

SIMULATION OF AN ACTIVE FRONT BUMPER SYSTEM FOR FRONTAL IMPACT PROTECTION

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ABSTRACT

This paper concerns the effectiveness of an active front bumper system to reduce the unwanted jerking of the vehicle during collision using magnetorheological (MR) damper. The mathematical model is developed using MATLAB 7.0 to simulate a collision between pendulum and the vehicle installed with an active front bumper system. This study also presents the performance characteristics of a MR damper for controllable bumper in the vehicle system. One of a promising candidate is the MR fluid undergoes significant instantaneous reversible changes in material characteristics when subjected to a magnetic field. The proposed damper is integrated with bellows to induce the flow motion which is operated under flow mode. The parameter is subjected to change based on situation of collision between pendulum and the vehicle model. For the situations which light and medium collision occurred, the mass of pendulum will be changed to 1/5 and 3/5 of vehicle mass respectively. For heavy collision, the mass of pendulum is set similar to the vehicle model mass. Acceleration and jerking of the vehicle model using passive damper and proposed skyhook controller system are investigated through simulation for light, medium and heavy collision. Simulation results show that an active front bumper system using skyhook controller is more effective compared to passive damper system during collision.

KEYWORDS: *An active front bumper, coefficient of restitution, kinetic energy, skyhook controller.*

1.0 INTRODUCTION

In passenger vehicle, technology is designed to taking over tasks of the driver in order to increase the level of safety and comfort ability.

Without technology, we can see a lot of fatal accident may occur. In Malaysia, traffic accidents have been increased at the average rate of 9.7% per annum over the last three decades. Total number of road accidents had increased from 24,581 cases in 1974 to 328,264 cases in 2005, reaching more than 135% increasing of accident cases over past 30 years. (Umar, 2005)

Vehicle front bumper is the first element which perceives the front impact in the most common cases of automobile accidents. In 1973, the National Highway Traffic Safety Administration (NHTSA) issued the first US bumper standards which required being capable of sustaining a 5 mile-per-hour (MPH) frontal crash and a 2.5 MPH rear crash without damage to vehicle safety systems. In 1974, the standard for rear crash was raised to 5 MPH. Phase I of the standard was first applied to model 1979 vehicles. In Phase II, starting from 1980 models, the bumper itself could sustain only superficial damage in a 5 MPH crash. (Flammang, 2000)

Based on the above statements, the problem of optimization and design improvement of a bumper with the aims to enhance the safety level of the vehicle is the important topics. For a decade, efforts were done to ensure the bumper more significant to absorb the energy due to impact occurred during accidents. Recently, the material selection of the bumper is investigated by researchers to optimize the energy absorption of the bumper (Bogdanov *et.al.*, 2003). Hooseinzadeh *et.al.* (2004) studied the structure, shape, and impact condition of glass mat thermoplastic (GMT) bumper by using LS-DYNA ANSYS 5.7 and the results are compared with conventional metals like steel and aluminium. GMT showed very good impact behaviour compared with steel and aluminium, which all failed and showed manufacturing difficulties due to strengthening ribs or weight increase due to use more dense materials. Lavrukhov *et.al.*(2003) investigated the effect of normal impacts of spherical steel on double layer bumpers in velocity range from 2 to 7 km/s. One layer of the bumper is made of fine copper powder and the other is made of duralumin. The result with a double layer bumper made from high-porosity copper/duralumin was better than a duralumin bumper at the impact velocities from 3 to 7 km/s.

The researchers also studied the physical improvement of the bumper for the lower extremity injury vehicle-pedestrian accidents. Matsui, Y. (2005) studied the effect of vehicle bumper height and vehicle impact velocity on the type of lower extremity injury in vehicle-pedestrian accidents. The results indicate that the type of injury to the tibia, knee ligament and femur were high with an increase in bumper height.

Furthermore, the major injury due to impact velocity of around 20–30 km/h was affected to the knee ligament. Davoodi *et.al.* (2007) proposed conceptual design of fibre reinforced epoxy composite bumper absorber as a pedestrian energy absorber. The energy absorption capacity of composite absorber was sufficient for pedestrian impact and it could possible to use as substitute for the existing materials such as EPP foam for low impact collision.

