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ABSTRACT

This paper is proposed to predict the ride quality of a specific road vehicle responding to ground irregularity (road roughness). Based on this prediction, the suspension characteristics of the vehicle can be optimized. This is implemented by using MATLAB-SIMULINK. Three types of models are being evaluated which consist of a single-degree of freedom model, two-degree of freedom model and car with tyre suspension system. The optimization of the suspension characteristic is evaluated by reviewing the Mean Square Response (MSR) of the vehicle displacement with parameters relating to the vehicle suspension. The results, which are presented on this paper shows that by increasing the degree of freedom in a suspension system, the accuracy of the result will also increase.

1. INTRODUCTION

Land-based vehicles such as cars and heavy goods vehicles can vibrate significantly as a result of irregularities in the ground surface on which they ride. Excessive dynamic response of this type can seriously affect the comfort of passengers and may lead to damage of transported goods. Moreover, in the case of heavy goods vehicles, the accompanying dynamic loads transmitted to the road may lead to rapid deterioration, together with the undesirable environmental effects [1]. In extreme cases the structural integrity of the vehicle itself may be called in to question. It is vital, therefore, at the design stage, to have methods for predicting the levels of dynamic response which vehicles are likely to exhibit when travelling on typical road surfaces, which have been conducted earlier by Joshi & Tamboli [2], Nishitani & Yoshihiro [3], Paola & Pirotta [4] and Schuller *et. al* [5]. Such methods provide the basis of a rational approach for optimizing the suspension characteristics of vehicles.

Due to the highly irregular nature of ground surfaces a deterministic approach to this problem is unsuitable - except, perhaps, in dealing with rare, isolated severe irregularities, such as potholes. A much more satisfactory approach is to model the ground surface as a random, or stochastic, process and to predict the statistical features of the resulting random vehicle response using either simulation methods or theoretical techniques available in the general field of random vibration. This paper is concerned with predicting the ride quality of a specific road vehicle, responding to ground irregularity, thus optimizing the suspension characteristics of the vehicle.

The prediction will be based on a simulation of the response of a lumped-mass model of the vehicle and a random process model of the ground surface variation. The simulation will be carried out using SIMULINK, a toolbox available in MATLAB [6], [7].

2. SELECTION OF A VEHICLE

In this paper, the vehicle type selected is a car. The mass (m), stiffness (k), damping (c) and moment of inertia (I) of the vehicle is estimated as shown in Table 1 below according to the suspension model.

Table 1. Vehicle's parameters for each suspension system.

Model	Constants
First (Single-degree of freedom)	m = 1660.7 kg; c = 3 673 N-s/m; k = 26 447 N/m
Second (Two-degree of freedom)	I = 587.717 kg.m^2; m = 2000 kg; k_1 = 161 622 N/m; k_2 = 26 447 N/m ; c_1 = 5 142 N-s/m ; c_2 = 3 673 N-s/m; L = 4 m
Third (Car and tyre suspension)	m_1 = 1660.7 kg; m_2 = 320 kg; k_1 = 26 447 N/m; k_2 = 161 622 N/m; c_1 = 3 673 N-s/m; c_2 = 5 142 N-s/m

3. ROAD ROUGHNESS

Road roughness encompasses everything from potholes resulting from localized pavement failures to the ever-present random deviations reflecting the practical limits of precision to which the road surface can be constructed and maintained. Roughness is described by the elevation profile along the wheel tracks over which the vehicle passes. Road profiles fit the general category of "broad-band random signals" and, hence, can be described either by the profile itself or its statistical properties. One of the most useful representations is the Power Spectral Density (PSD) function [3].

Like any random signal, the elevation profile measured over a length of road can be decomposed by the Fourier Transform process into a series of sine waves varying in their amplitudes and phase relationships. A plot of the amplitudes versus spatial frequency is the PSD. Spatial frequency is expressed as the "wavenumber" with units of cycles/foot (or cycles/meter), and is the inverse of the wavelength of the sine wave on which it is based.

