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Influence of Shock Absorber Installation Angle to Vibration Behavior of Automotive Vehicle

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Abstract

Numbers of studies in the automotive vehicle suspension regarding vibration behavior of the sprung mass have been carried out. Among these published works consider and modify only the characteristic of the shock absorber to attain the desired response. In this paper, the shock absorber installation geometry is examined in conjunction with damping force characteristic. The main aim of this work is to figure out the influence of the installation angle to the vehicle vibration behavior. Numerical simulation is employed to solve the base excited single degree of freedom (SDOF) quarter car model. The installation angle of the shock absorber is considered in three different angles regarding the direction of motion. The equations of motion are formed for each angle. The damping force characteristic is considered as a dual rate piecewise linear damper. The vehicle speed is assumed to be 90 km/h running over a sinusoidal road hump. The transient responses are examined. The installation angle is found to influence the vibration behavior in different ways. The installation angles of 90 degrees and 45 degrees are found to reduce the acceleration of the sprung mass by approximately 60%. This can imply that ride quality is improved. However, the sprung mass is oscillating longer than that for the conventional SDOF model. In other words, the handling quality is degraded. For other installation circumstances are found to be more detrimental the sprung mass. Therefore, it is significant for the design engineer to carefully consider the installation angle of the shock absorber in the vehicle to match the purpose.

***Keywords**:* Shock absorber, Installation angle, Piecewise linear damper, Sprung mass vibration

1. Introduction

Improvement of the vehicle suspension has been growing commercially. However, the know-how of such the improvement technique has not been academically reported. The known development is found to have the suspension system actively controllable. In this paper, the performance of the vehicle suspension system is examined by means of the passive design instead with respect to the installation geometry.

The installation geometry of the shock absorber is in focus because the force resulting from the damper component is dependent on the velocity across the damper. Therefore, having different installation angle can result in different damping force acting on the suspension system. The installation angle of the shock absorber in this paper is considered to be 0, 45, and 90 degrees with respect to the direction of motion of the sprung mass. The consideration of the damping force characteristic is also examined in conjunction to the installation geometry. Transient response of the sprung mass resulting from a sinusoidal road hump is to consider as the quality of the suspension system.

There are many the installation angles of the shock absorber in the commercial road vehicles. The vehicle model in the Fig. 1 (a) has the shock absorber installed vertically in the same direction of wheel movement. The model in Fig. 1 (b) shows the shock absorber in inclined installation. This study aims to find out the reasons behind these differences.

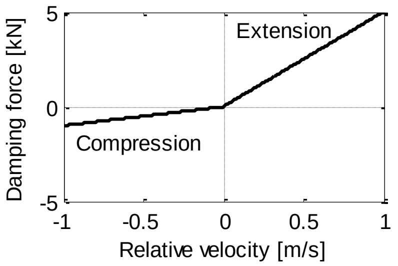
(a) Toyota Yaris

(b) Fiat 500

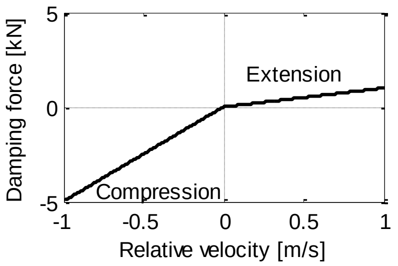
Fig. 1 The installation angles of the rear shock absorber [1]

The installation angle is known to affect the vibration behavior of the vehicle. Tang and Brennan [2] investigated the effects of installation angles of the damper on the vibration isolator. The damper was considered in two installation angles, i.e., 0 degree or in the direction of motion and 90 degree or perpendicular to the motion of the sprung mass. The perpendicular installed damper was found to reduce the vibration response at the frequencies higher than the natural frequency.

In addition, the damping force characteristic of the vehicle suspension system is known to be piecewise linear as shown in Fig. 2 (a). The damping force for the extension stroke is higher than that in the compression. This is to prevent the excessive force when the vehicle confronts the obstacle.



