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Modelling and simulation of motor vehicle suspension system

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Abstract

In this work, using a quarter-car model was adopted, the equations of motion were derived for a passive and then the sky-hook semi-active suspension systems. The derived differential equations, solved using the Dormand-Prince pair numerical formula, was then used to simulate values of displacements as affected by damping coefficients and the sky-hook constant. The simulated results showed that the maximum amplitude of the sprung mass, which is linked to ride discomfort, increases while those of unsprung masses, which affects the road holding ability, decreases with increasing depth of pothole. Furthermore, displacements for both sprung and unsprung masses varied directly with damping coefficient. Finally, as the sky-hook constant of the semi active system model increases, values of amplitudes of unsprung masses decreases while those of sprung masses increases. It was, thus, shown that the vertical displacements of vehicle bodies and wheels are dependent on the depth of potholes, damping coefficient and sky-hook constant, and that the sky-hook semi-active suspension system model gave a better result compared to the passive suspension system. Therefore, by applying the sky-hook control principle, the desired road comfort of passengers can be achieved as well as reduced rate of car damage and cost of maintenance.

Keywords: Passive suspension system, Semi-active suspension system, Skyhook control, Vehicle vibration model

1. Introduction

A suspension system is a mechanism that connects the body of the vehicle to its wheels, allows the relative motion between them, and reduces vibrations from irregular road surfaces and other sources. The suspension system helps to improve ride quality and ensures good road holding capabilities of the wheels: two qualities that are at odds with each other. Whereas ride quality is a measure of the vertical motion that is transmitted to the vehicle, which can cause inconveniences for passengers and damage vehicle bodies, road holding capability is the tendency of the wheel to remain attached to the road during motion [1].

There are primarily three types of suspension systems: passive, active and semi-active. The passive systems have elements whose properties cannot be controlled. That is to say the spring constant and damping coefficient of the system are constant regardless of road and vehicle conditions. Active systems are those that offer full control to properties of elements of the suspension system. For such systems, the spring stiffness and damping characteristics can be controlled for maximum ride quality. However, they are scarcely applied due to their complexity, cost and safety concerns.

As a trade-off for cost and other issues associated with the active system, technology that enables control of only the damping characteristics were developed. These kinds of suspension systems that allows partial control (damping properties only) are called semi-active systems. There are different types of these semi-active systems, and they are discussed in the literature (Guglielmino, et al., 2008). The changing damping properties can be achieved in different ways. For example, by varying the diameter of orifice in a piston of a twin tube viscous damper [2]. Also, magneto-rheological damper (MR damper) is another example in which the fluid's rheological properties changes in response to an applied magnetic field [3, 4] . By suitable control mechanism, the damping characteristic of the system can be adjusted to achieve better ride quality. [5, 6].

Among other means, the sky-hook method is effectively used to achieve the desired control. The principle of operation of the skyhook damper is based on a switching law that regulates the damper based on its velocity and damping force relationship. As an illustration, the control law can turn off the damper in order to reduce the undesired upward push from the suspension damper [7, 8]. Detailed description of the sky-hook control method are presented in the literature [1].

Suspensions systems are modelled to evaluate its performance on a motor vehicle. Several models have been developed over the years [9, 10]. In analysing suspension systems, a quarter model that consists of one of the vehicle wheel is used to simplify the problem. Such models are two degree of freedom equations of motion that constitute all the elements used to represent the system.

This work aims to investigate the sky-hook control of semi-active suspension systems in comparison to that of a passive control suspension system. This study can help draw further information on the performance of the two types of system studied as affected by certain road characteristics and the system properties.

2. Methodology

2.1 The passive suspension system

The passive system which is a system that assumes that the element of vibration has constant coefficient was first model to serve as reference for the semi-active model which is more current. The schematic diagram of a 2 degree of freedom quarter model for the passive system is shown in Figure 1. The different equations for the passive system derived using D'Alembert's principle are shown in Equations 1 and 2

