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AN INVESTIGATION OF THE SUSPENSION CHARACTERISTICS OF THE LINE MODEL OF THE VEHICLE USING THE TAGUCHI METHOD

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It can be considered that the suspension system is one of the most important systems in the VEHICLE. Where it is responsible for the stability and balance of the vehicle's structure on the roads and curves to ensure the comfort of passengers. Also, it absorbs the shocks resulting from the unevenness of the road and prevents it from reaching the wheelhouse. The influence of the suspension constructive parameters in order to obtain the smallest level of displacements of the sprung mass has been investigated. The following control parameters are the stiffness of the sprung, unsprung mass, and the damping of the sprung mass. The parameter which affects most displacements of the sprung mass was determined by applying the analysis of variance (ANOVA). The investigation was conducted using MATLAB/SIMULINK software, and a line model of a quarter of the vehicle was created. It was determined that the stiffness of sprung has the most significant influence on the displacement of the sprung-mass, which further affect the vehicle's comfort.

Keywords: ANOVA, vertical dynamics, MATLAB/SIMULINK, comfort.

1. Introduction

Ride comfort is one of the most important factors and criteria for evaluating any vehicle. Thousands of theoretical and experimental studies have been conducted by the automotive industry sector and university academics to develop and improve vehicle ride comfort. The roughness of the road produces forced vibration, which negatively affects the comfort of riding, as, in some cases, it can result in chaotic movements. The vertical dynamics deals with vertical oscillations, which are caused by road unevenness. The suspension system can be considered one of the main elements of building a successful vehicle model. Therefore, the optimal magnitudes of the elastic and damping parameters for the suspension should be selected. It can be summarized the main objectives of the suspension system as follows [1]:

- The maximum possible isolation of the oscillations which are transferred to the cabin.
- The minimum possible changes in the forces are transferred to the vehicle structure.
- Keep the displacement of the suspension within the allowable range based on the internal fenders of the vehicle.

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The characteristics of the vehicle suspensions are a function of many factors such as the type of vehicle, task of vehicle purpose, nature of the road terrain, etc. The design The design criterion of the suspension system is determined directly by the driving quality (comfort) [2].

In order to obtain the highest possible comfort, it should be taken into consideration the geometrical parameters and the most effective variables [3]. While Harris and Piersol [4] developed a new mathematical model of the suspension system to determine the optimal values of the design parameters. Their main objective was to make the vertical displacements as minimum as possible (minimum vertical accelerations) to enhance comfort during driving [5]. The other effective factors on the vehicle's comfort are the magnitude of the displacement of the sprung-mass and the quality of the road [6]. Materdey found that reducing the tire's stiffness and sprung-mass with increasing the damping of the sprung-mass led to decrease oscillations significantly [7]. Maher and Young [8] studied the effect of the stiffness of the tire and damping on the behavior and performance of the suspension system. They found that when the tire damping was applied, the vertical oscillations of the sprung mass were reduced.

This paper presented a full detail of building a new model of the quarter of the vehicle using Matlab/SIMULINK to investigate the characteristics of the suspension system. The Taguchi Method (L9 array) was used to determine the effect and contribution of each design parameter of the suspension system (stiffness's and damping factors). Furthermore, the results were analyzed statistically and practically using Minitab 16 software.

2. Model of the quarter of the vehicle

This section presents the oscillatory model of the quarter of the vehicle that drives on the flat road, as shown in Fig.1. It was assumed that the road contains some bumps, which it represents as an impulse (F_o). The model consists of the stiffness (k_2) and damping (c_2) of sprung mass (m_2), while the unsprung mass (m_1) has only stiffness (k_1). The differential equations which describe the model based on D'Alembert's principle can be written as follows:

$$m_2 \cdot \ddot{z}_2 + c_2 \cdot (\dot{z}_2 - \dot{z}_1) + k_2 \cdot (z_2 - z_1) = F_o, \tag{2.1}$$

$$m_1 \cdot \ddot{z}_1 - c_2 \cdot (\dot{z}_2 - \dot{z}_1) - k_2 \cdot (z_2 - z_1) + k_1 \cdot z_1 = 0. \tag{2.2}$$

