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Hybrid Controller Design based Magneto-rheological Damper Lookup Table for Quarter Car Suspension

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ABSTRACT

In this works, a combination of skyhook and groundhook control based magneto rheological lookup table technique called hybrid control for a quarter car is developed. Using the vertical acceleration measured data, the absolute velocity of the vehicle (sprung mass) and its relative velocity were estimated using bandpass filter. The effects of the mass distribution of a vehicle supported by a spring and load asymmetry due to changes in speed and displacement at the damping point are analyzed. The characteristics of the damper produced by the hybrid-lookup table control and the system's response to the road profile are evaluated. Simulation of the semiactive suspension design was integrated with the hybrid controller (integration of the sky-groundhook controls) based lookup table, then compared to the skyhook controller and hybrid conventional. The simulation indicates that the proposed Hybrid control lookup table provides better vibration isolation capability than other methods.

Keywords: Hybrid-lookup table, Skyhook, Groundhook, Magneto-rheological damper, semi-active suspension, quarter car.

Mathematics Subject Classification: 46N40, 47N70

Computing Classification System: I.4

1. INTRODUCTION

People daily use their cars for various reasons with some disadvantages. For instance, when a car crosses road irregularities, the vibration caused by it may unfavorably affect human health and discomfort. The vibration will certainly disturb the passengers, therefore it must be minimized to the desired tolerance level. The suspension systems are the primary equipment in a car that can be used to reduce the effects of vibrations that are transmitted from road surfaces. On the basis of this phenomenon, almost all automotive manufacturing companies and researchers are trying with various efforts to increase the quality of the suspension car. The suspension has several important roles, namely supporting the body of the car, isolate the body from external excitation, and to keep tires and road surfaces in contact. The suspension generally consists of two categories: passive and active in accordance with the presence of control inputs. Meanwhile, active suspension systems can be classified as active or semiactive depending on the presence or absence of power supply to the controller. If the controller requires outside energy, then it is called an active and vice versa is known as a semiactive suspension systems. The stability and comfort of the vehicle gives the opposite effect, therefore, the passive suspension which is usually used on the car or vehicle, cannot fulfill the driving comfort and stability simultaneously (Turnip and Fakhrurroja, 2013). Regarding driving comfort and safety issues, various studies on active suspension have been widely studied and various methods have been proposed (Turnip, Hong, and Park, 2009, Abdulhammed and Elsherif, 2017, Wang, et al., 2017, Huang, et al., 2015 & 2018). The resulting active suspension has shown remarkable developments both in comfort and stability and has even reached the market. Various control strategies such as optimal control (Marzbanrad, Ahmadi, Hojjat, Zohoor, 2002, Chen and Lei, 2013, Turnip and Hong, 2013) nonlinear control (Vaijayanti et al., 2017), robust control (Wang, Zhao, Gong, Yang , 2018), adaptive control (lin and Qian, 2002) and intelligent control (Lin and Lian, 2011) have been tested and implemented on active suspension systems. The control method most often used in active suspension is the optimal control method (Michael and Gerdts, 2015, Wang, Wang, Sun, and Zhao, 2017). Studies on control approaches that have been successfully applied in other fields have also been carried out aimed at ensuring the continuity and coherence of previous technologies (Tan, Zhao, Xu, 2007; Precup, Preitl, 2003; Precup, Preitl, 2006; Garcia et al, 2011; Yacoub, Bambang, Harsoyo, Sarwono, 2014).

In this study, a damper using Magneto-rheology (MR) type fluid as a damping medium in a semiactive suspension was investigated. Although the need for the use of MR dampers is increasing, in practice MR dampers for control applications are limited by hysterical dynamics and very nonlinear (Turnip, Hong, Park, 2009, Turnip, Park, Hong, 2011). Because of its highly nonlinear nature, the strategy for obtaining the desired control quality is by building dynamic models from accurate damping forces so as to be able to represent the congenital behavior of MR fluid hysteresis. The damper model must also be accurate if it is realized in an open loop which tends to be easier to implement and at a lower cost than a closed loop one. Many damper models have been designed to estimate the field-dependent hysteresis characteristics of MR fluid. Some of these are the Bouc-Wen model (Ikhouane, Mañosa, Rodellar, 2007), the Bingham plastic model (Ansley and Smith, 1967) and the polynomial model (Turnip, Hong, and Park, 2009). Their simulation results show that the polynomial model has a better capability to predict non-linear hysteresis behavior than the Binhgam and the Bouc-Wen models (Ansley and Smith, 1967, Turnip, Hong, and Park, 2009).