(a) normal configuration



(b) inverse configuration

Fig. 2 Damping force characteristics for the vehicle shock absorber

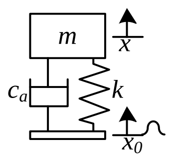
Wallaschek experimented the vehicle shock absorber and found the damping force characteristic as the piecewise linear with hysteresis loop. The occurrence of hysteresis loop was interpreted as the effect of friction. The damping force characteristic was also characterized and reported in many publications and was found to be in similar fashion, for example, Cafferty and Tomlinson [3], Rao et.al. [4] or Worden et.al. [5]. Among these publications, Calvo et.al. [6] found that using only the piecewise linear damping force characteristic without the hysteresis loop is appropriate to simulate the damping force characteristic and is assumed in this paper.

By considering the vibration response for the model using the piecewise damping force characteristic, Waters et.al. [7] found that the value of damping ratio has the direct effect on the response of the sprung mass. It was found that the maximum acceleration occurred on the sprung mass can be reduced by reducing the damping force in the compression stroke.

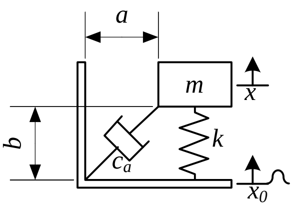
However, in this study, the values of damping ratio for both extension and compression strokes are kept constant. The damping force characteristic of the shock absorber is considered as shown in Fig. 2 (a) and inverse direction as shown in Fig. 2 (b).

2. Mathematical models

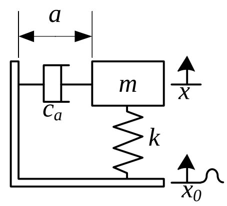
The Single Degree of Freedom (SDOF) system is employed in this study. It represents a quarter car model. The different installation angles for such the model are shown in Fig. 3. Fig. 3 (a) is the classical SDOF model. It has the damping element working in the direction of motion. In Fig. 3 (b) the damping element is inclined with 45 degrees to the direction of motion whereas that in Fig. 3 (c) is perpendicular to the direction of motion.



(a) 0 degree



(b) 45 degree



(c) 90 degree

Fig. 3 Single Degree of Freedom system having shock absorber installation angle with respect to the direction of motion

The mathematical equations of motion for these model are shown respectively to the Fig. 3 as follows:

$$my'' + (c_s + c_a)\,y' + ky = -mx_0'' \tag{1}$$

$$my'' + \left(c_s + c_a \frac{(b+y)\,y}{a^2 + (b+y)^2}\right) y' + ky = -mx_0'' \tag{2}$$

$$my'' + \left(c_s + c_a \frac{y^2}{a^2 + y^2}\right) y' + ky = -mx_0'' \tag{3}$$

where a and b are geometry parameters of installation, c_s is the equivalent viscous damping coefficient resulting from other effects of the system. m, c_a and k are the sprung mass, viscous damping coefficient of the shock absorber and system stiffness. y, y' and y'' are displacement, velocity and acceleration of the relative motion across the damper which is determined from $y = x - x_0$.

Free vibration response for equation (1) is well known. Fig. 4 shows free responses for the absolute displacement, relative displacement and acceleration obtained from equation (1). This figure shows the total absolute displacement of the sprung mass after impact. It also shows the maximum relative displacement and maximum acceleration.

Absolute displacement of the sprung mass represents the performance of suspension system. The suspension system which minimizes displacement of the sprung mass is considered to be appropriate for handling quality. The total displacement is obtained from the peak to peak value of the sprung mass travelling distance.

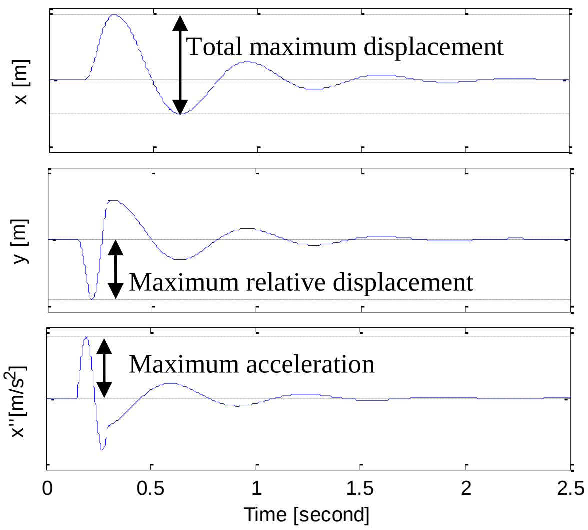


Fig. 4 Free response for a single degree of freedom vibration system as shown in equation (1)

