

# Comparison between Skyhook and Minimax Control Strategies for Semi-active Suspension System

Hongkun Zhang, Hermann Winner, and Wenjun Li

**Abstract**—This paper describes the development, modeling, and testing of skyhook and MiniMax control strategies of semi-active suspension. The control performances are investigated using Matlab/Simulink [1], with a two-degree-of-freedom quarter car semi-active suspension system model. The comparison and evaluation of control result are made using software-in-the-loop simulation (SILS) method. This paper also outlines the development of a hardware-in-the-loop simulation (HILS) system. The simulation results show that skyhook strategy can significantly reduce the resonant peak of body and provide improvement in vehicle ride comfort. Otherwise, MiniMax strategy can be employed to effectively improve drive safety of vehicle by influencing wheel load. The two strategies can be switched to control semi-active suspension system to fulfill different requirement of vehicle in different stages.

**Keywords**—Hardware-in-the-loop simulation, Semi-active suspension, Skyhook control, MiniMax control.

## I. INTRODUCTION

THE roles of a suspension system are to support the vehicle weight, to isolate the vehicle body from road disturbances, and to maintain the traction force between the tire and the road surface. The purpose of suspension system is to improve the ride comfort, road handling and stability of vehicles. Suspension systems are classified into a passive system, semi-active system and active suspension system. Semi-active suspension system can offer a compromise between the simplicity of passive systems, and the cost of higher-performance fully active suspension system. In comparison with an active suspension system, a semi-active suspension requires much less power, and is less complex and more reliable and can provide considerable improvement in vehicle ride quality. Consequently, Semi-active suspension systems are getting more attention in the development of suspension system. The skyhook control strategy introduced by Karnopp et al. [2] is undoubtedly the most widely used control policy for semi-active suspension systems. The skyhook control can reduce the resonant peak of the body mass and thus achieves a good ride quality. But, in order to

improve both the ride quality and the safety of vehicle, both resonant peaks of the body and the wheel need to be reduced. From this point of view, MiniMax control strategy proposed by Prof. Herrman Winner and Tobias Niemi [3] is introduced in this paper. In our research, models of skyhook and MiniMax control strategies of semi-active suspension system are established in Matlab/Simulink. Performance of passive suspension, skyhook and MiniMax strategies for semi-active suspension are compared using SILS. At the same time, the concept of hardware-in-the-loop simulation is also introduced and the process of setting up HILS system is outlined.

This paper is structured as follows. In Section II, a two-degree-of-freedom quarter car model for the semi-active suspension system is given. In Section III, on/off skyhook algorithm is introduced. Wheel load influence matrix is introduced and MiniMax controller is designed. In Section IV, the performances of passive system, skyhook and MiniMax strategies are compared and evaluated using SILS and the simulation results are given. In Section V, the outline of HILS of the system is described. The working steps of HILS are explained. Conclusions are given in Section VI.

## II. A QUARTER-CAR SEMI-ACTIVE SUSPENSION SYSTEM MODEL

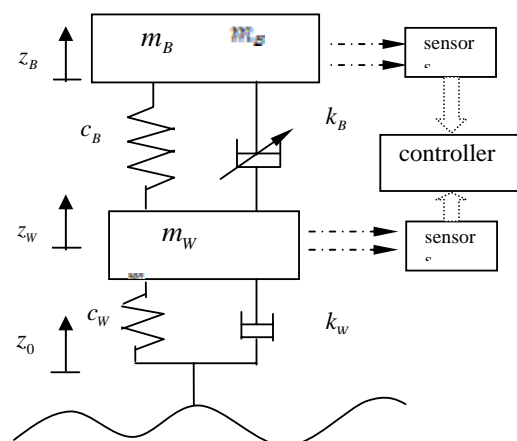


Fig. 1 2 DOF semi-active suspension system model

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It is well known that the ride characteristics of passenger vehicles can be characterized by considering the so-called 'quarter-car' model [4]. This method has been widely used to investigate the performance of passive [5], semi-active [6], and fully active [7] suspension system. The quarter car semi-active suspension system model is shown in Fig. 1.

Here, the model considers the body mass  $m_B$ , wheel mass  $m_w$ , body vertical stiffness  $c_B$ , wheel vertical stiffness  $c_w$  and damping coefficient of wheel damper  $k_w$ . It has two degrees of freedom, body deflection  $z_B$ , wheel deflection  $z_w$ , and is excited by  $z_0$ . The parameters of the model (front-left wheel) are shown in Table I.