Basically, MR fluid is obtained by blending silicon oil and a number of iron fleck called MR damper. The nature of MR damper will change if it is exposed to a magnetic field, but for control application only need to activate the solenoid with a normal battery. Skyhook's control method was first proposed by Karnopp, who introduced a controller design installed among the mass of the vehicle and the stationary sky (the vehicle seemed to be suspended from the sky). The algorithm used in the Skyhook method is usually very simple and inexpensive compared to the others. Furthermore, Algorithms tend to have a fairly good damping capability compared to similar other algorithms (Park, Turnip, and Hong, 2009a, Park, Turnip, and Hong, 2009b). Skyhook control applications tend to be better at minimizing vibrations due to mass movement of the vehicle but it becomes less good if used to reduce vibrations that come from uneven road surfaces. From these two conditions, skyhook control is very effective in reducing vibrations from the unsprung mass in the frequency region of around 10 Hz. To anticipate these shortcomings, other researchers found groundhook controls. Groundhook control, as investigated by Valasek (Valasek, Novak, Sika, Vaculın, 1997), is able to reduce vibrations originating from the road surface while increasing the grip of the wheels on the road. To improve the capability of the control design to muffle vibrations from car body and road surfaces, skyhook and groundhook with lookup table as reference are integrated called hybrid lookup table. Extensive studies on the performance of semi-skyhook, groundhook, and hybrid conventional controllers with different types have been explored (Koch, Spirk, Lohmann, 2010, Gawthrop, Neild, and Wagg, 2012, Mulla, Jalwadi, Unaune, 2014, Ghasemalizadeh, Taheri , Singh, Singh, 2017). In designing the integration of the two controllers, stability and ride comfort are the main criteria.

To anticipate the hysteresis and nonlinear characteristics of MR dampers and also overcome the possibility of the influence of uncertainty in the semiactive suspension system, the use of a hybrid controller based on a lookup table is pursued. One of the strengths of the lookup table method is that it does not require an perfect mathematical model design but is easily able to handle the irregularities and uncertainties of the controlled system (vehicles with semi-active controllers) with MR damper as a absorber. The quality of a quarter vehicle suspension system is validated and appraised based on the results of simulations with MATLAB. The contribution of this work is to modify the conventional skyhook control such that the control characteristics at 10Hz can be improved.

2. Modeling

In the design of vehicle suspension controls, there are three types of vehicle modeling ranging from full, half and quarter. Vehicle models with a quarter car are the most widely used because of the simplicity of the mathematical model, which only uses the vertical body movement of the reference vehicle. The quarter car representation of the suspension system in a vehicle is given in Figure 1.

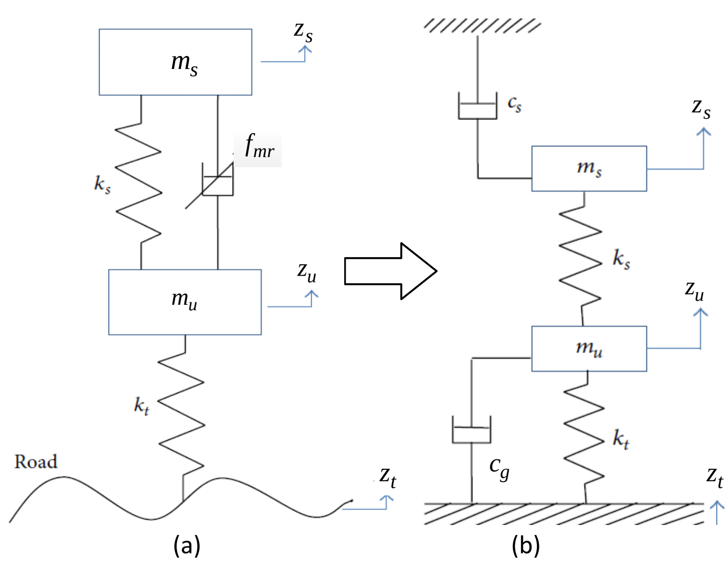

Figure 1. (a) Quarter car vehicle model, (b) hybrid control.

2.1. A quarter car model

The scheme of a quarter car with its suspension is presented in Figure 1 (a), where m_s and m_u are the sprung and unsprung masses, respectively; c_s and c_g are skyhook and groundhook absorber coefficient, respectively; k_s is spring constants of the skyhook, k_t is the tire equivalent constants, z_r is the rough road surface profile, z_s is the car body position and z_u is the tire position. Figure 2 (b) represents details on the skyhook model, where c_s is the damping coefficient of the sprung mass suspended to the sky.