Road elevation profiles can be measured either by performing close interval rod and level surveys, or by high-speed profilometers. When the PSDs are determined, plots such as those shown in Fig. 1 and Fig. 2 below are typically obtained. Although the PSD of every road section is unique, all roads show the characteristic drop in amplitude with wave number. This simply reflects the fact that deviations in the road surface on the order of hundreds of feet in length may have amplitudes of inches, whereas those only a few feet in length are normally only fractions of an inch in amplitude. The general amplitude level of the plot is indicative of the roughness level-higher amplitudes implying rougher roads [8]. Spectral of typical road surfaces for are obtained from [9]. The MATLAB output of the road roughness is shown in Fig. 1 below. The MATLAB output of road surface height with respect to time is shown in Fig. 2.

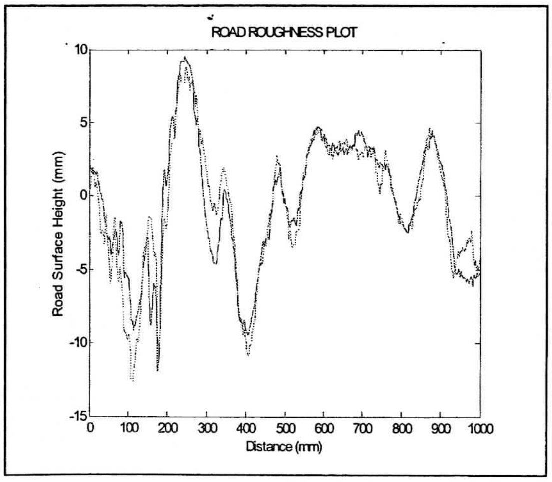

Fig. 1. Road roughness plot.

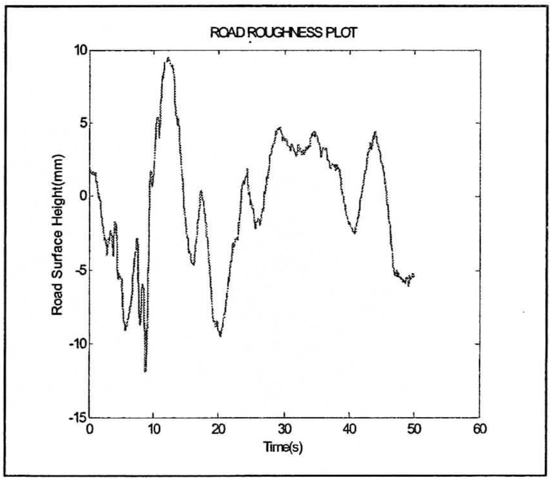

Fig. 2. Road roughness plot with time delay.

4. FIRST MODEL (A SINGLE DEGREE OF FREEDOM MODEL)

One or single degree of freedom model of a complicated system can be constructed where the analysis of a particular mode of vibration is to be carried out. To be able to analyse one degree of freedom systems is therefore essential in the analysis of structural vibrations. It should be noted that many of the techniques developed in single degree of freedom analysis are applicable to more complicated systems. The first model is shown in Fig. 3 below. A spring-mounted body moves along an undulating surface. The body has a mass, m and is connected to the wheel by a spring of stiffness, k, and a viscous damper whose damping coefficient is c.

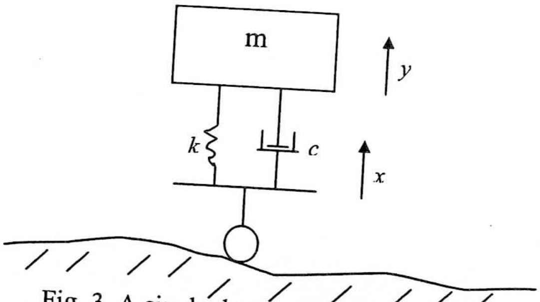

Fig. 3. A single degree of freedom model.