The model is governed in analytical form by the following system of equation:

$$\begin{bmatrix} m_B & 0 \\ 0 & m_w \end{bmatrix} \begin{bmatrix} \ddot{z}_B \\ \ddot{z}_w \end{bmatrix} + \begin{bmatrix} k_B(v_D, I_D) & k_B(v_D, I_D) \\ -k_B(v_D, I_D) & k_B(v_D, I_D) + k_w \end{bmatrix} \begin{bmatrix} \dot{z}_B \\ \dot{z}_w \end{bmatrix} + \begin{bmatrix} c_B & -c_B \\ -c_B & c_B + c_w \end{bmatrix} \begin{bmatrix} z_B \\ z_w \end{bmatrix} = \begin{bmatrix} 0 \\ k_w \dot{z}_0 + c_w z_0 \end{bmatrix} \quad (1)$$

TABLE I  
QUARTER-CAR SUSPENSION MODEL PARAMETERS (FRONT LEFT WHEEL)

| Parameter Description               | Symbol | Value  | Units |
|-------------------------------------|--------|--|-------|
| Body Mass                           | $m_B$  | 380  | kg    |
| Wheel Mass                          | $m_w$  | 31   | kg    |
| Stiffness of Body Spring            | $c_B$  | 29000  | N/m   |
| Stiffness of Wheel Spring           | $c_w$  | 228000                                       | N/m   |
| Damping Coefficient of Body Damper  | $k_B$  | 1500 ( $I_D = 1.6A$ )<br>6000 ( $I_D = 0A$ ) | Ns/m  |
| Damping Coefficient of Wheel Damper | $k_w$  | 400  | Ns/m  |

According to above equation the linear differential equations describing the dynamics of the semi-active suspension can be written as:

$$m_B \ddot{z}_B = -k_B(\dot{z}_B - \dot{z}_w) - c_B(z_B - z_w) \quad (2)$$

$$m_w \ddot{z}_w = k_B(\dot{z}_B - \dot{z}_w) - k_w(\dot{z}_w - \dot{z}_0) + c_B(z_B - z_w) - c_w(z_w - z_0) \quad (3)$$

Quarter car model can be established according to equations (2) (3) using MATLAB's dynamic system simulation software, Simulink.

### III. CONTROL STRATEGIES

#### A. Skyhook Control

It is typically classified as continuous skyhook control and on-off skyhook control. The on-off Skyhook controller is

usually simpler and better suited for the industrial applications. In this study, on-off skyhook control is implemented. The control law can be described as follows:

$$c_{sky} = \begin{cases} c_{max} & \text{if } v_r v_b \geq 0 \\ c_{min} & \text{otherwise} \end{cases} \quad (4)$$

in which  $v_b$  is the absolute velocity of the body and  $v_r$  is the relative velocity of the body and wheel across the suspension. This strategy indicates that if the relative velocity of the body with respect to the wheel is in the same direction as that of the body velocity, then a maximum damping force should be applied to reduce the body acceleration. On the other hand, if the two velocities are in the opposite directions, the damping force should be at a minimum to minimize body acceleration. This control strategy requires the measurement of the absolute velocity of body. Although the accurate measurement of the absolute vibration velocity of body on a moving vehicle is very difficult to achieve, it is easy to do for the laboratory experiment in order to evaluate the performance of damper and controller. In our research, we use accelerometer to obtain body acceleration. Velocity of the body can be calculated by body acceleration.

#### B. Minimax Control

To keep safety of vehicle, it is very important to reduce wheel load variations. How can the wheel load be influenced by a damper? A control algorithm is presented by Tobias Niemz [3]. A Wheel Load Influence Matrix can be induced by considering every possible state of damper movement. Wheel Load Influence Matrix is shown in Table II.

TABLE II  
WHEEL LOAD INFLUENCE MATRIX

| Shock abs.<br>stage<br>Switching<br>of shock abs. | Compression            | Rebound                |
|---|------------------------|------------------------|
| Hard to soft                                      | Decrease in wheel load | Increase in wheel load |
| Soft to hard                                      | Increase in wheel load | Decrease in wheel load |

The Matrix can be read as following manner: In rebound, if the damper is switched from hard to soft, this will lead to an increase in wheel load. In compression, if the damper is switched from hard to soft, this will lead to a decrease in wheel load. This wheel load influence matrix shows that it is possible to purposely influence the course of wheel load. This knowledge about the effect of switching the damper can be implemented into a switching logic. This logic chooses between the two characteristic lines 'soft' and 'hard', depending on the inputs 'damper velocity' and 'request of wheel load', and is therefore called MiniMax-controller.