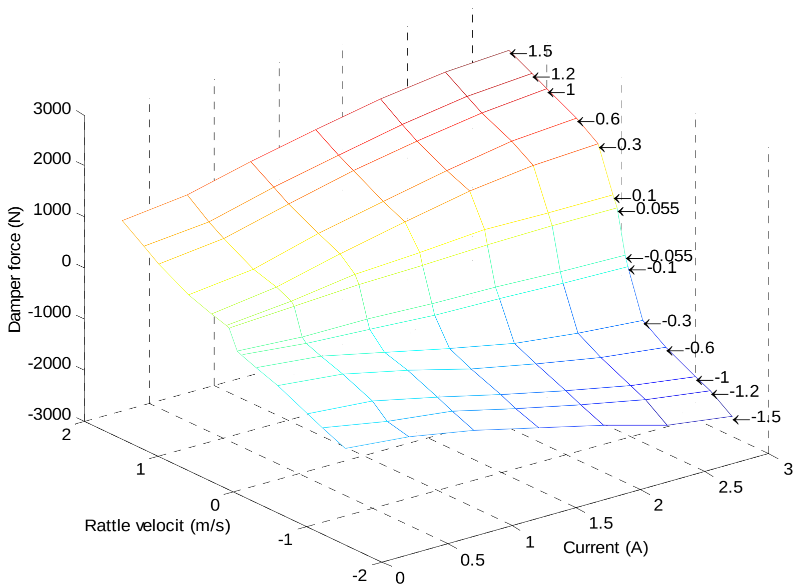

Figure 2. Lookup table damper force characterized by three parameters i.e. current I_v, rattle velocity I_v, and damper force f_d.

In deriving the suspension mathematical model in Figure 1, the parameter values to be used can be seen in Table 1. The integrated control system is developed so that the MR damping force f_{mr} is obtained perfectly by adjusting an input in the current form I to achieve the desired force of damper. At the same time relative displacement $z_s - z_u$ is obtained from a sensor and are used to estimate relative and absolute velocities. The quarter vehicle model is only limited to vertical movements and not to other movements of the quarter car. The equation model for the movement studied is

$$m_s \ddot{z}_s + k_s (z_s - z_u) + f_{mr} (\dot{z}_s - \dot{z}_u, I) = 0, \quad (1)$$

$$m_u \ddot{z}_u + k_u (z_u - z_d) - k_s (z_s - z_u) - f_{mr} (\dot{z}_s - \dot{z}_u, I) = 0, \quad (2)$$

where f_{mr} as a desired damping force is designed as a function of the estimated relative velocity $\dot{z}_s - \dot{z}_u$ and the current input I. In this experiment, all parameters information are estimated except relative displacement $z_s - z_u$, which is obtained from a sensor measurement.

Table 1: Suspension model parameters.

Parameter	Value
Sprung mass (m_s)	560 kg
Unsprung mass (m_u)	36 kg
Coil spring constant (k_s)	28.000 N/m
Tire stiffness (k_t)	186.000N/m
Rattle space ($z_s - z_u$)max	91mm

2.2. Nonlinear MR-Damper

Deriving mathematical model of the quarter vehicle suspension is the first step in building the proposed hybrid controller. Often we are limited in testing if we have to do direct experiments. This is because the high cost also requires time and a high level of difficulty. As a solution, simulation techniques using mathematical models of the system under study. The accuracy of the mathematical model that is built largely determines the results of simulations on the application of hybrid control. In the damper force model, the controller is described by three variables i.e. current I_v, rattle velocity I_v, and damper force f_d. The values of rattle velocity can be obtained from the datasheet. But the values of current I_v are found out experimentally. The initial value of the input I_v current is usually set to 1 and will gradually change to the desired damping force value according to the f_d-I_v character (obtained from the experimental results). The arrangement process is done well so that the lookup table model is able to represent the real damping force. If we are able to get the damping force model from the lookup table based only on the f_d-I_v characteristic information of the experimental results, then both the trial process and the real application will save a lot of calculation time. The time savings are obtained from the calculation process where sufficient results are taken from input data mapping. Rattle speed information, input current, and dampening force data are used to build lookup tables. The lookup table model is an array used to replace runtime calculations with simpler indexing operations.

By neglecting all dynamics of the suspension, the desired damper force is expressed in the form of lookup table model, which interpolates the input current I_v and the rattle velocity v_r to reach the desired damper force f_d (Figure 2). In fact, a combination of single current input can produce several values of the damper force due to the hysteresis properties of the used fluid. To overcome this problem, secondary variables are needed to describe the system completely with lookup tables. Therefore a study of alternative approaches to describe complex model is analyzed. The first approach, only the rattle velocity input affects the dynamics of the system, while the current only statically affects the damper force. To reach this desire, a polynomial model that has a nonlinear model structure is a combination of linear dynamics with static nonlinear mapping.