The equation of motion is,

$$m\ddot{y} + c(\dot{y} - \dot{x}) + k(y - x) = 0 \tag{1}$$

$$\ddot{y} + \frac{c}{m}\dot{y} + \frac{k}{m}y = \frac{c}{m}\dot{x} + \frac{k}{m}x \tag{2}$$

$$\ddot{x} = -\frac{c}{m}\dot{y} + \frac{c}{m}\dot{x} - \frac{k}{m}y + \frac{k}{m}x \tag{3}$$

These equations can be implemented in SIMULINK. x(t) is the input of this system and it can be all the inputs that were described before or something else that can be played the role of input. In this model, the response of the vehicle system to various sinusoidal road surface inputs will be evaluated. Before conducting the procedure, it is good to check the response of this system to a bump that can be modelled as a pulse response. Fig. 4 illustrates the details of this model. In SIMULINK, all variables are modelled respect to the time. By using the velocity, time of the vehicle passing the bump can be calculated as t = x/ V= 0.12/5 =0.024 secs. Fig. 5 shows the characteristics of pulse and response of system.

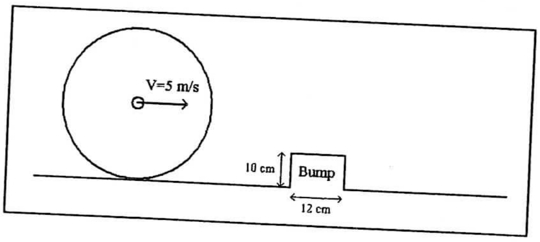

Fig. 4. The wheel is passing the bump.

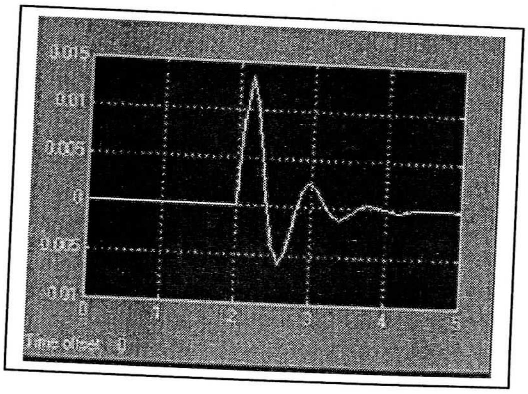

Fig. 5. Pulse and response of the system.

Response of SDOF model to irregular road surface

In this section, the response of single degree of suspension model to various levels of random ground surface variation will be evaluated. Then the mean square of the displacement response for typical ground surface irregularity will be calculated. Finally, the effect of changing the suspension stiffness and damping or vehicle speed on this system can be investigated.

It should be noted that the variation of realistic road surface is measured at the height of 0.154 m. Therefore, it is better to have same variation at white noise otherwise; these cannot be compared to each other.

As being discussed earlier, the data is achieved from measuring the surface height at each 0.154 m of road surface. Moreover, the graph of height variation in SIMULINK should be respect to time so by having a specific velocity, the data can be converted with respect to time variation. This procedure is done using MATLAB program and is shown in Road Roughness section earlier. Fig. 6 shows the input of realistic road and response of the system. The velocity of vehicle in this model is 20 m/s. It can be explained that, the model can only run for about 7.7 secs as it is depends on the distance because of the road roughness data.

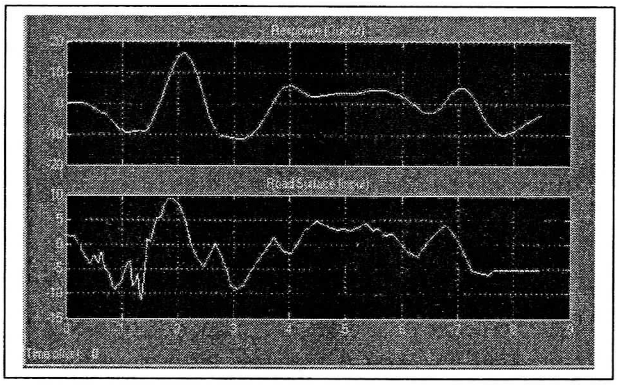

Fig. 6. The output response for the road roughness.