Relative displacement informs the characteristic of suspension. For relative displacement close to zero refers the stiff suspension. Such the characteristic is suitable for racing cars. This is because the car body and the wheel do not much travel. Therefore, it is also good for handling. In contrast for relative displacement much higher than zero can refer to soft suspension. This characteristic can be preferable for sedan or passenger cars. The maximum relative displacement is taken from the maximum of its absolute value.

Maximum acceleration of the sprung mass is also carried out from its maximum absolute value. This value represents harshness of impact received by passengers. The higher level of acceleration means the higher level of impact on the passengers. This refers to the poor quality of ride-comfort. Therefore, the appropriate suspension system should be good in reducing transferred acceleration from the base input. That has been achieved by lowering the damping force during the compression stroke. For the passive design, the designer must compromise the trade-off between ride-comfort quality and handling quality.

Equations (2) and (3) appear to be non-linear equation. It is not convenient to solve these equations mathematically. Thus, the numerical simulation method was employed to solve these equations numerically.

In addition, the damping force for the shock absorber, c_a, in equations (2) and (3) appear to be dependent on the value of y and y' whereas that in equation (1) is only a function of the relative velocity y'. Thus the damping force for the inclined shock absorber can be higher for the more relative displacement between the base input and the sprung mass.

It is also seen that the damping forces for the installation angles in Figs. 3 (b) and 3 (c) is also dependent on the installation geometry. The length of the shock absorber is important. The longer the shock absorber can result in the weaker the damping force.

3. Numerical simulation parameters

Numerical simulation employed in this study was done using ODE45 with time step of 1 millisecond. The input x_0 was assumed to be a sinusoidal road hump. The hump has the dimensions as shown in Fig. 5.

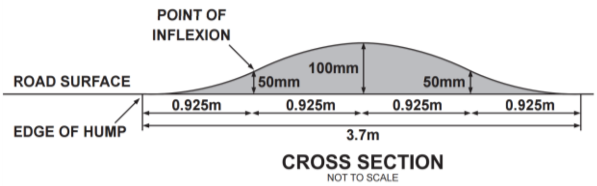


Fig. 5 Cross-section of a sinusoida road hump [8]

The horizontal velocity of the vehicle running over the hump was assumed to be 90 km/h or 25 m/s. Thus the time for the displacement input of 0.148 s was applied.

Considering the suspension system without the shock absorber or with worn shock absorber subject to transient input, though the vibration response of the sprung mass is going to stop in a while. Thus the suspension itself already has damping force from other parts. The value of damping ratio resulting from the other effects, ζ_s, was set to be 0.1 as recommended in [9].

Initially, the values of damping ratio for the shock absorber, ζ_a, were set for both the extension, ζ_{ae}, and compression strokes, ζ_{ac}. The extension stroke damping ratio was sat as an array ranging from ζ_{ae} = 0.1 – 1.0. Damping ratio for the compression stroke was kept constant at ζ_{ac} = 0.1. The values of damping ratio for the extension and compression strokes were considered as the ratio of these quantities, i.e., $\zeta = \zeta_{ae}/\zeta_{ac}$. This is to find the influence of the value of damping ratio.

Parameters a and b for the case of 45 degree were set to be 0.2 m. Thus the total length of the shock absorber at the equilibrium position is 0.2828 m or about 0.3 m. For the case of 90 degree, parameter a was set to be 0.2828 m. This is to be corresponding to the case of 45 degrees.

The heave natural frequency for the passenger road vehicle is recommended in [9] to be around 1.6 Hz or approximately equal to 10 rad/s. These parameters were used by the numerical simulation in this study.