The lookup table is a representation of a non-parametric model where the dynamics of the output are determined by the parameters set in the table. The table is made on 2D grid and interpolation techniques as shown in Figure 2. A 2D rectangular grid map is defined in space or as a function of f_d-i_v. For each bin on the grid, the desired damping force is interpolated based on the measured data points (obtained from recorded experiments) available in the grid. If the grid is empty, the desired damper force is interpolated from the non-empty grid around it. If you want to improve driving quality on different road conditions (without compromising vehicle handling performance) on a semi-active damping system, the damping force range must be widened while minimizing the response time of the damping response. Most sophisticated vehicles already use control dampers and their demand tends to increase continuously. One important feature proposed in this paper is the application of relative displacement sensors where in the conventional skyhook control design is obtained using two acceleration sensors placed on the sprung and unsprung mass, respectively. Measurements using relative displacement are used to detect the phase difference between input and output in sinusoidal signals (these changes occur along with the movement of the piston). Through this approach, the relative displacement up to the size of the micro meter can be estimated more accurately.

2.3. Hybrid control

In this section, a hybrid controllers based on skyhook schemes are designed and developed. The traditional skyhook method is usually used to control the vehicle body so that passengers remain comfortable from external disturbances or vibrations. The problem is how to determine the optimal value of SkyHook controller parameters so that the vehicle can be comfort and stable. The sky-groundhook laws are mathematically represent as (Turnip, Park, & Hong, 2011)

$$F_{sky} = \begin{cases} c_{sky}\dot{z}_s & \dot{z}_s(\dot{z}_s - \dot{z}_u) > 0 \\ 0 & \dot{z}_s(\dot{z}_s - \dot{z}_u) \leq 0, \end{cases} \tag{3}$$

$$F_{ground} = \begin{cases} -c_{ground}\dot{z}_u & \dot{z}_u(\dot{z}_s - \dot{z}_u) < 0 \\ 0 & \dot{z}_s(\dot{z}_s - \dot{z}_u) \geq 0, \end{cases} \tag{4}$$

where $\dot{z}_s$ and $\dot{z}_u$ are the absolute velocities of the sprung (quarter car body) unsprung (the wheels and its devices) masses, respectively, which estimated from the relative velocity of the sprung to the unsprung masses $\dot{z}_s - \dot{z}_u$; F_{sky} and F_{ground} are the skyhook and groundhook damping forces, respectively, and c_{sky} and c_{ground} are the skyhook and groundhook gains. For the hybrid controller purpose, the estimated parameters (velocity of sprung and unsprung masses), and the relative velocity between sprung mass and unsprung mass, respectively, are then applied as an input to the design hybrid control and the lookup table. The output of the lookup table is used to be the desired damper forcef_d. The control law of the integration of the skyhook and groundhook called hybrid controlis modeled as (Gawthrop, Neild, & Wagg, 2012)

$$F_{hybrid} = \eta F_{sky} + (1-\eta) F_{ground}\,, \tag{5}$$

where $\eta \in (0, 1)$ is a weighting factor, which is tunable to balances the effect of skyhook and groundhook control for improving the quality ride comfort and handling stability. The sheme of hybrid-lookup table control is shown in Figure 3.

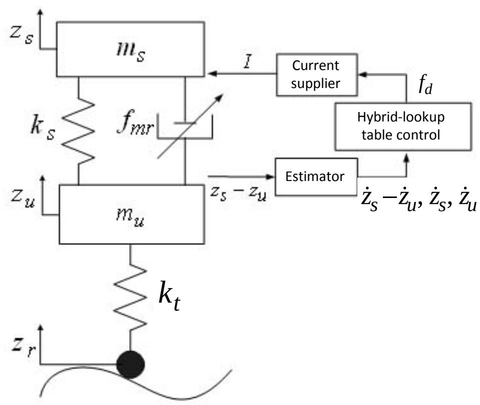

Figure 3. Scheme of hybrid-lookup table control.

3. RESULTS AND DISCUSSIONS

The vibration performance of cars in low frequency range can be improved without lowering the high frequency vibration performance. The application of hybrid-lookup table control for semi-active damper with low energy consumption can produce damping force (close to active control)for vibration reduction between car body and bogie. Figure 4 shows the overall simulation procedures: a comparison of the conventional hybrid control and hybrid lookup table control in the Simulink scheme with step input road profile. The estimated absolute velocity of the sprung mass compare with the simulated signals is shown in Figure 5. The estimated one is used to develop the damper force signals. The force tracking performance of the developed semi-active damper is depicted in Figure 6. The conventional hybrid control is developed by applying a determined value of gains c_{sky} and c_{ground}, however in the hybrid-lookup table control the gain values is selected from the table based on the road conditions. The value of each variable used in the simulation was obtained in Table 1, the parameter η equals to 0.85. The performance of each control policy is evaluated in controlling the sprung and unsprung masses based on the desired criteria. The output of the hybrid lookup table control is compared to the hybrid conventional control.