Effect of Changing the Suspension Characteristics and Velocity on Response of Vehicle (SDOF)

The effect of changing the vehicle speed, stiffness and damping coefficient of suspension are evaluated through mean square of the displacement response. Mean square response is the mean variation of square response that can be determined from following formula:

$$\text{MSR} = \frac{1}{t}\int R^2(t)dt \tag{4}$$

where R (t) is the displacement response of system

The less amount of MSR that a system has, the more comfort the ride will has, so in order to have less amount of MSR the characteristics of system modified to achieve the best situation of ride for passenger. MSR also depends on the ground surface and velocity of vehicle therefore optimization of suspension characteristics can be done for particular road surface and speed. Based on the MSR calculation for the first model, the optimum MSR is obtained when stiffness is 30 000 N/m and damping is 5 000 Ns/m at the velocity of 20 m/s.

5. SECOND MODEL (TWO-DEGREE OF FREEDOM)

Fig. 7 below shows a simple two-degree of freedom model for a vehicle. The vehicle's suspension system (front and rear springs and shock absorbers) is modelled by linear springs and dampers and the compliance of the tyres are modelled by front and rear springs. The vehicle cab motion is limited to heave in the y-direction and a small amount of pitch θ of the vehicle's longitudinal axis. The body structure of the vehicle is represented by the mass, m and the moment of inertia, I with respect to the central axis perpendicular to the vehicle's plane of symmetry. The vehicle is subjected to displacement excitation $x_1(t)$ and $x_2(t)$ respectively at the front and rear. Since there is a difference between amplitudes the $x_1(t)$ and $x_2(t)$, angular displacement about the mass centre arises.

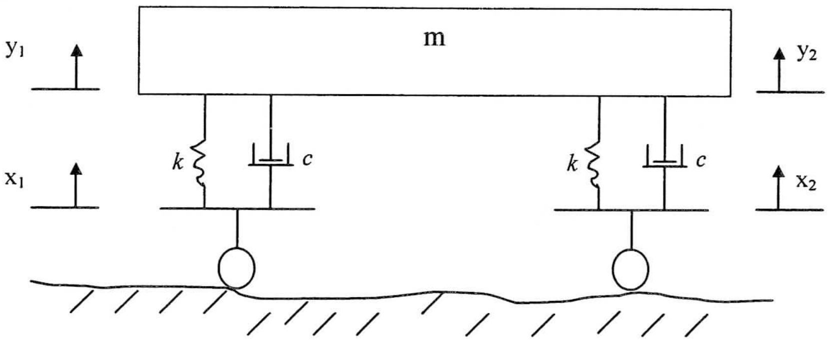

Fig. 7. Model of two-degree of freedom.

The assumptions to develop the governing equation for this model are as follow: Linear springs and dampers; Small angles on the rotations; The tyres remain in contact with the road surface at all times; Neglecting affects of weight transfer due to acceleration; Only modelling one side of the vehicle so neglect the effects of yaw and roll; Vehicle can be modelled as a slender rod to find the moment of inertia; The system is at steady state which means the springs already have a load in them due to the weight of the vehicle. The equation of motions for this model is given as follow:

$$M\ddot{y} = -k_1x_1 - k_2x_2 - c_1\dot{x}_1 - c_2\dot{x}_2 + (k_1 + k_2)y + (c_1 + c_2)\dot{y} - \frac{L\theta}{2}(k_1 - k_2) - \frac{L\dot{\theta}}{2}(c_1 - c_2) \qquad (5)$$

$$I\ddot{\theta} = \frac{k_1L}{2}x_1 - \frac{k_2L}{2}x_2 + \frac{c_1L}{2}\dot{x}_1 - \frac{c_2L}{2}\dot{x}_2 - \left(\frac{k_1L}{2} + \frac{k_2L}{2}\right)y - \left(\frac{c_1L}{2} - \frac{c_2L}{2}\right)\dot{y} + (k_1 + k_2)\frac{L^2}{4}\theta$$
$$+ (c_1 + c_2)\frac{L^2}{4}\dot{\theta} \qquad (6)$$

The output of the system after being simulated with the road roughness data is shown in Fig. 8.