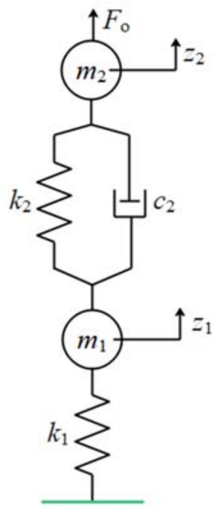

Fig.1. The line model with two masses.

The model of the quarter vehicle mass has two degrees of freedom (z_1 and z_2). It was simplified the algorithm in order to show the vehicle's comfort with respect to the unevenness of the road [9]. Besides that, the developed model is compatible with the independent suspension system. Also, it must be satisfied the conditions of the uncoupled oscillations in the front and rear axles. Some other researchers applied half of the vehicle [10] and the entire vehicle [11]. A new Matlab/SIMULINK was built to find the solution to the differential equations, as shown in Fig.2. It was selected MATLAB/SIMULINK because of its ability to model the nonlinear systems with a minimum cost of time and to take into consideration the initial conditions [12-14]. Where the stiffness of the tire is proportional linearly to the tire pressure [15]. Table 1 lists the values of applied characteristics used in the analysis. Fig.3 shows the impulse that faced the vehicle and the time of the impulse duration. After $3\,s$ of driving, the vehicle encounters the impulse with a value of $160\,N$. This impulse acts on the vehicle for a period of $2\,s$ and disappears after that.