The graphics in Figure 7 to Figure 12 show further responses of the system with step input signals as a disturbance to the vehicle. All responses show a smaller overshoot and a less settling time compared to the hybrid conventional damper. Figure7 is the comparison of the sprung masses acceleration. The semi-active suspension with proposed and developed control can also achieve a slightly smaller peak-to-peak acceleration of the sprung mass but highly less settling time. Figure 7 is the comparison of the unsprung masses acceleration, a highly smaller peak-to-peak acceleration of the unsprung mass than that of the hybrid conventional control. When those reductions were compared to the skyhook control suspension systems, they showed that these semiactive suspension systems using the hybrid-lookup table control could improve the ride comfort and the ride handling under a road random function.

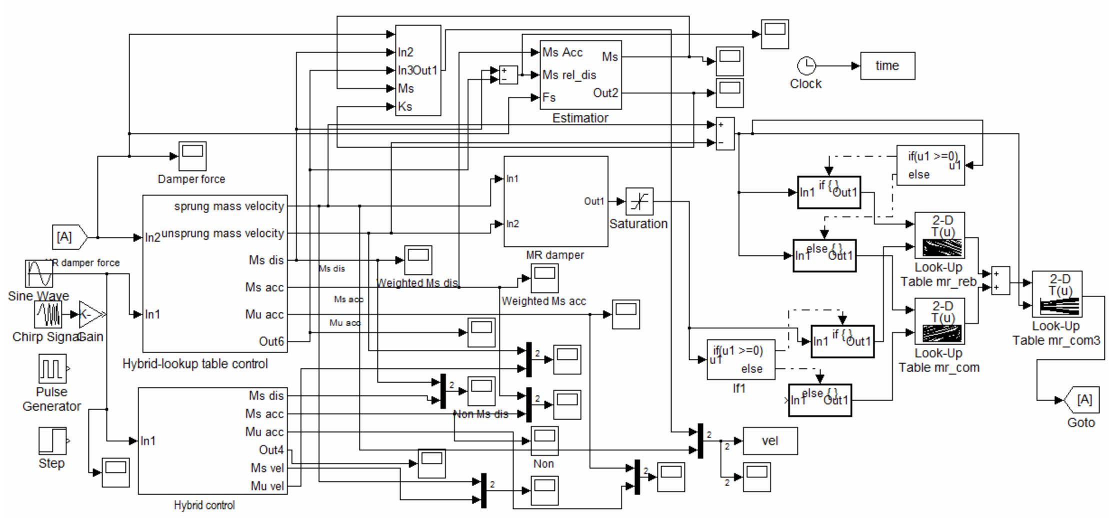

Figure 4. Simulink diagram of hybrid and hybrid-lookup table controller.

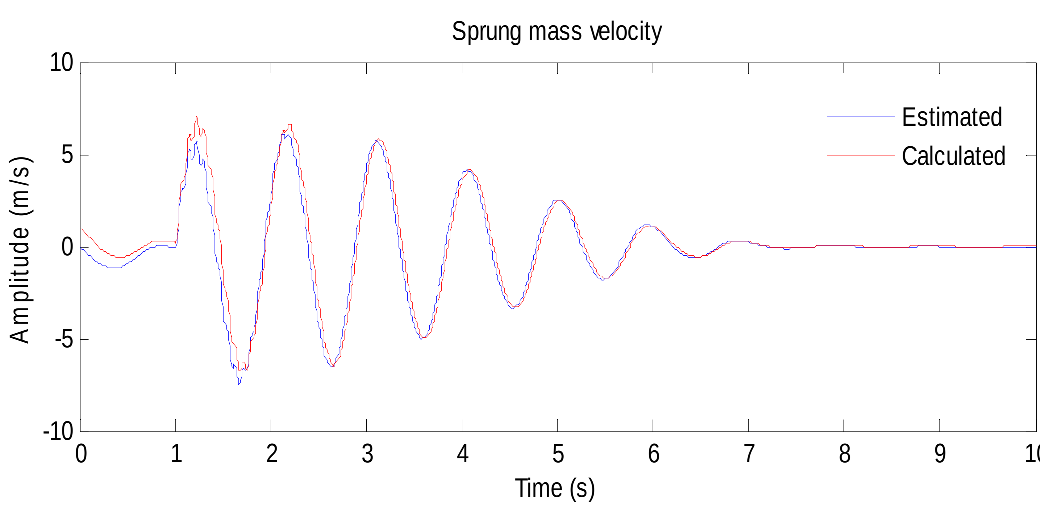

Figure 5. The estimated sprung mass velocity.