In Fig. 2, the principle function of the MiniMax controller is shown. Depending on the inputs  $v_D$  and  $F_{z,req}$  the damper current  $I_D$  is switched to either 0 or 1.6A (hard or soft

damper). This means if either the request of wheel load or the damper velocity changes its sign, the damper will be switched from hard to soft or vice versa. The damper velocity  $v_D$  or the sign of the damper velocity sign ( $v_D$ ) provides with information about the direction into which damper is moving compression or rebound. The request of wheel load  $F_{z,req}$  has values of either one (increase of wheel load) or minus one (decrease of wheel load).

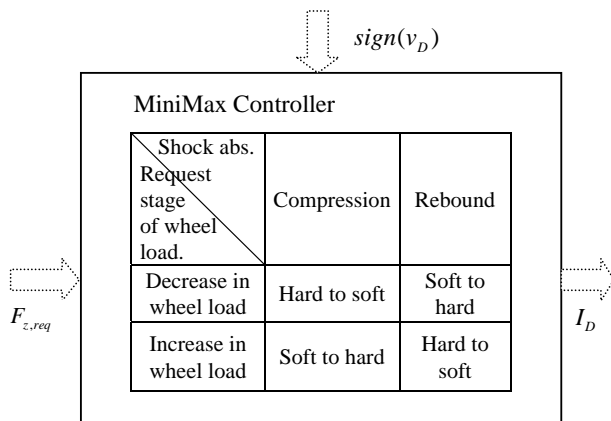


Fig. 2 MiniMax Controller

#### IV. SILS AND RESULTS

The control model of passive suspension, skyhook and MiniMax control for semi-active suspension are established in Simulink. SILS are implemented using Matlab/Simulink. In SILS stage of development, components and control algorithms are simulated on an arbitrary computer without real-time requirements to obtain. The simulation results are shown in Fig. 3, Fig. 6. In order to compare the control performance, they were all excited by sine wave that the amplitude is 1cm. Fig. 3 shows vertical body acceleration response of passive, skyhook and MiniMax control. As can be seen from Fig. 3 the body acceleration of skyhook control has more reductions than that of passive and MiniMax control. That means skyhook control can decrease vertical body acceleration effectively and improve ride comfort of vehicle.

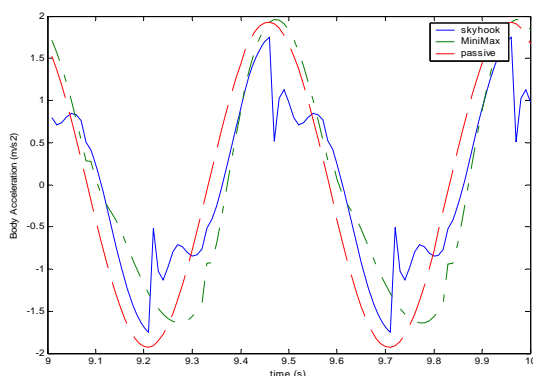


Fig. 3 Comparison of Body Acceleration Response of Passive, Skyhook and MiniMax

Wheel load force of passive, skyhook and MiniMax are compared in Fig. 4. In comparison with passive system and skyhook, drive safety can be improved using MiniMax controller.

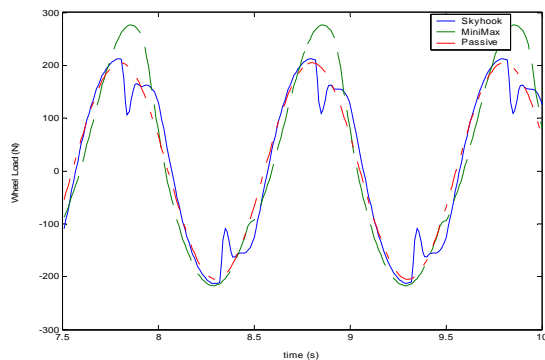


Fig. 4 Comparison of Wheel Load Response of Passive, Skyhook and MiniMax

From the results, the conclusion can be drawn that the ride comfort improvement is almost completely owing to the skyhook component. MiniMax strategy can effectively improve drive safety of vehicle by influencing wheel load.