Present bumper design is less efficient in total amount of energy absorbed during front collision because of the front bumper is fix directly to the chassis. Thus, more collision energy will be transferred from the front bumper to the vehicle chassis. The large energy transferred to the chassis could lead the driver and the front passenger to have serious injury and yet resulting as factor of death. Therefore, active front bumper system is designed to absorb impact energy especially in light and moderate collision. In this paper, we have proposed the passive damper that installed between bumper and the chassis of the vehicle to protect the vehicle from large amount of jerk due to impact during collision. Besides that, we also proposed semi-active damper using skyhook controller scheme that replaced the passive damper in this system. The mathematical model is done by using MATLAB 7.0 to get the results of vehicle jerk for those situations.

2.0 THEORY

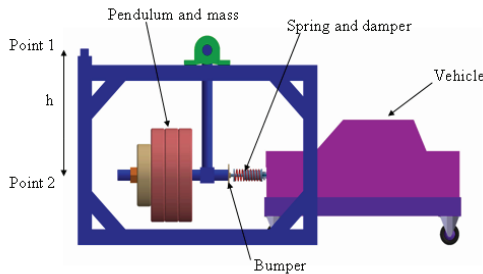


FIGURE 1
Vehicle collision model

Mass of pendulum is used as the method of vehicle crash test where it can fall freely due to effect of gravity and collide to the vehicle. Figure 1 shows the situation of the collision between pendulum and the vehicle model. At the initial condition, the vehicle model is at static condition. The pendulum will collide to the vehicle model by moving from point 1 to point 2. Referring to point 1 as shown in Figure 1, the pendulum only

has the potential energy, E_p . When it moves to point 2, the potential energy will be converted to the kinetic energy, E_k . At this point, the pendulum will collide to the vehicle model.

Potential energy, E_p at point 1,

$$E_p = M_p \cdot g \cdot h \tag{1}$$

Kinetic energy, E_k at point 2,

$$E_k = \frac{1}{2} \cdot M_p \cdot v_{1i}^2 \tag{2}$$

Where,

- M_p = mass of pendulum
- g = gravity acceleration
- h = height of pendulum
- v_{1i} = velocity pendulum at point 2

Based on the principle of energy conservation, the potential energy at point 1 is equal to kinetic energy at point 2.

$$E_k = E_p$$

$$\frac{1}{2} \cdot M_p \cdot v_{1i}^2 = M_p \cdot g \cdot h$$

$$v_{1i} = \sqrt{2gh} \tag{3}$$

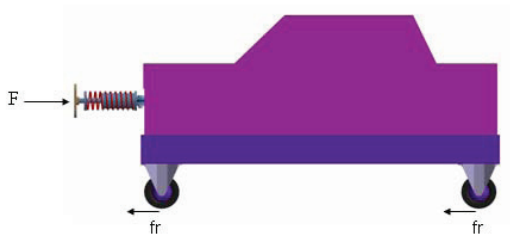


FIGURE 2

Momentum force generated transfer into the vehicle model

By using the equation of impulse and momentum, force generated from the collision, F as shown in Figure 2 is obtained as follow,

$$M_p v_{1i} + (M_v + M_b) v_{2i} = M_p v_{1f} + (M_v + M_b) v_{2f} \quad (4)$$

Where,

M_p	= mass pendulum
M_v	= mass vehicle
M_b	= mass bumper
v_{1i}	= velocity pendulum at point 2
v_{2i}	= velocity of vehicle before collision
v_{1f}	= velocity of pendulum after collision
v_{2f}	= velocity of vehicle after collision
f_r	= friction force of tire