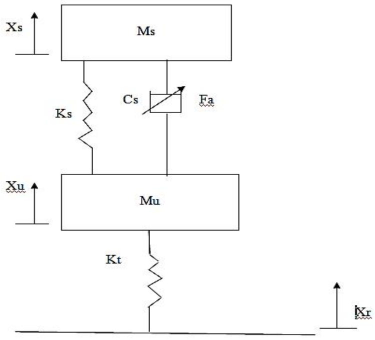

Figure 1: A diagrammatic representation of the passive motor vehicle suspension

The equations of motion of the above model is given below;

$$M_s\ddot{x_s} = -K_S(x_s - x_u) - C_s(\dot{x_s} - \dot{x_u}) \quad 1$$

$$M_u\ddot{x_u} = K_s(x_s - x_u) + C_s(\dot{x_s} - \dot{x_u}) - K_t(x_u - x_r) \quad 2$$

Where;
M_s= sprung mass (chassis' mass)
M_u= unsprung mass (mass of the tire)
K_s= the suspension system's spring stiffness
K_t= spring stiffness of the tire
x_s= chassis displacement
x_u= unsprung mass displacement
x_r= road displacement

Parameter values for evaluating vehicle model has been standardised and the values in the work of [11] were adopted for this study. They are given as follows:

M_s = 315kg
M_u = 37.5kg
K_s = 29500N/m
C_s = 1500Ns/m/
K_t = 210000N/m
XdefSuspmax = 0.1m

With C_s and XdefSuspmax being suspension linearized damping and maximum deflection of the suspension respectively.

2.2 Sky-hook controlled semi-active suspension system model

The principle behind the sky-hook control is to design an active suspension control in such a way that the chassis of the vehicle is "linked" to the sky by a damper, known as the "sky-hook damper," as shown in Figure 2. By this technique, the sprung mass is isolated from the road thereby allowing a reduction in vibration. If the suspension damper is expanding and the spring body is moving upwards, the sky-hook control turns on the damper and it pulls down on the spring body. The equations governing the above model is given in Equations 3 and 4

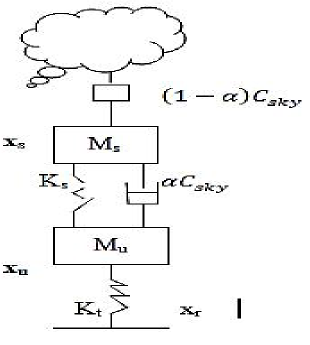

Figure 2: The schematic representation for an ideal skyhook suspension system

$$M_s\ddot{x_s} =-(1-\alpha)C_{sky}\dot{x_s} - K_s(x_s - x_u) - \alpha C_{sky}(\dot{x_s} - \dot{x_u}) \qquad 3$$
$$M_u\ddot{x_u} = \alpha C_{sky}(\dot{x_s} - \dot{x_u}) + K_s(x_s - x_u) + K_t(x_r - x_u) \qquad 4$$
$$C_{sky} > 0$$
$$\alpha \in [0;1]$$

The sky-hook damper has a damping coefficient, C_{sky}, and a sky-hook constant, α. The choice of α will allow the damping of the vertical motion of the axle to be fixed. If $\alpha = 0$, the control force will not depend on the vertical velocity of the axle and it will imply the oscillations of x_u, and if $\alpha = 1$, the control force will be independent from the vertical velocity of the vehicle body and it will result in the oscillations of x_s.

2.3 Simulation flow chat

For the simulation process, the differential equations were solved using the MATLAB embedded Dorman-Prince Pair method [12] . The defined paremeters and initial condions for the models were the input variables in the software, and with them the program was processed to solve the equations and send the results as output. The flowchart describing the process for the simulation of the models is shown in Figure 3.

This simulation for both the passive and semi-active suspension models were carried out for the following:

1. Road displacement was varied and the amplitudes of both the sprung and unsprung masses were observed and examined for both the passive and semi-active models.
2. Damping coefficient was varied and the amplitudes of both the sprung and unsprung masses were observed and compared for both the passive and semi-active models.
3. The sky-hook constant was varied and the amplitudes of both the sprung and unsprung masses were observed for only the semi-active model.