4. Results and discussion

The numerical results focused in this study are acceleration and absolute displacement of the sprung mass, and relative displacement between the sprung mass and the base input. The numerical results were carried out for the following six study cases :

i. 0° - normal damping force (blue line)
ii. 0 ° - inverse damping force (red line)
iii. 45 ° - normal damping force (green line)
iv. 45 ° - inverse damping force (brown line)
v. 90 ° - normal damping force (black line)
vi. 90 ° - inverse damping force (magenta line)

The qualities of vehicle ride-comfort and handling are known to be in contrast. Improving quality of ride-comfort can reduce vehicle handling quality and vice versa. Ride-comfort quality means to reduce the unpleasantness to the passengers [9]. Thus ride-comfort can be minimized by reducing acceleration to the passengers. This means that the suspension needs to be soft which results in high relative displacement between sprung and unsprung masses.

In contrast, handling quality, which refers to an ability to control the vehicle, can be improved by minimizing relative displacement between sprung and unsprung masses. This implies that the suspension is stiffer. Such that the acceleration caused by the road is transmitted to the passengers and ride-comfort quality is reduced.

The results for absolute displacement, x, relative displacement, y, and acceleration, x'', are shown in Figs. 6 to 8, respectively.

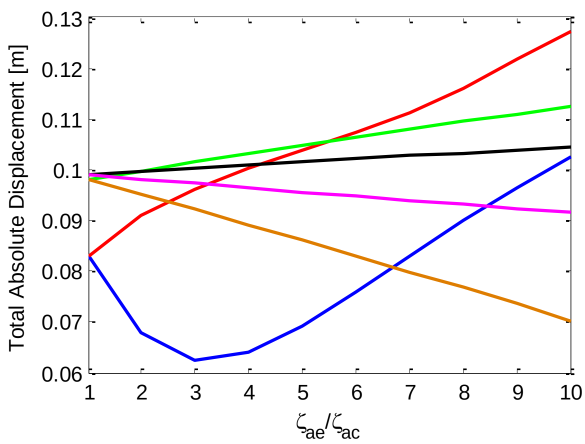


Fig. 6 Total displacement of the sprung mass measured from the first period of oscillation after impact

Fig. 6 shows the total displacement of the sprung mass for the first period after the impact. The total displacement is measured from the maximum peak to the minimum peak of the response. It is seen that installing shock absorber with case i and $\zeta_{ae}/\zeta_{ac} = 3$ provides the lowest total displacement of the sprung mass. But it causes the higher total displacement for the increasing the ratio of ζ_{ae}/ζ_{ac} .

On the other hands, the total displacement for the sprung mass is seen to reduce for the installation of case vi. Reduction of the total displacement is seen to be directly proportional to the value of ζ_{ae}/ζ_{ac} .

Fig. 7 shows the maximum relative displacement. This value is taken from the absolute value of the peak occurred in the first period of motion. The value shown can be either maximum compressed distance or maximum extended distance. The lower the value means the stiffer the suspension system. The higher value refers to the soft suspension system.

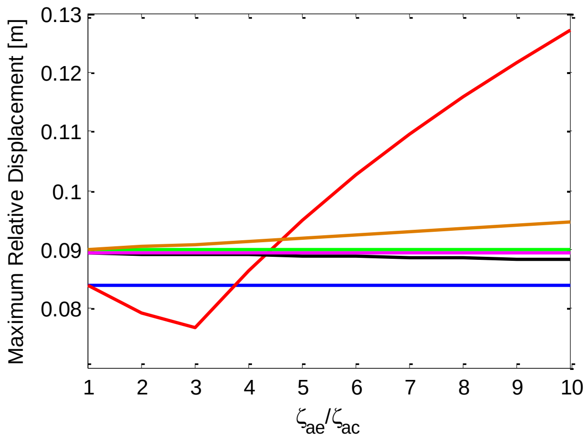


Fig. 7 Relative displacement between the sprung mass and the best input measured from the maximum of absolute value at the first period of oscillation

It can be seen in Fig. 7 that for the installation cases i, iii, v and vi provide almost constant characteristic with case i stiffer than others. For the case vi, the suspension becomes softer for increased value of ζ_{ae}/ζ_{ac} .

By considering the maximum acceleration at the first period after impact as shown in Fig. 8, it is seen that the cases i and ii provide poor isolation. These cases transfer most of the force from the base input to the passengers. Thus the passengers can be uncomfortable as increasing the value of ζ_{ae}/ζ_{ac} .

