi Method

A specifically designed experimental procedure is required to identify the performance distinctiveness of system and to evaluate the effects of input parameters on objective parameters (Javad Marzbanrad *et al*. March 2013). The traditional methods cannot be used because, when the number of input parameters increases, large number of experiments have to be done. In this paper, Taguchi method is used to identify the optimal suspension parameters for minimum DS and minimum ST in quarter car model. In Taguchi method the process parameters are separated into two main groups. One is control factor and another is a noise factor (P.J. Ross, 1996). The noise factors denote all factors that cause variation and the control factors are used to select the best input parameters. Taguchi proposed orthogonal arrays to acquire the attribute data, and to analyze the performance measure of the data to decide the optimal process parameters (Shyam Kumar Karna, *et al* .November 2012). The orthogonal array forms the basis for the experimental analysis using Taguchi method.

In this paper four machining parameters were used as control factors and each factor was designed to have 3 levels (Table 2). A L27 orthogonal array table with 27 rows was chosen for the experiments (Table 3).

5. Data Analysis and Discussion

The analysis of variance was used to identify the important input parameters which effects seat displacement (DS) and settling time (ST). In Taguchi method (P.J. Ross 1996), a loss function is used to calculate the deviation between the experimental value and the desired value. The signal-to-noise (S/N) ratio is then derived from the loss function. Lower is better (LB), nominal is best (NB), higher is better (HB) are the three types of S/N ratios available depending upon the type of characteristics. In vehicle suspension system lower seat displacement (DS) and lower settling time (ST) be as a sign of better ride quality. Therefore "LB" is chosen for the both seat displacement (DS) and settling time (ST) and it is calculated as the logarithmic transformation of the loss function as shown below

$$Lower\ is\ better\ characteristic\ n_{ij} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (4)$$

"HB" is calculated as logarithmic transformation of loss function as shown below.

$$Higher\ is\ better\ characteristic\ n_{ij} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (5)$$

The greatest value of n_{ij} corresponds to the optimal level of input parameters. The above mentioned equations [4] is applied to calculate the Şij values for each experiment of L27 [table 3].

On analyzing the S/N ratio, the optimal input parameters for seat displacement (D_S) was obtained at 60 N/mm stiffness of shock absorber (level 1), 15 Ns/mm damping co-efficient of shock absorber (level 3), 2 N/mm stiffness of seat (level 1) and 0.2 Ns/mm damping co-efficient of seat (level 1). The effect of input parameters on seat displacement (D_S) is shown in Fig. 5. The optimum values of settling time (S_T) is obtained at 500 N/mm stiffness of shock absorber (level 3), 15 Ns/mm damping co-efficient of shock absorber (level 3), 6 N/mm stiffness of seat (level 2) and 0.8 Ns/mm damping co-efficient of seat (level 3). The effect of input parameters on settling time (S_T) is shown in Fig. 6. Accurate and optimum combination of machining parameters and their relative importance on surface roughness and material removal rate was obtained using ANOVA. The result of ANOVA is shown in Tables 4,5,6 and 7.

Table 4 Analysis of variation test for seat displacement using S/N Ratio

S/N Ratio Response Table for Displacement				
Run	K_2	C_2	K_3	C_3
1	2.228	-0.10252	3.375	1.1819
2	0.226	0.666689	0.201	0.6742
3	-0.724	1.166105	0.031	-0.1259
Delta	2.952	1.2686	3.344	1.3078
Rank	2	4	1	3

Table 5 Analysis of variation test for seat displacement using Mean

Mean Response Table for Displacement				
Run	K_2	C_2	K_3	C_3
1	0.792	1.090	0.893	0.838
2	1.017	0.960	0.990	0.862
3	1.140	0.899	1.259	1.049
Delta	0.348	0.191	0.366	0.211
Rank	2	4	1	3

Table 6 Analysis of variation test for Settling Time using S/N Ratio

S/N Ratio Response Table for Settling Time				
Run	K_2	C_2	K_3	C_3
1	-8.298	-8.191	-8.360	-13.499
2	-8.156	-8.263	-7.705	-6.467
3	-7.469	-7.468	-8.051	-3.955
Delta	0.829	0.795	0.309	9.544
Rank	2	3	4	1

Table 7 Analysis of variation test for Settling Time using Mean

Mean Response Table for Settling Time				
Run	K_2	C_2	K_3	C_3
1	2.833	2.791	2.908	4.744
2	2.888	2.844	2.771	2.112
3	2.736	2.677	2.778	1.600
Delta	0.152	0.167	0.137	3.144
Rank	2	3	4	1