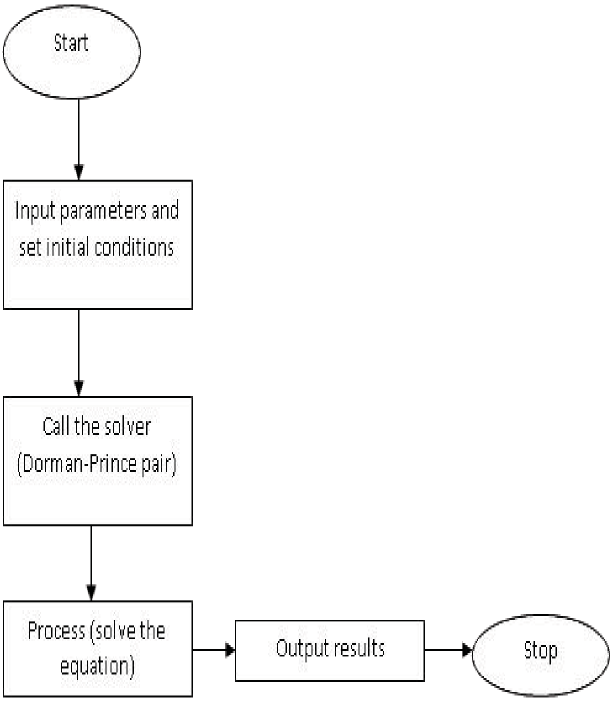

Figure 3: Simulation Flowchart.

3.0 Results and discussion

Figure 4 shows the response of the sprung masses of both the passive and semi-active suspension systems when road displacement $Xr = 0.3$, damping coefficient $Cs = C_{sky} = 1500$, and alpha, $\alpha = 0.5$, the amplitude of the passive suspension system (red) is a little bit higher compared to semi-active suspension system (black). This implies that there is a little improvement in the road comfort by the semi-active suspension system.

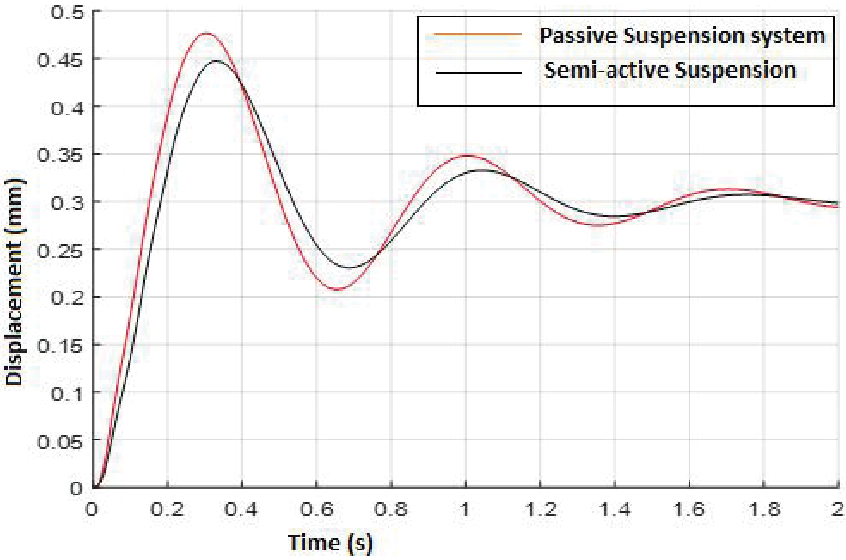

Figure 4: Response of the sprung masses of both passive and semi-active suspension

systems with a damping coefficient of 1500Ns/m.