#### V. SCHEME OF HILS

A more realistic method called HILS should be implemented after SILS. But in our research only give the outline of HILS for our system because of time reason. HILS is a technique that is used increasingly in the development and test of complex real-time embedded systems. HILS scheme is being widely adopted in automotive industries [8] [9]. HILS refers to a computer simulation in which some of the components of the simulation have been replaced with actual hardware. It integrates the actual ECU and its peripheral hardware with the virtual vehicle model, forming a closed loop to be simulated in real time. This allows one aspect of the system to be physically tested, while the remainder of the structure is simulated in real time. This increases the realism of the simulation and provides access to controller features currently not available in software-only simulation models. HILS method can shorten the research period of vehicle semi-active controller and reduce the cost of research. In addition, it is easy to introduce a new component or a new algorithm because the test procedure, once it is set up, can be easily repeated. In our research, HILS system is built using the dSPACE real-time environment, which is based on a dSPACE I/O board allowing the processor to interact directly with the sensors during real-time simulation. The process of simulation is managed and monitored by ControlDesk.

Fig. 5 shows the HILS configuration. Here, Matlab/Simulink is used as a computer aided-control system tool for modeling the non-physical quarter car parameters, passive system, skyhook and MiniMax control algorithm. A host PC is used to implement both the damper control strategies and quarter car semi-active suspension model. AutoBox is the ideal environment for using dSPACE real-

time system for HIL experiments. The processor DS1005 PPC board, multi-Channel A/D Board DS2003 and CAN interface board DS4302 are integrated on the AutoBox. The DS1005 PPC Board provides the basis of dSPACE's modular hardware. It not only gives the real-time calculation power to a modular system, but also provides the interface to the I/O boards and to the host PC. DS4302 board is used to transmit current signal which calculated from the dynamic model in the computer to ECU to control the damper. Two accelerometers record the vertical body acceleration and wheel acceleration, respectively. Another two sensors called force sensor and spring displacement sensor are utilized to obtain wheel load and spring travel. These sensors signals are converted to digital signal by DS2003 board and provide the input data to control model.

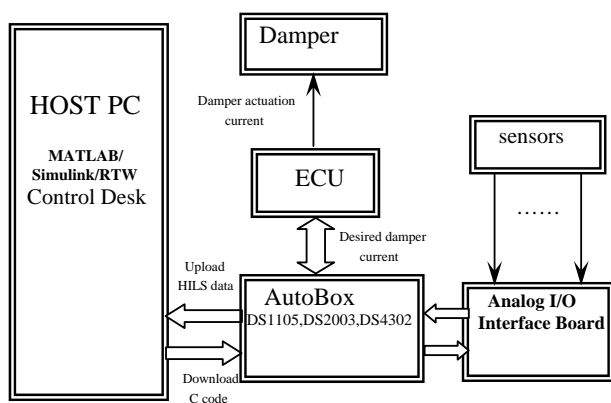


Fig. 5 Configuration for the hardware-in-the-loop simulations

The working procedure for the HILS is summarized as follows:

- 1) The control algorithm is first of all designed off-line using Matlab/Simulink.
- 2) Using the Real-Time-Workshop, a C-code of the control algorithm is generated. The C-code is again downloaded to the target board using the Real-Time-Interface. Therefore, the dynamic models developed can be reused easily for the HILS.
- 3) The PWM voltage signal related to the damping force calculated from the dynamic model in the computer are transmitted to the damper drive unit ECU through CAN interface board DS4302.
- 4) ECU transforms the PWM voltage signal into a current signal to switch damper current either 0 or 1.6A in order to control damper from soft to hard or from hard to soft.
- 5) Signals of sensors are converted to digital signal by DS2003 board and transferred to the dynamic model in the computer. By varying the control parameters in real time, the procedures 3–5 can be repeated.

## VI. CONCLUSION

The current paper has described the performance comparison of passive system, skyhook and MiniMax strategies for semi-active suspension systems using software-in-the-loop simulation method. From the results of

simulations, skyhook control can achieve more reduction of resonant peak of the body mass than that of passive suspension and MiniMax controller and thus gives a good ride comfort. Otherwise, it is possible to purposefully increase or decrease the wheel load by using MiniMax controller to improve the safety of vehicle. Consequently, skyhook and MiniMax strategies can be switched during the vehicle is running in proper moment for effectively improving both riding comfort and safety of vehicle. In addition, the concept of hardware-in-the-loop simulation is also introduced and the process of setting up HILS system is outlined.

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