RESEARCH ON RIDE COMFORT AND ROAD FRIENDLINESS UNDER HYBRID EXTENSION DAMPING CONTROL FOR HEAVY TRUCK VEHICLE SUSPENSION SYSTEM

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Abstract

In order to improve the performance of ride comfort and road friendliness, this paper proposed a novel control strategy, weighting the sky-hook proportion and the ground-hook proportion for heavy truck vehicle suspension system based on the extension theory. First of all, the model of heavy truck vehicle suspension system is established. The control strategies logic based on extension theory is introduced and the controller system is established, made up of upper and lower controllers. Then the deviation signals of acceleration and tire deformation were chosen to establish an extension set. The correlation function of the extension controller was established to calculate the correlation degree, which is divided into classical domain, extension domain and non-domain. According to the reasoning mechanism, corresponding control were adopted in different control areas to realize the switching of sky-hook control, hybrid control and ground-hook control, and to improve the dynamic performance of vehicles. The results show that the weight allocation has a significant impact on the ride comfort and road friendliness performance for suspension system and based on the extension theory, the comprehensive performance of body acceleration and tire transformation is better than the sky-hook control and passive suspension.

Keywords: Heavy vehicles dynamics, suspension system model, extension theory, sky-ground hook control;

1. Introduction

The heavy commercial vehicle are widely used due to the development of road construction and social needs. In order to achieve more economic benefits, the heavy commercial vehicle, which is different from passenger car, should carry extensive load for a long time. Therefore, it is necessary to decrease the indexes of body acceleration, suspension deflection, and tire deflection under suspension design. However, the performance of body acceleration and tire deflection, which represent the sprung mass vibration and the unsprung mass vibration, are contradiction. Therefore, this paper proposes a method to adjust the damper coefficient to improve the performance of body acceleration and tire deflection at the same time.

2. Method

2.1 Vehicle model construction

In this section, the 2-DOF suspension model is introduced to describe the vertical vibration and the schematic diagram of the vehicle dynamics model is shown in Figure 1. The model assumed tire damping is ignored. The stiffness of the tire is represented by K_t. m_2 and m_1 denote the sprung mass and the unsprung mass respectively. The suspension control force is u. z_1, z_2, and q represent tire vertical displacement, body vertical displacement, and road excitation respectively [22]. ECU represents Electronic Control Unit. The positive direction is shown in Figure 1.

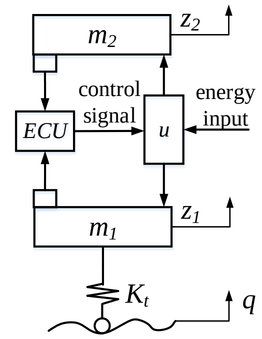


Figure 1. 2-DOF vehicle controllable suspension model.

Base on Newton's second law, the dynamic equation of the 2-DOF controllable suspension model is established as follow .

$$\begin{cases} m_2\ddot{z}_2 = u \\ m_1\ddot{z}_1 + K_t(z_1 - q) = -u \end{cases} \tag{1}$$

Where $\ddot{z}_2$ and $\ddot{z}_1$ denote the acceleration of the spring mass and the acceleration of the unsprung mass respectively.

2.2 Hybrid damping Control

The semi-active suspension system with hybrid control is shown in Figure. 2 :

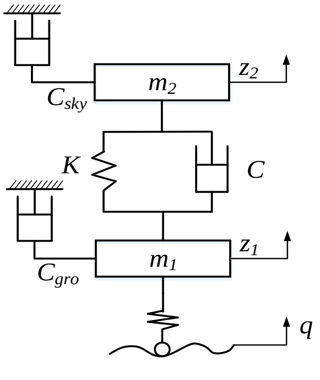


Figure.2 Principle diagram of the hybrid damping control.

The desired hybrid control force is expressed as equation (2):

$$u(t) = -(u_1(t) + u_{td}(t)) \tag{2}$$

Where $u_1(t) = K(z_2 - z_1)$ represents the spring force, K is the spring stiffness, $\dot{z}_2$ and $\dot{z}_1$ represent the sprung mass velocity and the unsprung mass velocity. The damping force is represented as $u_{td}(t) = [1 + k(S)]C_{sky}\dot{z}_2 - k(S)C_{gro}\dot{z}_1$, where C_{gro} is the desired ground-hook damping coefficient. C_{sky} is the desired sky-hook damping coefficient. $k(S)$ is the weight of the hybrid damping coefficient.

As illustrated in Figure 2, based on the equation (1) and equation (2), the equations of hybrid control suspension system which is illustrated in figure (2) are represented as:

$$\begin{cases} m_2\ddot{z}_2 + K(z_2 - z_1) = -[1 + k(S)]C_{sky}\dot{z}_2 + k(S)C_{gro}\dot{z}_1 \\ m_1\ddot{z}_1 - K(z_2 - z_1) + K_t(z_1 - q) = [1 + k(S)]C_{sky}\dot{z}_2 - k(S)C_{gro}\dot{z}_1 \end{cases} \tag{3}$$

However, considering vehicle state and road excitation, the weights of the hybrid system should be determined adaptively. Therefore, to cope with the problem, the extension control system is established.

2.3 *Extension theory*

The extension control system consists of upper and lower controllers, as depicted in Figure. 3. The signal *e* which is the deviation between output signal *y* and desired signal *r* is taken as the input of the controller. The damping coefficient *u*, which meets the performance requirements of the suspension and the driving requirements of the vehicle, is calculated by the suspension extension switching controller. Therefore, the suspension with the extension control system forms a closed-loop control system.