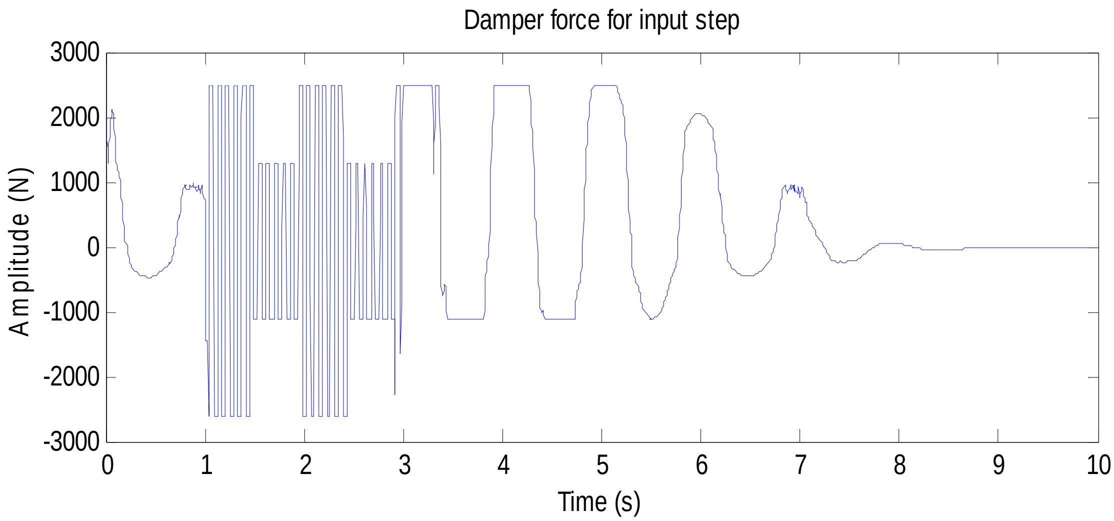

Figure 6. Damper force amplitude for input step road profile.

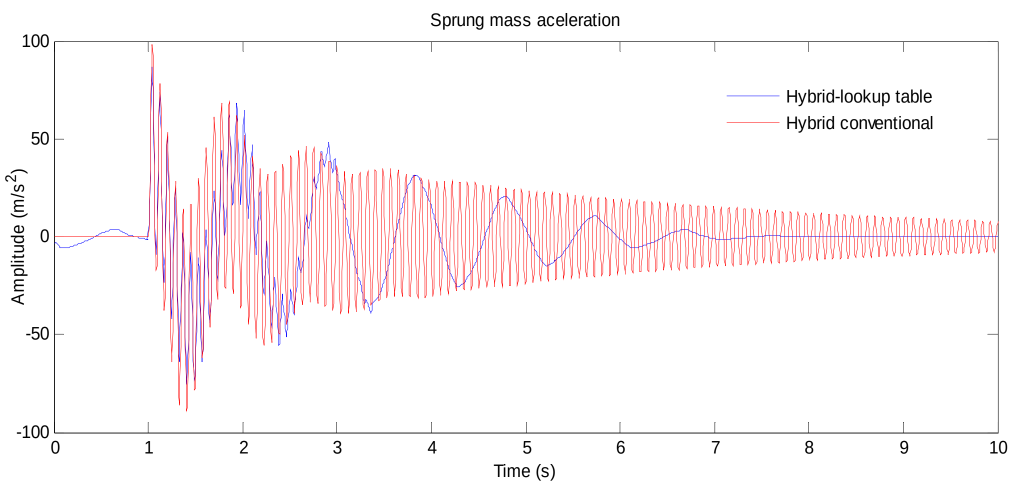

Figure 7. Sprung mass acceleration: Hybrid-lookup table vs hybrid conventional control.