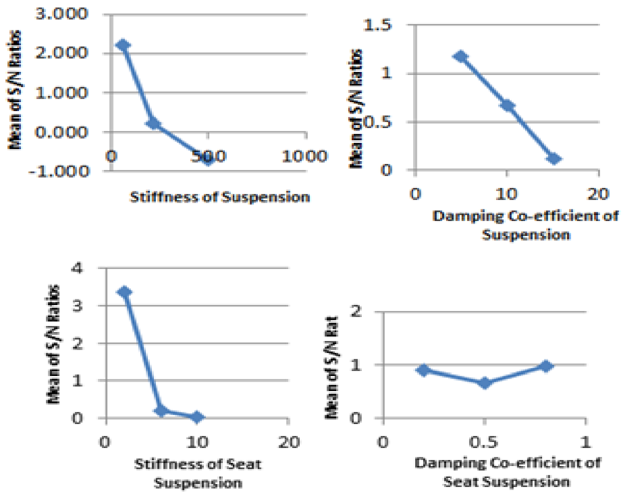

Fig.5 S/N Ratio Plot for Minimization of Seat Displacement (D_S)

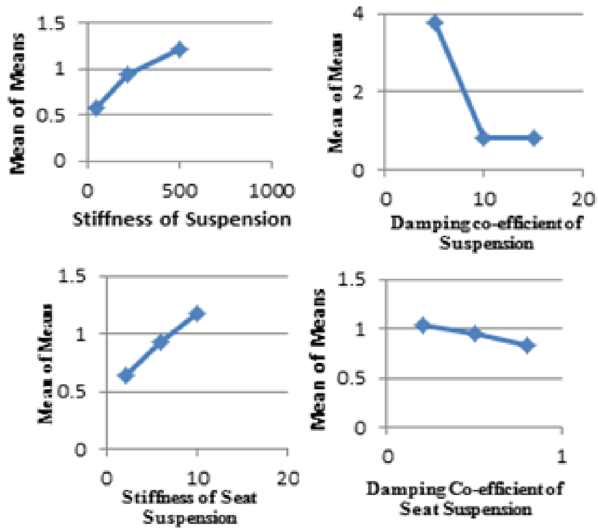

Fig.6 Mean Plot for Minimization of Seat Displacement (D_S)

From the Fig. 5 and 6 stiffness of shock absorber and stiffness of seat are the most significant parameters which effect seat displacement (D_S), while the effects of damping co-efficient of shock absorber and damping co-efficient of seat on seat displacement (D_S) were insignificant. From Fig 7 and 8, we conclude that damping co-efficient of shock absorber and damping co-efficient of seat is the most significant parameter which effect settling time (S_T), while stiffness of shock absorber and stiffness of seat have less effect on settling time (S_T).

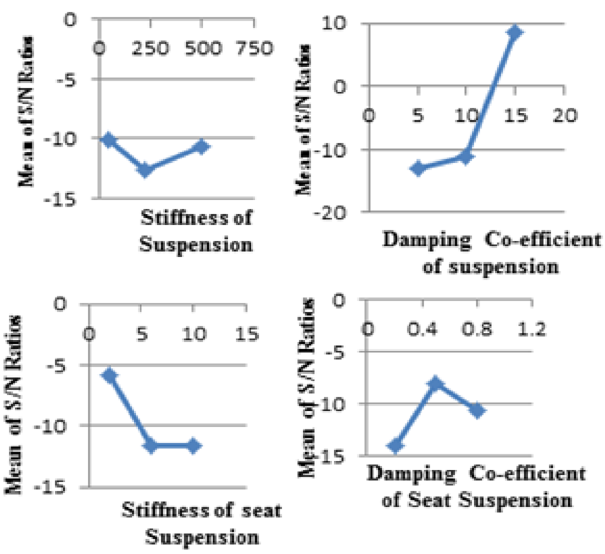

Fig.7 S/N Ratio Plot for Minimization of Settling Time (ST)

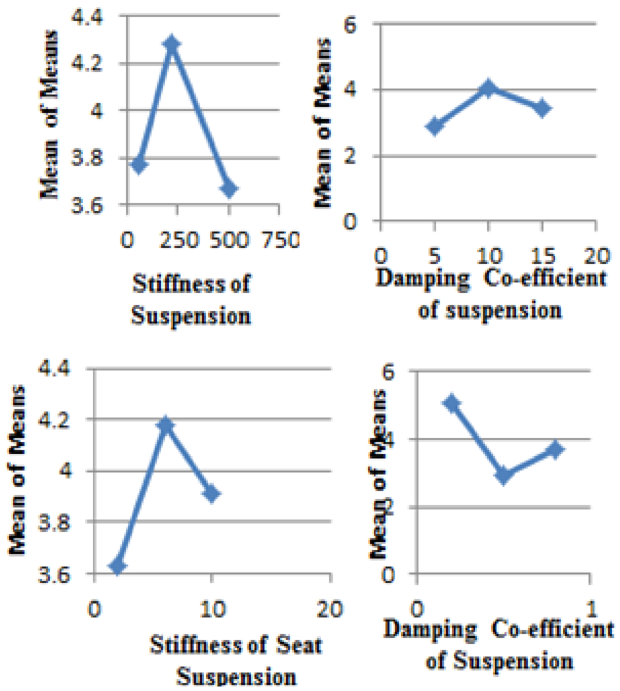

Fig.8 Mean Plot for Minimization of Settling Time (ST)