In this case, the coefficient of restitution equation will be used to find the velocity of pendulum after collision, v_{1f} . The coefficient of restitution is a measure of the elasticity in a one-dimensional collision. If $e=0$, type of collision is perfectly elastic. Otherwise, if $e=1$, type of collision is perfectly plastic. The coefficient of restitution can be formulated as below;

$$e = \frac{v_{2f} - v_{1f}}{v_{2i} - v_{1i}}$$

$$v_{2f} = e(v_{1i} - v_{2i}) + v_{1f} \quad (5)$$

Substituting Equation (5) into Equation (4) and at initial, the vehicle model is in the static condition $v_{2i} = 0$, final velocity of the pendulum is:

$$v_{1f} = \frac{v_{1i}(M_p - e(M_v + M_b))}{(M_p + M_v + M_b)} \quad (6)$$

Then, impulse and momentum equation are used to find the force produced by the collision.

$$I = F dt = m dv$$

$$F = m dv / dt$$

$$F = \frac{M_p (v_{1i} - v_{1f})}{dt}$$

$$F = \frac{M_p \sqrt{2gh}}{dt} \left(1 - \frac{M_p - e(M_v + M_b)}{(M_p + M_v + M_b)} \right) \quad (7)$$

Where,

- F = force produced by the collision
- dt = the time interval over which the force is applied
- dv = the change in velocity produced by the force in the consideration of time interval
- e = coefficient of restitution

In this vehicle model, three pairs of spring and passive dampers are installed between front bumper and vehicle model as representing in Figure 3.

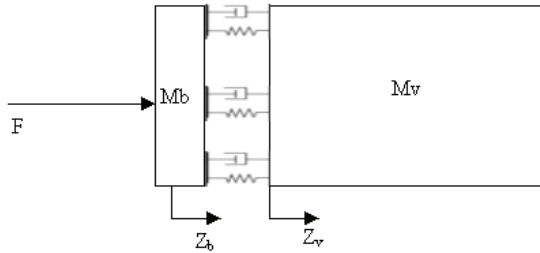


FIGURE 3
Plan view of the vehicle model and front bumper

The free body diagram of front bumper and vehicle model are illustrated in Figures 4 and 5 respectively.

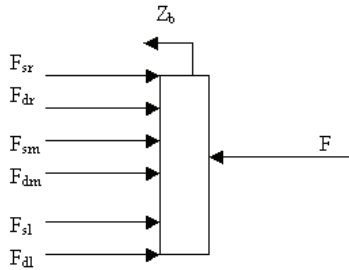


FIGURE 4
Free body diagram for front bumper

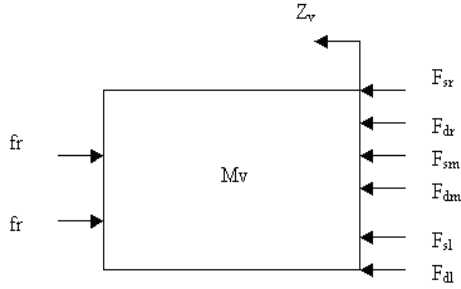


FIGURE 5
Free body diagram of the vehicle model

Total forces on the front bumper is,

$$\Sigma F_b = M_b \ddot{Z}_b$$

$$F - F_{sr} - F_{dr} - F_{sm} - F_{dm} - F_{sl} - F_{dl} = M_b \ddot{Z}_b \quad (8)$$

Then, total forces on the vehicle model can be expressed by,

$$\Sigma F_v = M_v \ddot{Z}_v$$

$$F_{sr} + F_{dr} + F_{sm} + F_{dm} + F_{sl} + F_{dl} - \dot{f}r - \dot{f}r = M_v \ddot{Z}_v \quad (9)$$

Where:

$$F_{sr} = K_{sr} (Z_b - Z_v) \quad (10)$$

$$F_{dr} = C_{dr} (\dot{Z}_b - \dot{Z}_v) \quad (11)$$

$$F_{sm} = K_{sm} (Z_b - Z_v) \quad (12)$$

$$F_{dm} = C_{dm} (\dot{Z}_b - \dot{Z}_v) \quad (13)$$

$$F_{sl} = K_{sl} (Z_b - Z_v) \quad (14)$$

$$F_{dl} = C_{dl} (\dot{Z}_b - \dot{Z}_v) \quad (15)$$

$$\dot{f}r = (M_v \times g \times \mu) / 2 \quad (16)$$

Substituting Equations (10) to (15) and Equation (7), into Equation (8) to simplify the equation.