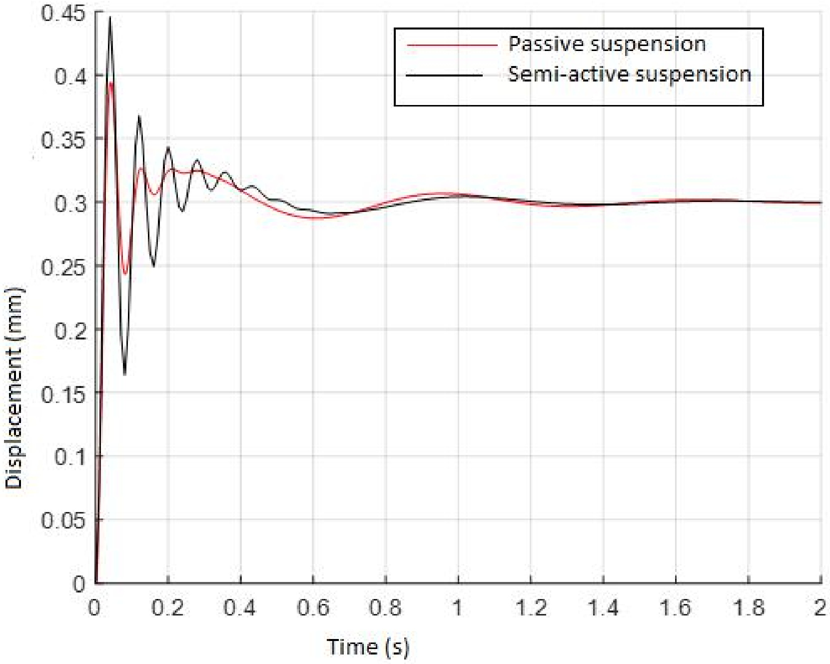

Figure 5: Response of the unsprung masses of both passive and semi-active suspension system to a damping force of 1500Ns/m.

Figure 5 shows the response of the unsprung masses of both passive (red) and semi-active (black) system when road displacement $Xr = 0.3$, damping coefficient $Cs = C_{sky} = 1500$, and alpha, $\alpha = 0.5$. From the graph, the unsprung mass of the semi-active system is thrown into higher amplitude when compared with the passive system, but both oscillations tend to die out at the same time. The skyhook principle for a damping coefficient of 1500Ns/m did not have any better effect on the unsprung mass of the system. This indicates that the skyhook control for a damping coefficient of 1500Ns/m reduced the road holding ability of the vehicle tires compared with the passive suspension system. When the vehicle passes through a pothole or a bump, with the semi-active system the tire will hardly retain balance on the road compared with the passive suspension system.

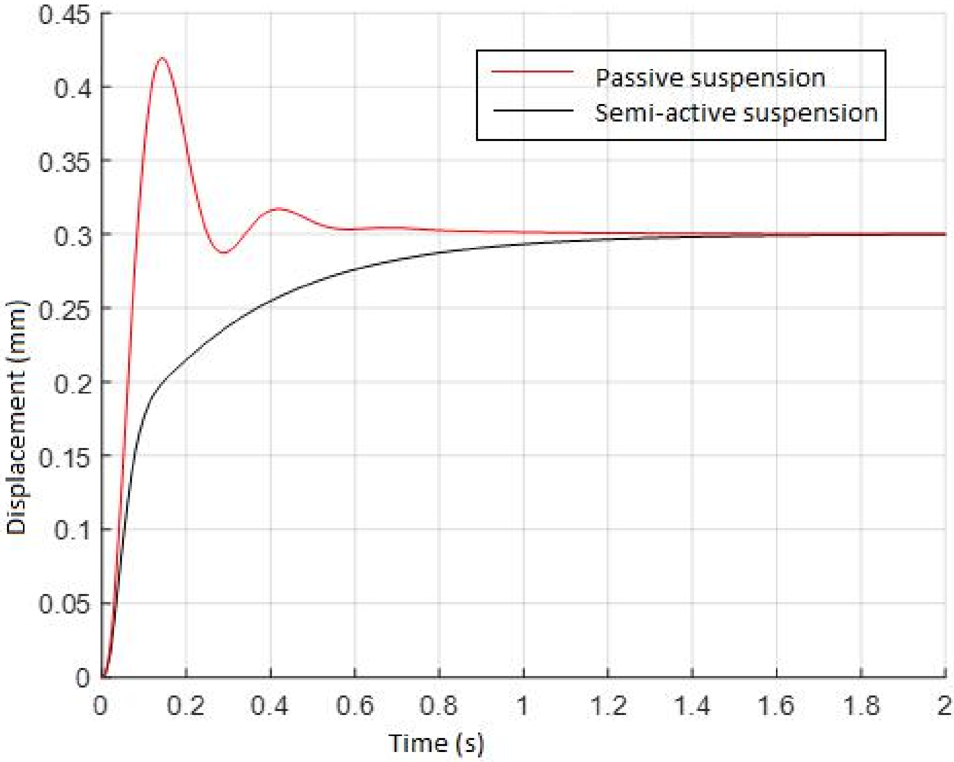

Figure 6: Response of the sprung masses for both the passive and semi-active suspension system to a damping coefficient of 10000Ns/m.