The cases iii to vi are seen to provide comparable maximum acceleration. The maximum acceleration for the case iv is seen to reduce for increasing the value of ζ_{ae}/ζ_{ac} whereas that for the cases iii and vi are almost constant. Although that for the case v is increasing with increasing value of ζ_{ae}/ζ_{ac} , it is considerable lower than those for the cases i and ii. The maximum acceleration for the installation angles of 45° and 90° is seen to be lower than that of 0° for about more than 60%, with respect to the value of ζ_{ae}/ζ_{ac} .

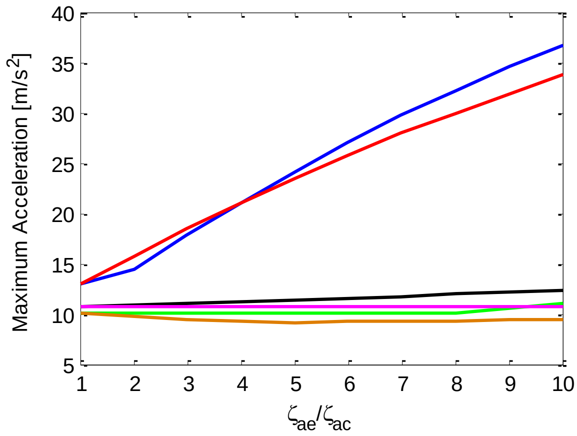


Fig. 8 Maximum acceleration of the sprung mass measured from the maximum of absolute value at the first period of oscillation

To this end, one may decide to apply or install the shock absorber depend on the response characteristic as shown. For example, one can install inversed damping force characteristic shock absorber having higher ratio between extension and compression with angle of 45º to reduce the absolute displacement and maximum acceleration. One may also install the shock absorber with the normal damping force characteristic having ζ_{ae}/ζ_{ac} of around 3 to reduce the total absolute displacement in order to improve handling.

However, one other factor to be considered is the oscillating time. Fig. 9 shows time for the sprung mass to stop oscillating. It is seen that the cases i and ii brings the sprung mass to the equilibrium in shorter time. This appears even shorter for increased ζ_{ae}/ζ_{ac} . In contrast, those for the cases iii to vi are about 11 seconds for all value of ζ_{ae}/ζ_{ac} .

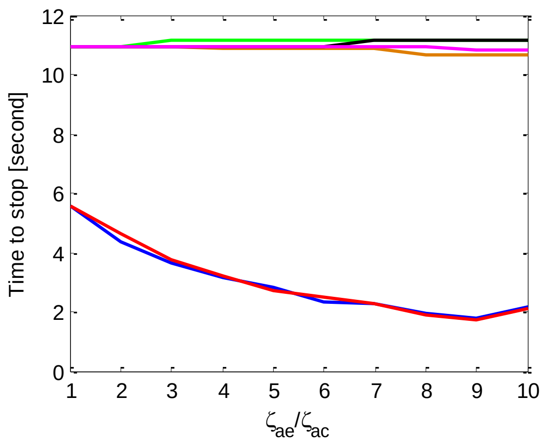


Fig. 9 Time for the sprung mass to stop oscillating

In addition, the installation of case ii is seen to be the worst case for all absolute displacement, relative displacement and acceleration. The responses are increased as the value of ζ_{ae}/ζ_{ac} increased. So this case can be disregarded for further studies.

From the results shown, the comparison of the individual case can be made. The installation with the value of ζ_{ae}/ζ_{ac} = 7 for the cases i, and iv are interesting. This is because these cases provide low absolute displacement compared to other cases. The maximum absolute displacement for the case i is about 0.083 m and that for the case iv is about 0.079. The responses for these cases are shown in comparison as shown in Figs. 10 – 12. The dotted line in Figs. 10 and 11 are displacement of the base input.