$$\frac{M_p \sqrt{2gh}}{dt} \left(1 - \frac{M_p - e(M_v + M_b)}{(M_p + M_v + M_b)} \right) - K_{sr}(Z_b - Z_v) - C_{dr}(\dot{Z}_b - \dot{Z}_v) - K_{sm}(Z_b - Z_v) - C_{dm}(\dot{Z}_b - \dot{Z}_v) - K_{sl}(Z_b - Z_v) - C_{dl}(\dot{Z}_b - \dot{Z}_v) = M_b \ddot{Z}_b \quad (17)$$

Substituting Equations (10) to (16) into Equation (9) to simplify the equation;

$$K_{sr}(Z_b - Z_v) + C_{dr}(\dot{Z}_b - \dot{Z}_v) + K_{sm}(Z_b - Z_v) + C_{dm}(\dot{Z}_b - \dot{Z}_v) + K_{sl}(Z_b - Z_v) + C_{dl}(\dot{Z}_b - \dot{Z}_v) - (M_v \times g \times \mu) = M_v \ddot{Z}_v \quad (18)$$

where,

- F_{sr} = right spring force
- F_{sm} = middle spring force
- F_{sl} = left spring force
- F_{dr} = right damper force
- F_{dm} = middle damper force
- F_{dl} = left damper force
- K_{sr} = right spring stiffness
- K_{sm} = middle spring stiffness
- K_{sl} = left spring stiffness
- C_{dr} = right damper stiffness
- C_{dm} = middle damper coefficient
- C_{dl} = left damper coefficient
- Z_b = distance of the bumper move after collision
- \dot{Z}_b = velocity of the bumper after collision
- \ddot{Z}_b = acceleration of the bumper after collision
- Z_v = distance of the vehicle model move after collision
- \dot{Z}_v = velocity of the vehicle model after collision
- \ddot{Z}_v = acceleration of the vehicle model after collision

3.0 MODELLING OF MAGNETORHEOLOGICAL DAMPER

Figure 6 (a) shows the configuration of MR impact which can be installed in a bumper structure of a vehicle model. The damping force is generated by MR fluid flow when a certain, such as frontal collision occurs as illustrated in Figure 6(b). A MR damper consists of an upper

chamber, a magnetic circuit to produce magnetic field, a lower chamber located under the magnetic circuit, and a diaphragm.

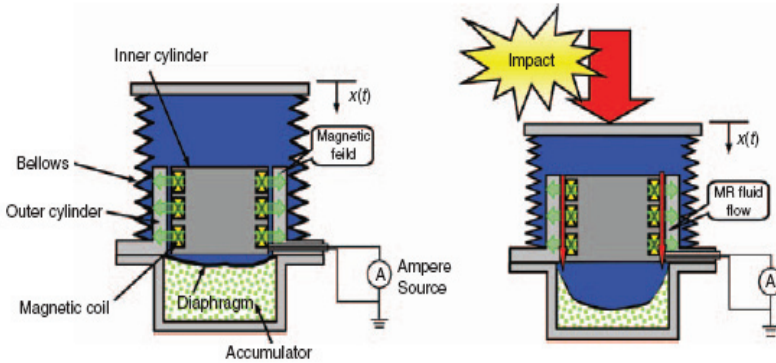


FIGURE 6

Configuration of MR damper (a) Before impact (b) After impact (D. Woo *et.al.*, 2007)

The diaphragm shown in Figure 6 plays a role in containing and accumulating the fluid flow. The flow channel is located between the upper and lower chambers. Fluid flow is generated for the motion of each chamber, and then fluids move on the flow channel. Bellows located at the position of the upper chamber have a good compression property to large deformation and a good volume change to fluid flow. It has oil resistance, moisture resistance, pressure resistance, and airtight characteristics for filled MR fluid. The damping force is produced only by fluid resistance of the MR fluid without magnetic field. If magnetic field is applied to the magnetic pole, the MR damper produces damping force on it. It can be continuously generated by adjusting the intensity of the magnetic field (Woo *et.al.*, 2007).