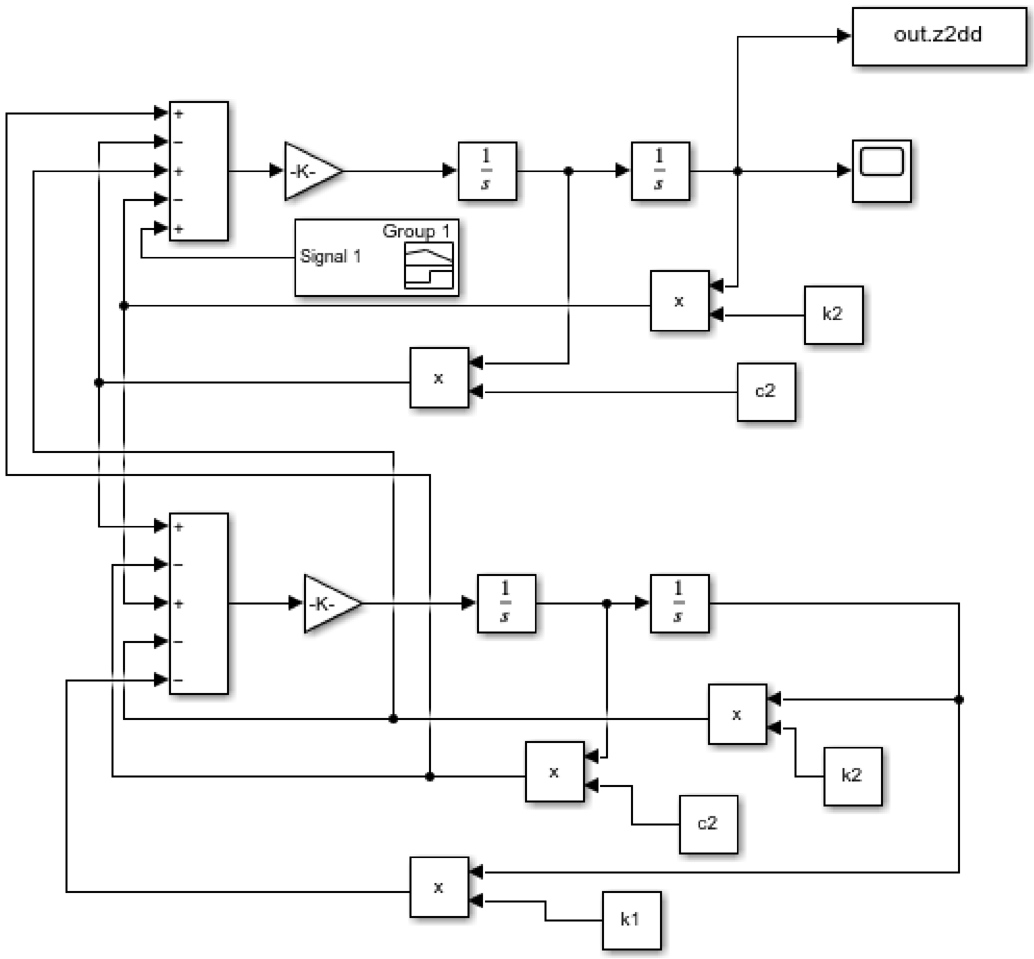

Fig.2. The developed model using Matlab/ SIMULINK.

Table 1. The values of applied characteristics [1, 15].

$m_1\,(kg)$	$m_2\,(kg)$	$k_1\,(N/m)$	$k_2\,(N/m)$	$c_2\,(N/m{\cdot}s)$	$F_o\,(N)$
26	*220*	*200,000*	*29,114*	*1,725*	*160*

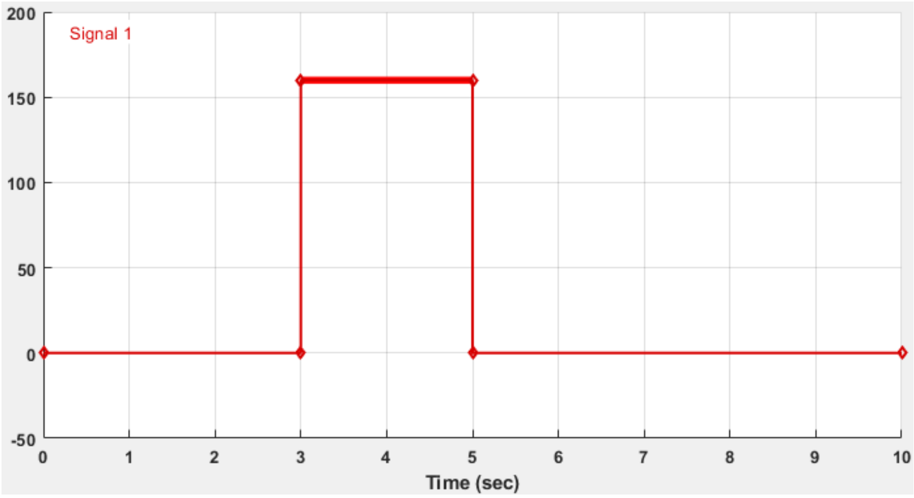

Fig.3 The impulse function during the analysis time.

3. The influential parameters on the displacement of sprung mass

The Taguchi method was used in a wide range of applications to improve the quality of products in different branches of the industry sectors [16]. Furthermore, during the estimation of the most influential parameters on the behavior of the systems [17]. In the control problems, the values of parameters should be specified based on demands, where Table 2 lists the demand values for the present case. Based on the defined values of each level of control parameters, the design of the experiments was planned using MINITAB software. Table 3 lists the results of the design of the experiments.

Table 2. The parameters of the suspension and their levels

Parameters	Symbol	Level 1	Level 2	Level 3
$k_1 (N/m)$	A	*190,000*	*200,000*	*210,000*
$k_2 (N/m)$	B	*28,114*	*29,114*	*30,114*
$c_2 (N/m{\cdot}s)$	C	*1,625*	*1,725*	*1,825*

Table 3. The design of the experiments

No. test	Factor A	Factor B	Factor C
1	*190,000*	*28,114*	*1,625*
2	*190,000*	*29,114*	*1,725*
3	*190,000*	*30,114*	*1,825*
4	*200,000*	*28,114*	*1,725*
5	*200,000*	*29,114*	*1,825*
6	*200,000*	*30,114*	*1,625*
7	*210,000*	*28,114*	*1,825*
8	*210,000*	*29,114*	*1,625*
9	*210,000*	*30,114*	*1,725*