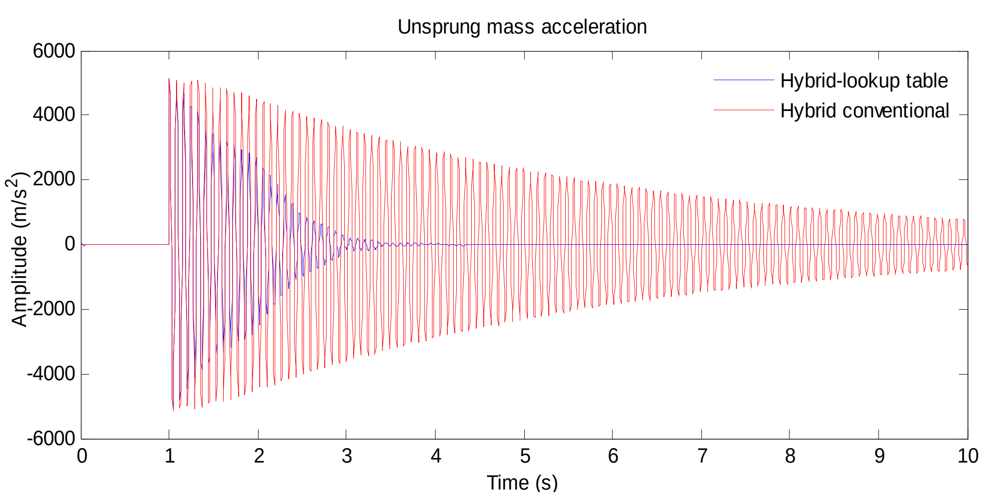

Figure 8. Unsprung mass acceleration: Hybrid-lookup table vs hybrid conventional control.

Figure 9 to Figure 12 describe the comparison (i.e., hybrid lookup table and the conventional hybrid) of the velocity and the displacement responses of thesprung and unsprung masses, respectively. Except sprung mass velocity, all plot results show the significant improvement in their vibration reduction. Sprung mass velocity with conventional hybrids has a smaller average amplitude than the hybrid lookup table but has a higher frequency (Figure 9). The high frequency of vibration speed will cause discomfort for passengers. This means that even though the amplitude is greater but the comfort tends to be better. From the results of other simulations, it can be seen that in the disturbance of bumpy or regular bumps, the semi-active hybrid lookup table suspension system designed can produce a deflection control signal of the vehicle body suspension which is relatively faster towards the reference / setting point, which means it provides better comfort than the system conventional conventional semi-active suspension.

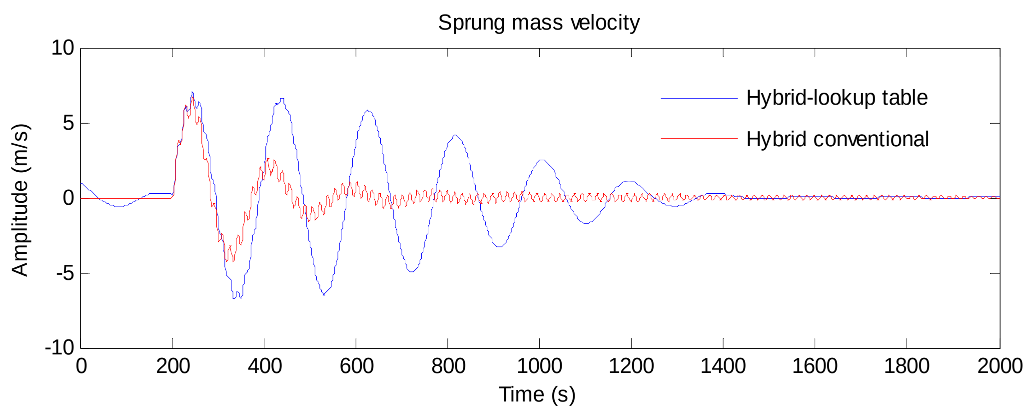

Figure 9. Sprung mass velocity: Hybrid-lookup table vs hybrid conventional control.

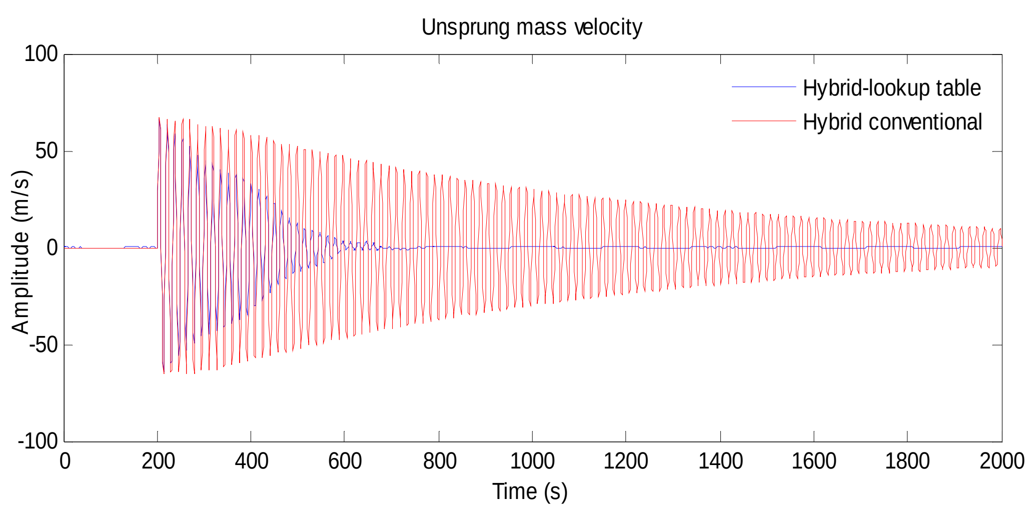

Figure 10. Unsprung mass velocity: Hybrid-lookup table vs hybrid conventional control.