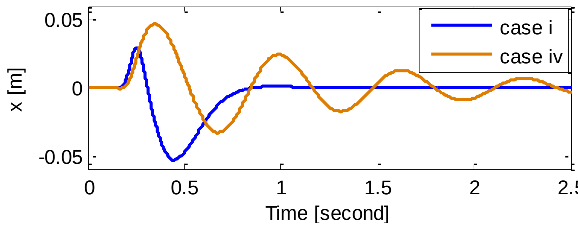


Fig. 10 Absolute displacement of the sprung mass

It is seen in Fig. 10 that the sprung mass for the case iv spends longer time to stop oscillating whereas that for the case i stops oscillating at about 1 second after impact. Fig. 11 also shows the longer time to stop for the case iv. However, the relative displacement for the case iv is seen to be greater than that for the case i. This can imply that case iv provides the softer suspension system compared to the case i.

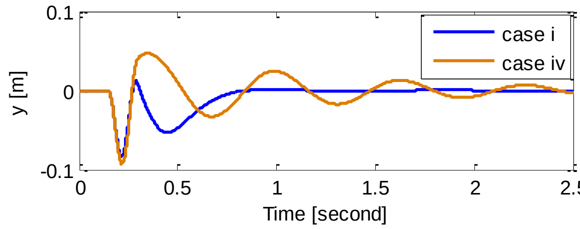


Fig. 11 Relative displacement between the sprung mass and the base input

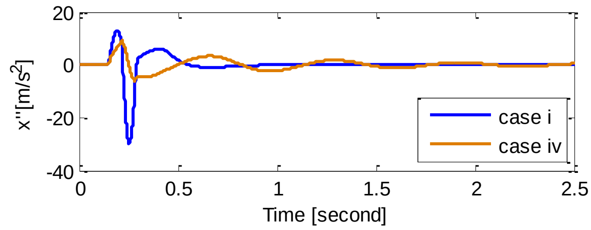


Fig. 12 Acceleration of the sprung mass

It is evidenced as shown in Fig. 12 that the case iv provides the softer suspension system. It is seen in Fig. 12 that the acceleration after impact for the case iv is much lower than that for the case i.

One may consider information from both absolute and relative displacement in this study to conclude that the suspension system in case i is most appropriate for the race cars. Installing the shock absorber having the normal damping force characteristic in the same direction of the motion can help improving handling quality.

On the other hands, installation angle other than zero for the shock absorber having either normal or inverse damping force characteristic allows the sprung mass to oscillate. However, by considering the acceleration, installing shock absorber as stated in cases iii – vi provides lower level of acceleration of the sprung mass. Thus the passengers can feel less discomfort compared to those obtained from cases i and ii.

It is seen in Fig. 12 that the absolute maximum acceleration for the case i is higher than those for the cases iv around more than 60%. This shows the improvement of ride quality. However, it is also seen oscillation for those inclined installation. This can be implied to soft suspension. As such, handling quality is reduced. Therefore, the installation angle in the passenger cars should be considered as inclined geometry.

However, this study assumed all parameters following the accessible publications. There might be other recommendations for assuming the parameters for the quarter car model. As such, the reader should be aware of the difference of the results.

5. Conclusions

The single degree of freedom quarter car model having the horizontal velocity of 90 km/h running over the sinusoida road hump had been examined. The installation geometry of the shock absorber was focused. The angle of shock absorber was considered as 0º, 45º and 90º to the motion of the sprung mass. The shock absorber characteristic was also considered in two different patterns. The ratio of damping force between the extension and compression strokes was also adjusted. The sinusoidal shape road hump was employed to obtain numerical results.

Installing the shock absorber with 0º degree to the motion of the sprung mass was found to be good in reducing the oscillation of the sprung mass. However, it was found to provide the highest maximum acceleration. This installation angle can be suitable for the race cars for which the handling quality is improved.

In contrast, installing the shock absorber in the angle other than zero can cause in more oscillation to the sprung mass. The installation angle of 45º was found to reduce the maximum acceleration better than others. Thus, installing the shock absorber at 45º can improve ride-comfort quality, despite reducing the handling quality. Therefore, it is essential for the vehicle to have the suitable shock absorber installation angle to suit the specific purpose.

However, this paper introduces the results only for an example by using a quarter car model with a single velocity of 90 km/h. It is also interesting for what would happen for the vehicle running at other velocities. The different installation angle might provide different vehicle characteristic. It is also interesting for the models with more complexity, for example, a half car model or a full car model. Thus, in order to improve either ride-comfort or handling quality, the more research and experimental study by mean of installation angle should be done.

6. References

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