In order to obtain the minimum possible displacements of sprung mass, which means to drive comfortably as much as possible (small value of S/N ratio). It can be written the formula to find S/N ratio as follows

$$S/N = -10\log\frac{1}{n}\left(y_1^2 + y_2^2 + \ldots + y_n^2\right). \tag{3.1}$$

3. Results and discussions

This section will present the results of the suspension system and discuss the effect of each parameter on the displacement of the sprung-mass system.

3.1. The size of the displacement of sprung-mass of the vehicle

During the vehicle driving, in one moment, the vehicle faced impulse as a force with value $160\,N$, in the up direction. After that, it was calculated the vertical displacement of $0.008794\,m$, for a time period of $0.304435\,s$ as shown in Fig.4. After the time when the maximum value of the displacement occurred, the suspension damped very quickly. As a result of this damping, oscillations appeared. The sprung mass was kept in a constant position by applying the force for $2\,s$.

After $2\,s$, the force stopped acting on the sprung mass, which caused to retrieve the sprung mass quickly in the down direction. This caused the compression in the suspension system, and again suspension damps the oscillations. After that, the sprung mass return to the initial position (the same position before applying the impulse force).

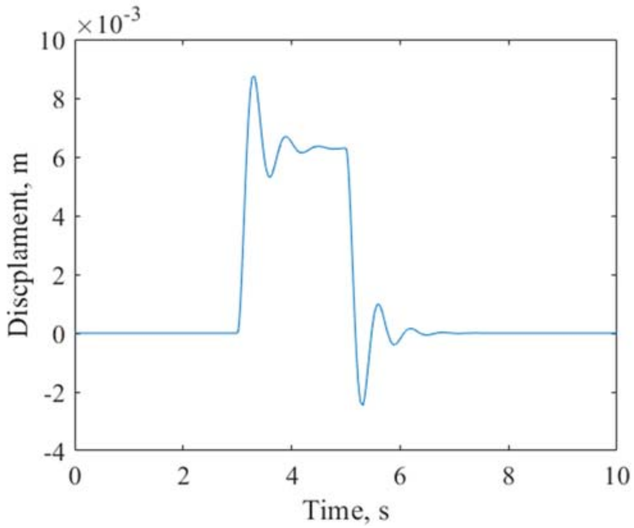

Fig.4. The variation of displacement with time.

3.2. Determination of the influential parameters on the displacement of the sprung mass using ANOVA

The maximum values of the displacement and SN ratio of the sprung mass (for each test) are shown in Table 4. Based on the results of the parameters, it was noticed that the most significant effect on the displacement of the sprung mass occurred by the stiffness. While the lowest effective parameter was the value of the tire's stiffness, as shown in Table 5.

It was found that the most significant that affects the behavior of the system is the stiffness, with a contribution of *58.63%*, pursued by the damping of the sprung mass with a contribution of *33.61%*. While the lowest contribution was for the stiffness of the unsprung mass, with *7.49%*, as listed in Table 6. Based on the F ratio (Test) results, the same conclusions can be found: the highest value has the highest effect on the output. The smaller stiffness of the sprung mass pulls the greater relative displacements of the sprung mass, which can further negatively influence the comfort due to the oscillation.

Table 4. The values of displacement and S/N ratio.

No. of test	Displacament (m)	SN ratio (db) for displacament
1	*0.009208*	*40.7167*
2	*0.008847*	*41.0641*
3	*0.008544*	*41.3668*
4	*0.009005*	*40.9103*
5	*0.008619*	*41.2909*
6	*0.008752*	*41.1579*
7	*0.008778*	*41.1321*
8	*0.008872*	*41.0396*
9	*0.008522*	*41.3892*

Table 5. The ranking of control factors of the output variable.