Figure 6 shows the response of the sprung masses of the passive and semi-active suspension systems when the damping coefficient was increased to 10000Ns/m and other parameters remain constant. With an increase in the damping coefficient, the semi-active system gave a better response than the passive system and better than the semi-active system with a damping coefficient of 1500Ns/m. The response of the semi-active system showed a smooth and gradual move till the point of the road displacement (0.3m), while the passive system showed a sharp displacement of the sprung mass before dying out.

This implies that when the damping coefficient was increased, the semi-active system gave a successful improvement to the road comfortability of the vehicle. When the car goes through a pothole, the car will be smoothly displaced to the depth of the pothole that the passengers in the vehicle will not feel the impact. This same high damping coefficient has a lesser effect on the passive system; the vehicle was still thrown into vibration though it lasted for a little while.

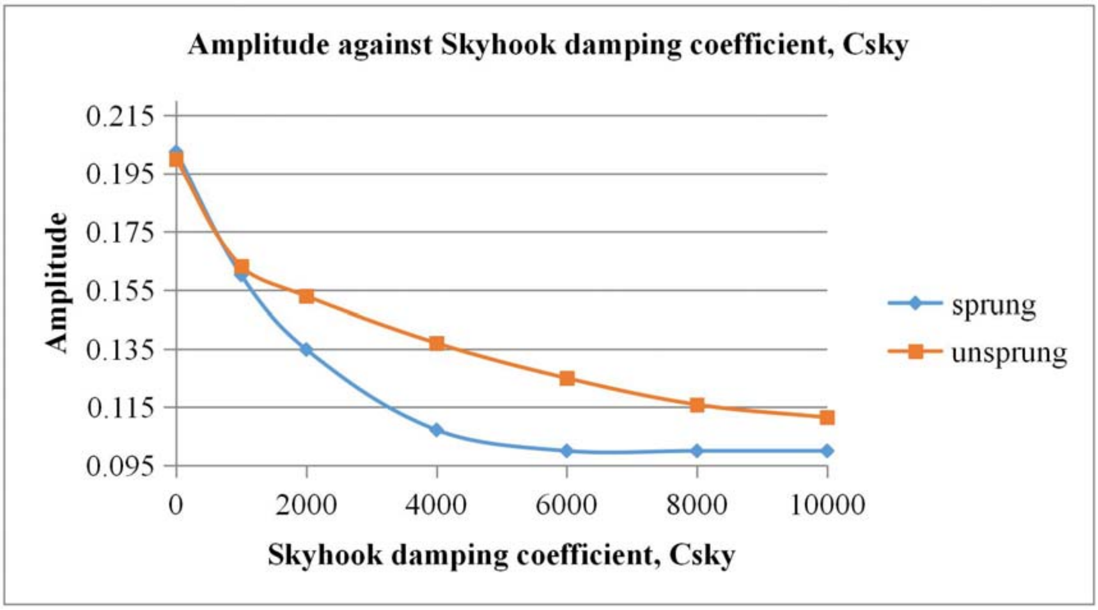

Figure 7: Graphs of amplitude against skyhook damping coefficient for both sprung and unsprung masses for the semi-active suspension system.

Figure 7 shows the graphs of amplitude against the skyhook damping coefficient for both sprung and unsprung masses of the semi-active suspension system for different values of the skyhook damping coefficient, a road displacement of 0.1m and an alpha constant of 0.3. The graph is non-linear. From the graph, the amplitude of both masses decreases as the skyhook damping coefficient increases. Both masses start with the same rate of decrease in amplitude after which the rate of amplitude decrement of the unsprung mass reduces, making the amplitude of the sprung mass lower than that of the unsprung mass. The amplitude of the sprung mass decreases till it gets to a point where it becomes constant. However from Figure 6, there is a limit to which the damping coefficient of the skyhook damper can be increased to. Figure 6 showed that from a damping coefficient of 6000Ns/m, the optimal comfort of the motor vehicle was achieved, that it, it was smoothly displaced to the point of the road displacement. The disadvantage of this is that the cost of such high damping coefficient in dampers might be expensive.