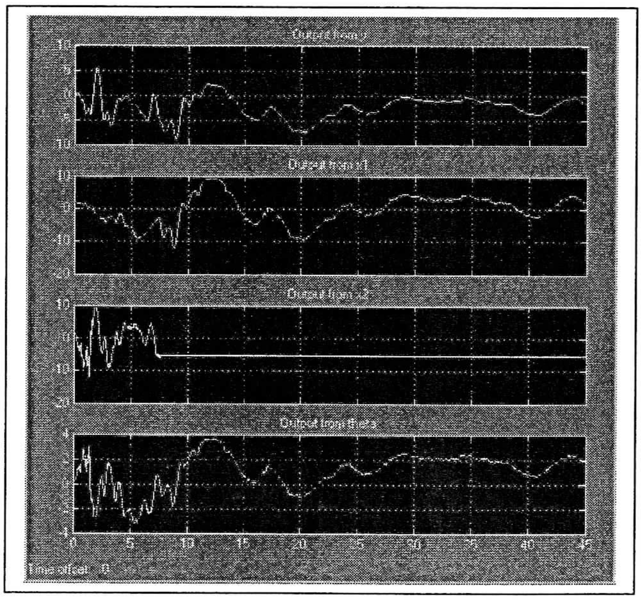

Fig. 8. Road roughness output for the second model.

Effect of Changing the Suspension Characteristics and Velocity on Response of Vehicle (TDOF)

Based on the MSR calculation for the second model, the optimum amounts of suspension characteristics are as following:
Damping coefficient of front wheel c1= 2 000 Ns/m; Damping coefficient of rear wheel c2= 1 500 Ns/m; Spring stiffness of front wheel k1= 18 000 N/m; Spring stiffness of rear wheel k2= 12 000 N/m.

It should be emphasized again that the less amount of MSR that a system has, the more comfort the ride will has. Besides that, it should be noted that normally the amount of stiffness and damping coefficient of front wheel are higher than the rear wheel. These characteristics help the car to maintain a better handling behaviour.

6. THIRD MODEL (TYRE AND SUSPENSION MODEL)

Based upon such a simplified manner, car suspension is represented by a two-degree-of-freedom (2DOF) model as shown in Fig. 9, in which the upper mass represents the car body and the lower mass represents the tyre. Further simplicity can be introduced into the modelling of each subsystem by assuming that the vertical movement of the tyre is almost identical with the ground irregularities or roughness.

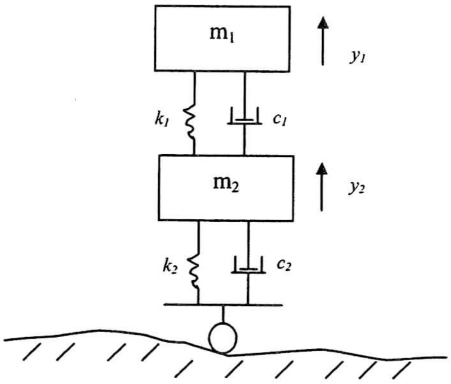

Fig. 9. Tyre and suspension model (Third model).

In terms of inputs and the states itself,

$$\ddot{y}_1 = \frac{-c_1}{m_1}(\dot{y}_1 - \dot{y}_2) - \frac{k_1}{m_1}(y_1 - y_2) \tag{7}$$

$$\ddot{y}_2 = \frac{c_1}{m_2}(\dot{y}_1 - \dot{y}_2) + \frac{k_1}{m_2}(y_1 - y_2) + \frac{c_2}{m_2}(\dot{w} - \dot{y}_2) + \frac{k_2}{m_2}(w - y_2) \tag{8}$$

Fig. 10 shows the output when the road roughness data is added to the model.