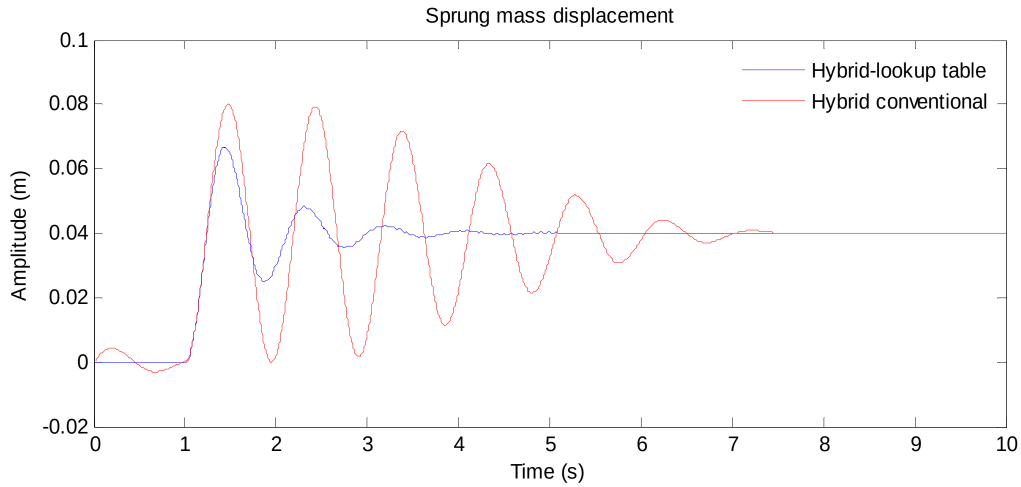

Figure 11. Sprung mass displacement: Hybrid lookup table vs hybrid conventional control.

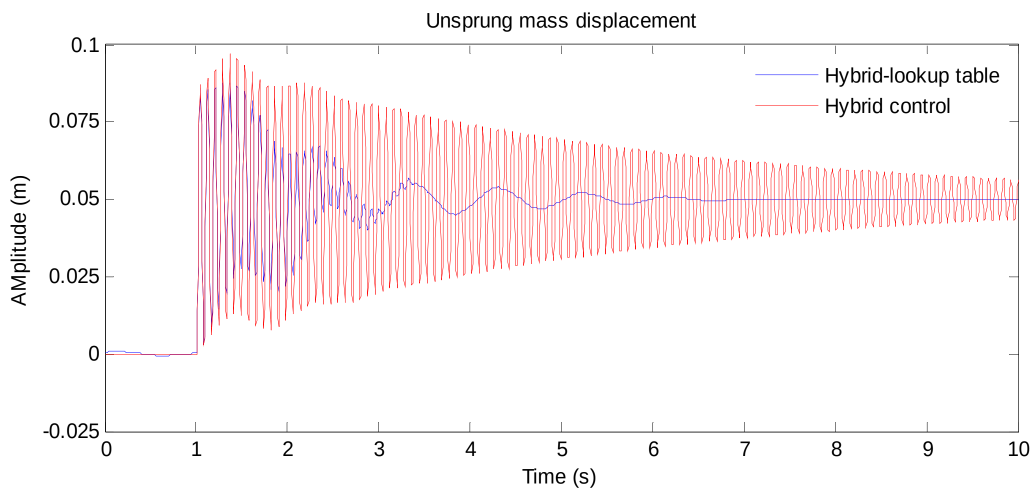

Figure 12. Unsprung mass displacement: Hybrid lookup table vs hybrid conventional control.

4. CONCLUSIONS

The design of a quarter vehicle suspension system requires a trade-off between stability or ride handling and ride comfort. For this purpose, the quality of the four parameters namely acceleration and removal of mass sprung, removal of unsprung mass, and suspension deflection must be recognized. Semi-active suspension with a proposed hybrid-lookup table controller design can reduce acceleration and displacement of the mass sprung thereby increasing passenger comfort. In order to increase vehicle stability, the parameters of acceleration and displacement of masses and suspension deflection must be reduced so that the increase in vehicle stability is achieved.

Simulation results show that vehicle comfort and stability with the hybrid lookup table method is achieved well with a very significant increase in performance compared to other methods especially with conventional hybrids. Considering the complexity of the hydraulic semi-active damper, it was demonstrated that the actuator dynamics, which is represented by damper scheduling through lookup table could achieve a competitive control performance.

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