4.0 CONTROLLER STRUCTURE

In this analysis, three semi-active dampers (MR dampers) are being installed between front bumper and vehicle model that replace the passive dampers position in the system. A semi-active control method, skyhook control is introduced in this study to demonstrate the application of MR damper in terms of jerk control of the vehicle model during collision.

The controller structure implemented in this study was representing in Figure 7, which consists of outer loop and inner loop controllers. The outer loop controller is used for disturbance rejection control to reduce

unwanted vehicle motions such as the acceleration and jerk of the vehicle. The inputs of the outer loop controller are vehicle condition, namely, vehicle velocity and bumper velocity, whereas the output of the outer loop controller is the target force that must be tracked by the MR damper.

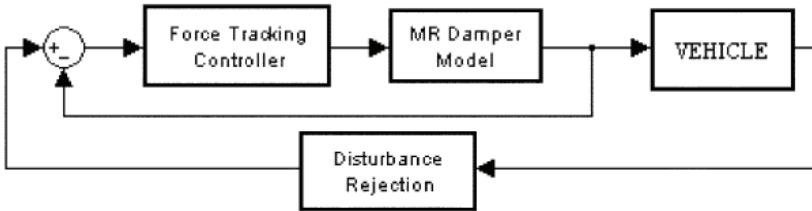


FIGURE 7

The controller structure of active front bumper (Hudha *et.al.*, 2005)

On the other hand, the inner loop controller is used for force tracking control of the MR damper in such a way that the force produced by the MR damper is as close as possible with the target force produced by the disturbance rejection control.

5.0 RESULT

5.1 Light collision

Figure 8 and Figure 9 show the acceleration and jerk of the vehicle model in light collision respectively. From the acceleration graph, at time 2 seconds, the pendulum had collided to the vehicle model and results an acceleration of 5.9 ms^{-2} . After 0.2 seconds, the vehicle model decelerates to negative range of acceleration. The vehicle model stops at 2.65 seconds after collision. The comparison between acceleration of passive and skyhook controller are indicated almost similar trend occurred during collision.

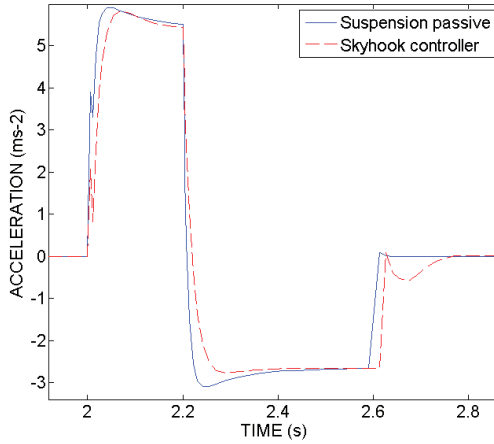


FIGURE 8
Acceleration of vehicle model in a light collision

In contrast, the jerk of the vehicle model with passive dampers shows peak value of 750 ms^{-3} . After 2.2 seconds being impacted, it shows maximum negative value, -1000 ms^{-3} before back to zero. The jerk of the vehicle model turns into positive value at 2.6 seconds due to the vehicle model stopped and generated small jerk into vehicle model. By using the skyhook controller, the jerk of the vehicle model can reduce effectively. It can be clearly seen that the highest positive value and the highest negative value are 400 ms^{-3} and 400 ms^{-3} respectively. These shown the energy absorbed during collision up to 50% through the proposed skyhook controller which results less jerking occurred in the vehicle model.

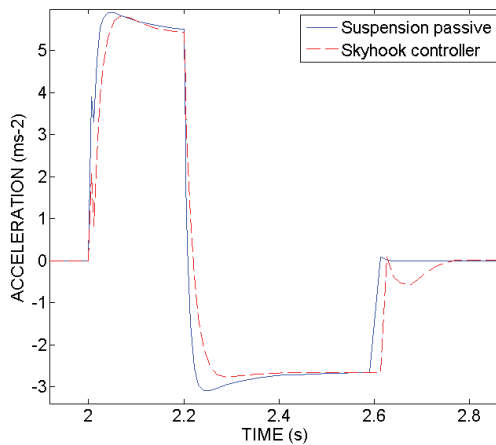


FIGURE 9
Jerk of vehicle model in a light collision

5.2 Medium collision

Figure 10 and Figure 11 presents the acceleration as well as jerk versus time for the vehicle model subjected to a medium collision.