	Control factors		
	A	B	C
1	*41.05*	*40.92*	*40.97*
2	*41.12*	*41.13*	*41.12*
3	*41.19*	*41.30*	*41.26*
Delta	*0.14*	*0.41*	*0.29*
Rank	*3*	*1*	*2*

Table 6. Analysis of variance for signal-to-noise ratio.

	Degree of freedom	Sequential sum of squares	Adjacent sum of squares	Adjacent mean squares	Test	Pure sum of squares	Percentage Contribution, %
A	*2*	*0.028472*	*0.028472*	*0.014236*	*26.62*	*0.036*	*7.49*
B	*2*	*0.222967*	*0.222967*	*0.111484*	*208.43*	*0.005*	*58.63*
C	*2*	*0.127812*	*0.127812 .*	*0.063906*	*119.48*	*0.008*	*33.61*
Residual error	*2*	*0.001070*	*0.001070*	*0.000535*			
Total	*8*	*0.380321*					*100.00*

Table 4 lists the values of the displacements and values of S/N ratio, and also it was presented the results in Figs. 5 and 6. The other criterion to assess the influence of the control factor is the slope of the line of the control factor, where the small slope means the low influence of the control factor on the output variable. While the slope of the control factor rises, the influence of the control factor increases on the output.

It was found that the optimal variant occurred when the value of the unsprung mass stiffness and sprung mass stiffness were the highest values. The value of the sprung mass damping was *1725 N / m·s*, that is, A3-B3-C2.

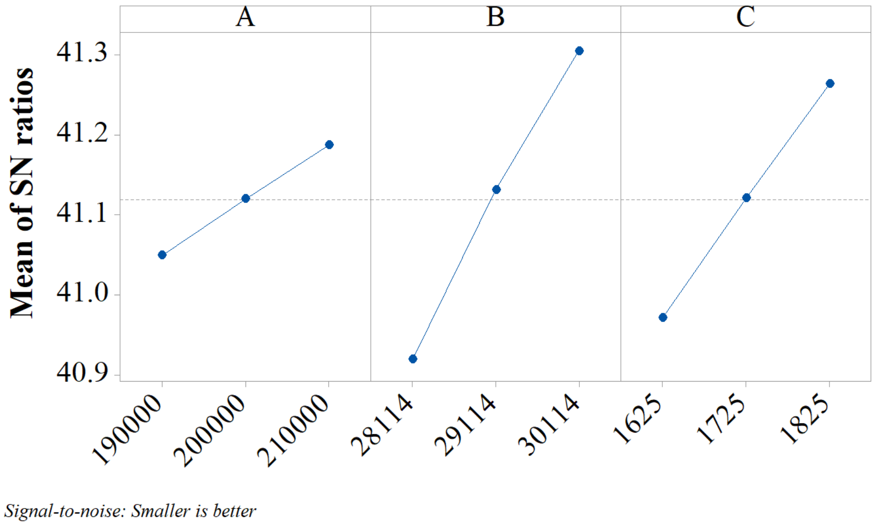

Fig.5. Main effects plot for SN ratio of displacement.