6. Confirmation

The validation is the final step in the first iteration of the design of experiment process. Validation is done to validate the conclusion drawn from the analysis phase. The validation is performed with specific levels previously evaluated. In this study after predicting the response under optimum conditions, a new experiment was conducted with the most favorable levels of system parameters. MSC ADAMS is multi-body dynamic simulation software which always shows real results as compared to MATLAB/Simulink software.

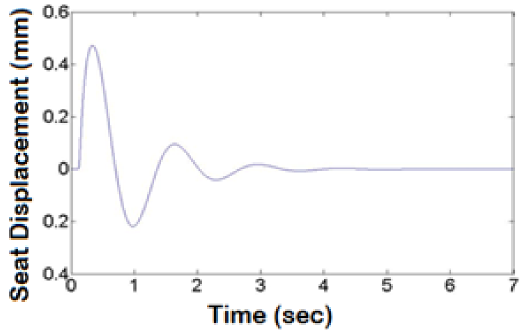

Fig.9 Graph for Optimum Level of Seat Displacement (D_S) using MATLAB/Simulink

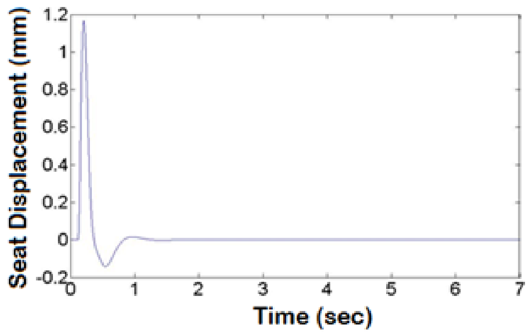

Fig.10 Graph for optimum level of Setting Time(S_T) using MATLAB/simulink

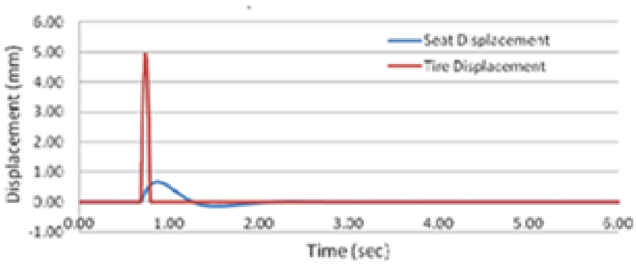

Fig.11 Graph for Optimum Level of Seat Displacement (D_S) using MSC ADAMS

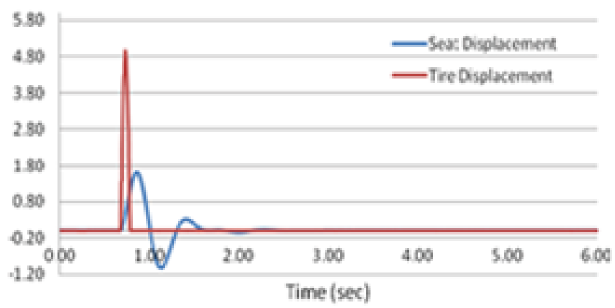

Fig.12 Graph for optimum level of Setting Time(S_T) using MSC ADAMS

The results of validation against MSC ADAMS using optimal system parameters are shown in Table 8. The optimum level for Seat displacement (D_S) obtained from numerical analysis is0.48. The MSC ADAMS shows a result is about 0.55 with an error percentage of about 12.72%. The optimum level for settling time (S_T) obtained from numerical analysis is 1.7sec, while The MSC ADAMS shows results is about 2.0sec with an error percentage of about 4.8%. The Fig. 7 shows the graph of vehicle seat displacement for optimal level of Seat displacement (D_S) and Fig. 8 shows the graph of vehicle seat displacement for optimal level of settling time (S_T).

Table 8 Confirmation

Output Parameter	Results in MATLAB/Simulink	Results in MSC ADAMS	Error in %
Seat Displacement (mm)	0.48	0.55	12.72
Time for Stabilization (sec)	1.7	2.0	17.6

Conclusion

The factors like The stiffness of shock absorber (A), damping co-efficient of shock absorber (B), stiffness of seat (C) and damping co-efficient of seat (D) are selected for minimization of Seat displacement (DS) and minimization of settling time (ST) of seat for the quarter car model. The results of the MATLAB/Simulink satisfied with the MSC ADAMS. An error of about 12.72% is observed for Seat displacement (D_S) and an error of about 17.6% is found with settling time (S_T).

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