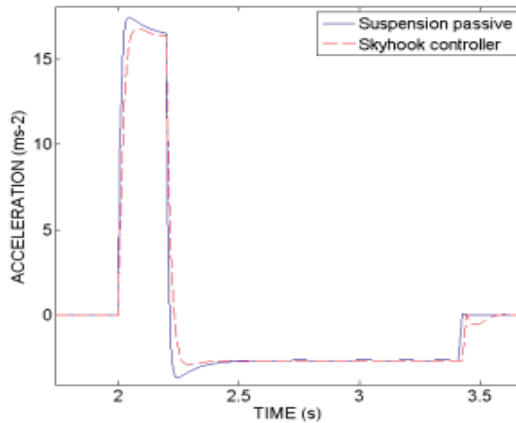


FIGURE 10

Acceleration of vehicle model in a medium collision

From the acceleration graph, the pendulum had collided at 2 seconds to the vehicle model and indicates the maximum acceleration of 18.8 ms^{-2} for passive suspension system and 17.2 ms^{-2} for skyhook controller. Then, the vehicle model decelerates to negative range of acceleration after 0.2 seconds being collided and stable until 3.4 seconds prior stop at 3.5 seconds. The active bumper through skyhook controller demonstrates less acceleration occurred during collision compared with passive damper.

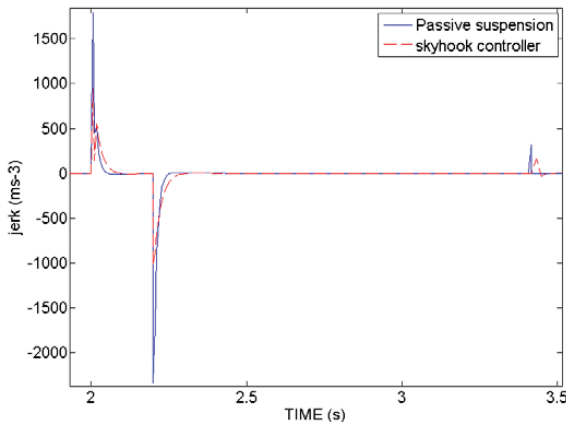


FIGURE 11

Jerk of vehicle model in a medium collision.

Besides that, the jerking of the vehicle model using skyhook controller presents better performance which indicates maximum values of -1000 ms^{-3} compared to passive dampers recorded -2350 ms^{-3} after 0.2 seconds. Moreover, the skyhook controller shown in Figure 11 demonstrates the consistencies in maintaining the maximum jerk through energy absorption via MR damper. Approximately at 3.4 seconds, the jerk of the vehicle model turns into positive range because the vehicle model stopped and generated small jerk into the vehicle model.

5.3 Heavy collision

Figure 12 and Figure 13 show the acceleration and jerk of the vehicle model in heavy collision respectively. From the acceleration graph, the pendulum had collided to the vehicle model at 2 seconds and results an acceleration value 24.8 ms^{-2} . After 0.2 seconds, the vehicle model decelerates to negative range of acceleration. The vehicle model is not accelerated and stops at its position at 3.8 seconds and onwards. Comparison in terms of acceleration between passive and skyhook controller were demonstrated similar trend with the improvement on skyhook which reduces the acceleration occurred of vehicle model during heavy collision.