Figure 8 shows the response of the usnprung masses of both passive and semi-active suspension systems when the damping coefficient was increased to 10000Ns/m, all other parameters remaiming constant. The response of the unsprung mass of the semi-active showed a positive response with the increase of the damping coefficient. The amplitude of the semi-active system was reduced as the damping coefficient was increased, while the amplitude of the passive system was increased as the damping coefficient was increased from 1500 to 10000. There was a slight displacement of the unsprung mass of the semi-active system and the oscillation dampened out more quickly.

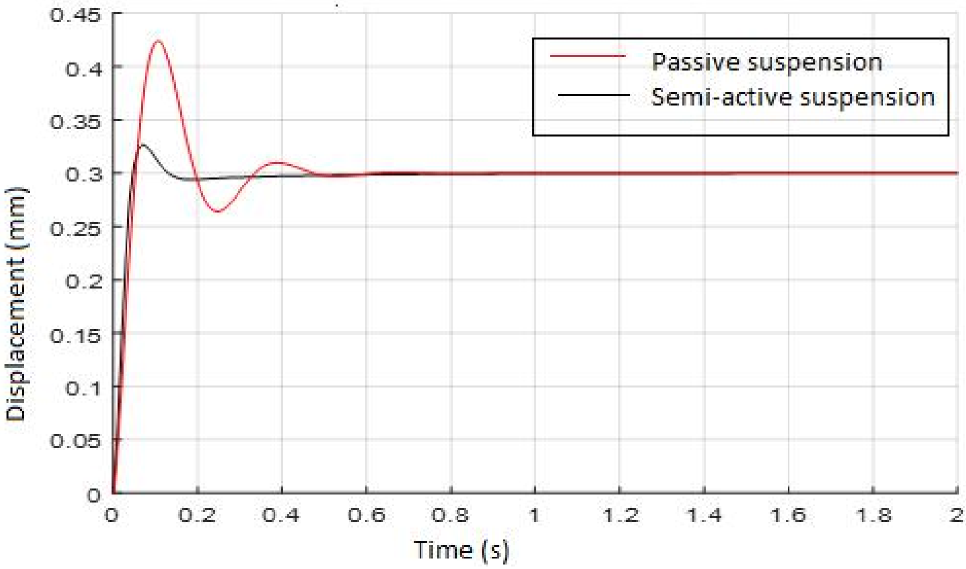

Figure 8: Response of the unsprung masses of both passive and semi-active suspension systems to a damping force of 10000Ns/m.

This implies that an increase in the damping coefficient for the passive system reduced the road holding ability of the vehicle’s tires but has a tremendous effect in improving the road holding ability of the car’s tires when a semi-active system is used. So when the motor vehicle passed through a pothole, for the semi active system, the tires still retain its grip on the road surface, which is not so for the passive system.

From these observations, it can be deduced that when applying the skyhook control, the damping coefficient has to be increased and α kept at 0.5 for an optimal result when striking a balance between the comfortability and the vehicle’s road holding ability. However, the cost of these dampers with high damping coefficient might be very expensive. Also, there is a limit to the damping coefficient of the skyhook damper to be used, exceeding it will yield no further improvement in the comfortability of the vehicle though they might still be little results in improving the road holding ability of the vehicle’s tires.

From the results, it can be deduced that an increase in the road displacement (i.e. the bumps on the road, the depth of the pothole) leads to the increase in the amplitude of the motor vehicle both of the sprung mass (chassis) and the unsprung mass (tires) and an increase in the damping coefficient reduces the amplitude of both sprung and unsprung masses. That is, the deeper the pothole or road bump, the higher the tires and the body of the vehicle is thrown into oscillation, which dampens out with time. However, when a very high damping coefficient (10000Ns/m) is applied to the passive system, it has very little effect in improving the comfortability of the passengers.

4.0 Conclusion

This work has simulated responses of the models of both passive and semi-active suspension systems. The performance assessment of both the passive and semi-active suspension system based on the results gotten from the simulations carried out showed that the problems of comfortability and road holding ability of the passive suspension system can be improved by the application of the skyhook control principle to a semi-active suspension system. So, by applying the skyhook control principle, the desired road comfort of passengers can be achieved as well as reduced rate of car damage and reduced maintenance cost.

Acknowledgement

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