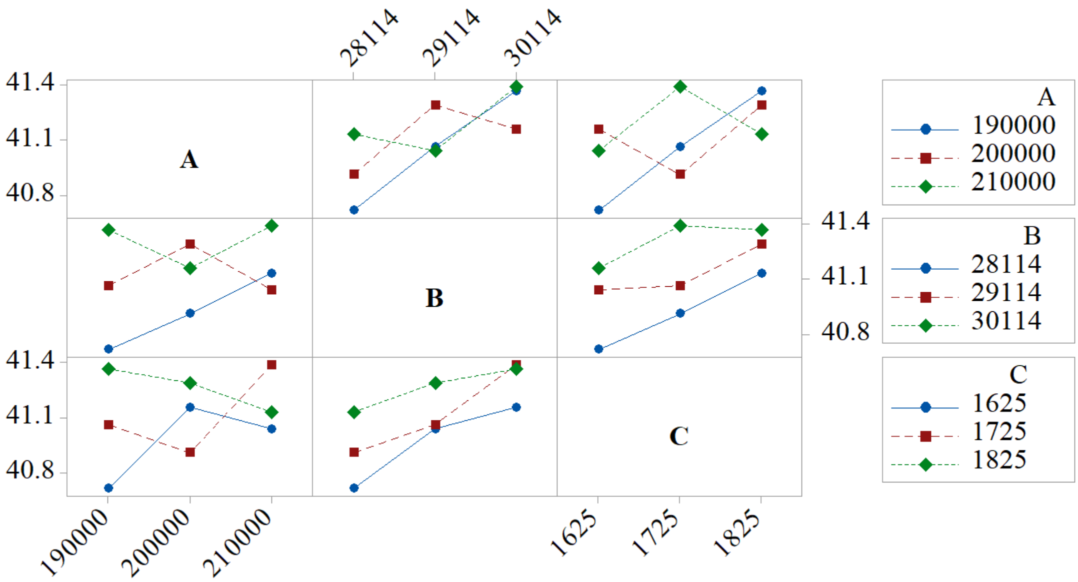

Fig.6. Interaction plot for SN ratio for the average values of the displacement.

The research of Ebrahimi-Nejad *et al*. [18] showed that the increase in the stiffness of the sprung mass spring led to reducing the displacement of the sprung mass. The best-ranked parameter corresponds to the combination of A3-B3-C2. While the most inconvenient characteristics of comfort were obtained when the values of all control parameters were the lowest.

It can be noticed that the parameters of the stiffness and damping for the sprung mass located in the first and second places have the same value, except the values of the stiffness of the unsprung mass are different. In the first case, the value of the unsprung mass stiffness was considered to be the highest. While in the second case, it was the lowest value. Also, it was found that the value of the unsprung mass stiffness didn't significantly influence the displacement of the sprung mass (the contribution is only 7.49%, as shown in Table 6).

Table 7. The ranking of the tests based on Taguchi method

No. of test	Factor A	Factor B	Factor C	Displacament, *m*	Rank
1	*190,000*	*28,114*	*1,625*	*0.009208*	*9*
2	*190,000*	*29,114*	*1,725*	*0.008847*	*6*
3	*190,000*	*30,114*	*1,825*	*0.008544*	*2*
4	*200,000*	*28,114*	*1,725*	*0.009005*	*8*
5	*200,000*	*29,114*	*1,825*	*0.008619*	*3*
6	*200,000*	*30,114*	*1,625*	*0.008752*	*4*
7	*210,000*	*28,114*	*1,825*	*0.008778*	*5*
8	*210,000*	*29,114*	*1,625*	*0.008872*	*7*
9	*210,000*	*30,114*	*1,725*	*0.008522*	*1*

4. Conclusions

The vehicle's comfort is essential for the driver and passengers to feel good during the drive. When the vehicle is driven on an unpaved road, it is necessary to keep the transferred oscillations into the vehicle's cabin as minimum as possible.

In this research paper, it was studied and analyzed the effective parameters and their weights on the characteristics of suspension of a line model for a quarter of the vehicle. The objective was to find which suspension parameter has the most significant influence on reducing the sprung mass displacement. ANOVA software was used to achieve the analysis. It was concluded that the stiffness of the sprung has the most significant influence on the reduction of the sprung- mass displacement. In subsequent research, other techniques such as Fuzzy Logic and Neural Network will be used to obtain solutions for more complex suspension systems of the vehicles

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Nomenclature

k_1, k_2 – stiffness $[N/m]$

m_1, m_2 – mass $[kg]$

F_o – the impulse force $[N]$

c_1, c_2 – damping $[N.m/s]$

z_1, z_2 – the displacement $[m]$

$\dot{z}_1, \dot{z}_2$ – the velocities $[m/s]$

$\ddot{z}_1, \ddot{z}_2$ – the accelerations $[m/s^2]$

A,B,C – control factors

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