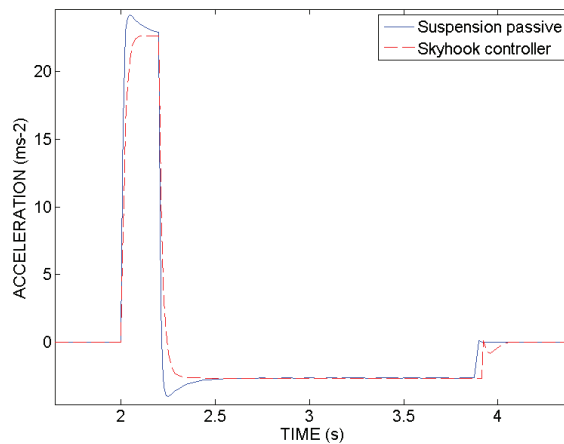


FIGURE 12

Acceleration of the vehicle model in a heavy collision

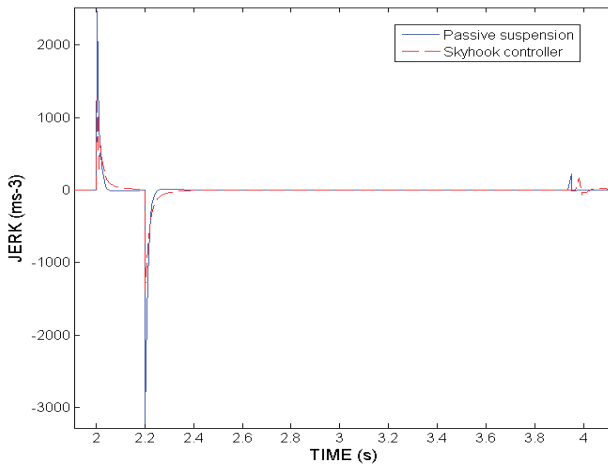


FIGURE 13
Jerking of the vehicle model in a heavy collision

Figure 13 show the jerking of the vehicle model with passive dampers indicates maximum value of 2500 ms^{-3} . After 0.2 seconds being impacted, it shows maximum negative value of -3100 ms^{-3} prior back to zero. At 3.9 seconds, the jerk of the vehicle model turns to positive value because the vehicle model stopped and generated small jerk into vehicle model. By using the skyhook controller for light and medium collision, it also can reduce jerking occurred effectively in heavy collision. It can be clearly seen that the highest positive and negative value is about 1200 ms^{-3} and -1500 ms^{-3} respectively.

6.0 DISCUSSION

The simulation result is carried out with MATLAB SIMULINK software. In this simulation, the parameter value for pendulum mass are varies according to the situation or the behaviour of collision between pendulum and vehicle model. For a light and medium collision, the mass of pendulum will be changed to $1/5$ and $3/5$ of the vehicle mass. For heavy collision, mass of pendulum is equal with mass of the vehicle model. All above cases use the constant value of coefficient of restitution, $e = 0.5$.

Figure 8 to Figure 13 shows the response of the vehicle model in term of the acceleration and jerking of the vehicle model in various conditions such as light, medium and heavy collision. The acceleration and the jerk of the vehicle model went from maximum to minimum value at 0.2 seconds after the collision had occurred. During collision, the time for

a pendulum contact with the vehicle model must be extended longer to prevent the jerk change from maximum to minimum in a short time. Thus, this will delay time where energy occurred due to impact being transferred to the passenger compartment and yet reduce the injury risk of passengers because energy absorbed by the MR damper. The acceleration and the jerk of the vehicle model are highest at heavy collision followed by the medium collision and light collision. The pendulum has the highest kinetic energy (larger mass of pendulum) in heavy collision that will be transferred to the vehicle model during collision.

From the above graphs, the acceleration and jerking for the vehicle model using passive damper display a higher value compared to the vehicle model using the skyhook controller which are installed between the front bumper and the chassis of the vehicle model. Furthermore, in heavy collision, the vehicle model acceleration and jerk using skyhook controller show significant improvement compared to the medium and light collision. Therefore from the simulation results, the skyhook controller is suitable to be installed between the front bumper and the chassis of the vehicle model to protect the passengers and the driver from unwanted jerk during collision.

7.0 CONCLUSION

From the simulation results, it is show that an active front bumper is more effective to reduce jerking of the vehicle during collision compared to common design of front bumper that was fixed to the chassis. Meanwhile, an active front bumper via the proposed skyhook controller can reduce the acceleration and jerking of the vehicle model compared to passive suspension system. From simulation, the comparison is investigated between light, medium and heavy collision for passive and active bumper system. The acceleration and the jerk of the vehicle model show highest value in heavy collision followed by medium collision and light collision.

8.0 ACKNOWLEDGEMENT

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