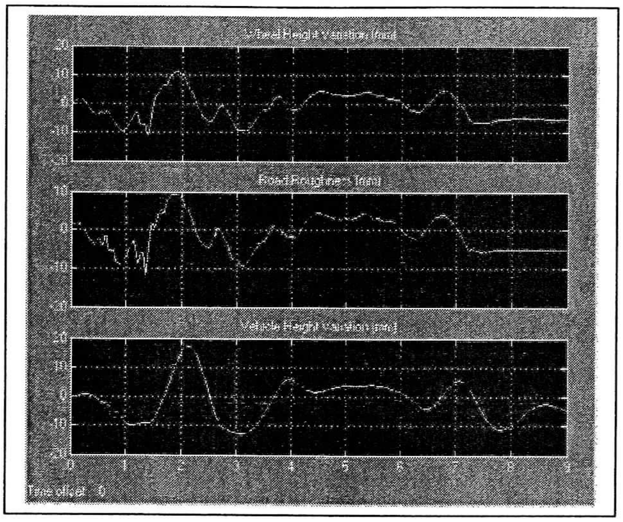

Fig. 10. Output for the road roughness data.

Optimization of Suspension Parameters

In this model, it must be noted that there is a limitation of the parameters for MSR. As example, the value of stiffness should be in between 10 000 N/m and 30 000 N/m and so on. If it is over the limit, the suspension might become too rigid. It should be noted that the comparison for MSR of a system cannot be analyzed by evaluating different velocity as when the vehicle speed is getting less, the MSR is getting lower. Based on the MSR calculation, the least amounts of MSR are occurred in the following parameter; c1= 2 000 Ns/m, c2= 8 000 Ns/m, k1= 25 000 N/m and k2= 10 800 N/m where optimization level is achieved on those parameters.

7. CONCLUSION

A good vehicle suspension system should have satisfactory road holding ability, while still providing comfort when riding over bumps and holes in the road. When the vehicle is experiencing any road disturbance (i.e. pot holes, cracks, and uneven pavement), the vehicle body should not have large oscillations, and the oscillations should dissipate quickly. Through this project, the conclusion can be summarized as follow:

(a) Overall, the suitable suspension parameters for the different models discussed earlier are shown in Table 2 below.

Table 2. Suspension parameters for the different models.

Model	Suspension Parameters
First (SDOF)	v = 20 m/s k = 30 000 N/m c = 5 000 N-s/m
Second (TDOF)	v = 20 m/s c1 = 2000 N-s/m c2 = 1 500 N-s/m k1 = 18 000 N/m k2 = 12 000 N/m
Third (Tyre and Suspension System)	v = 10 c1 = 2000 N-s/m c2 = 8000 N-s/m k1 = 25 000 N/m k2 = 10 800 N/m

(b) By increasing the degree of freedom in a suspension system, the accuracy of the result will also increase and optimizing the system.

(c) The roll of tyre in a suspension system cannot be neglected due to the high value.

(d) Besides that, it is also shown that pitch motion in vehicle vertical height variation is a factor to be considered to evaluate a comfort ride.

(e) In addition to the importance of vertical height variation of car, the variation of pitch motion is also an important aspect in evaluation for a comfort ride. Thus, it is recommended that a suitable suspension system of a vehicle which consists of a four-degree of freedom model for the vehicle, as shown in Fig. 11 below. In this case, it is predicted that the suspension system level can also be optimized by implementing this model.

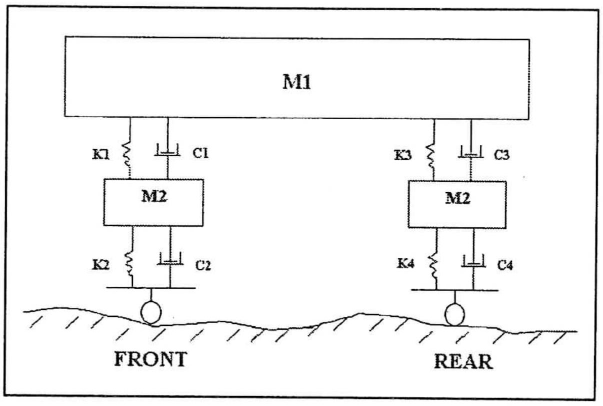

Fig. 11. Four-degree of freedom suspension model.

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