The upper part is an extension controller, which divides the control area and decides the control strategy for the lower controller. In addition, control weight *α* of the lower controller is also calculated in the upper part. According to the change of control weight *α*, control methods are changed to expand the control range of the suspension control system. The lower controller is a damping controller. By means of the control weight α calculated by the upper part, the control damping force is obtained. There are three control modes in the low controller, which correspond to separately sky-hook control, ground-hook control, and hybrid control, as shown in Figure. 4.

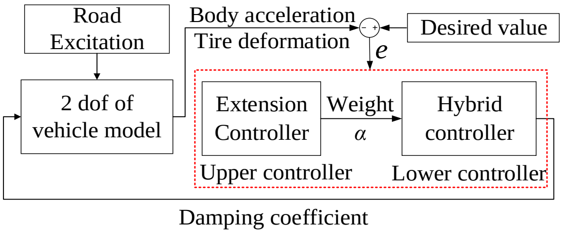


Figure.3 Hybrid control suspension system.

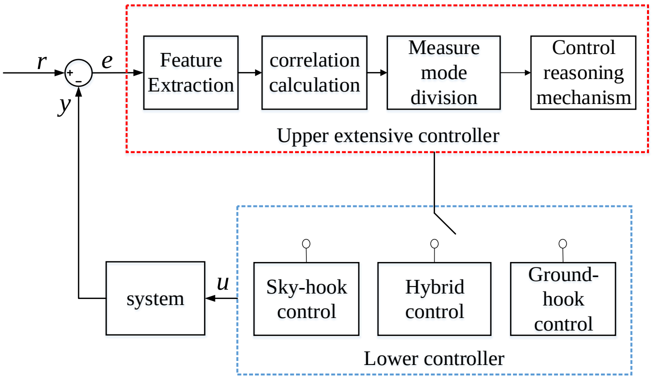


Figure.4 Extension controller with suspension hybrid control.

3. Result

3.1. Parameter of the extension controller

In order to determine the parameters of the extension controller, the extension controller is simulated, compared with passive suspension and the sky-hook control. Because the extension controller is a nonlinear time-varying system, the time-domain analysis is applied to the extension controller [43]. The amplitude responses of each control method are obtained by MATLAB/Simulink under sinusoidal excitation. The parameters of the vehicle model depend on the data in Table. 1. The parameters of the extension controller are determined in Table. 1 based on the low-frequency signal and high-frequency signal simulation. When the parameters of the extension controller are determined as table 2, the suspension system could obtain good control performances.

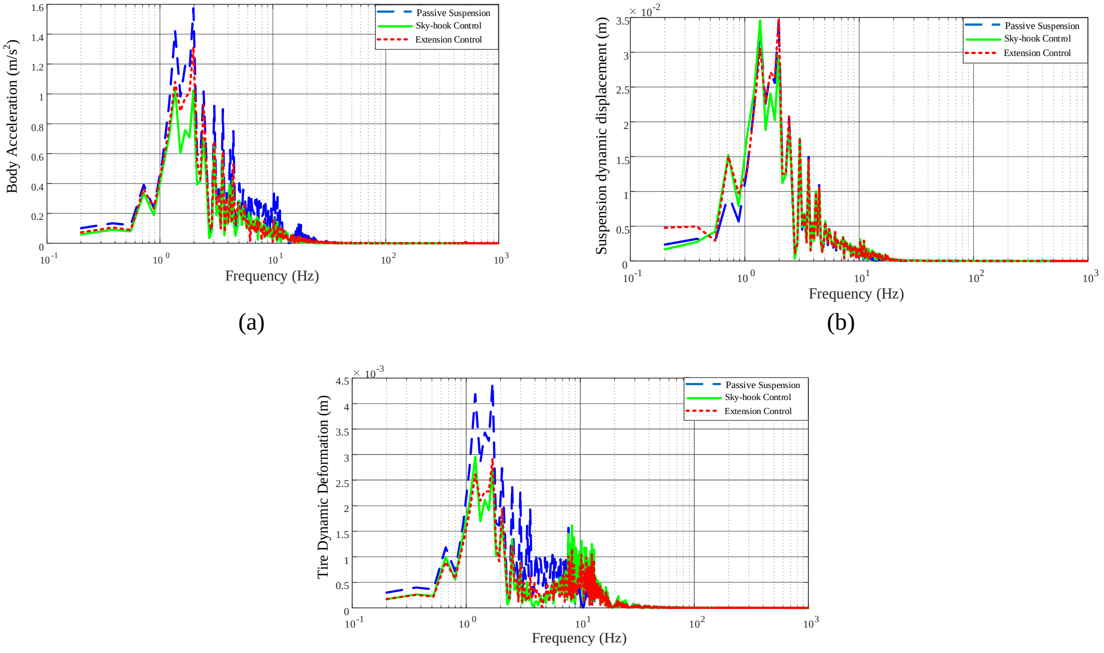
Table.1 Parameters of extension controller.

Parameters	Value
Maximum error of ride comfort under Sky-hook control e_{10lim} ($m\cdot s^{-2}$)	0.16
Maximum error of safety under Sky-hook control e_{20lim} (cm)	0.09
Maximum error of ride comfort under Sky-hook control e_{11lim} ($m\cdot s^{-2}$)	3.1
Maximum error of safety under Sky-hook control e_{21lim} (cm)	2.5
Factor k_1	1
Factor k_2	40

3.2 Random road excitation

It is more significant to study the response of vehicles under random road excitation, which is the main input in the suspension system. The road excitation is constructed by the integral white noise.

The simulation time is 20 seconds. The results that the responses of ride comfort and driving safety are compared under the passive suspension, sky-hook control and extension control are shown as Figure. 5.



(a)

(b)

(c)

Figure.5 Comparison of system responses under random excitation: (a) Body acceleration; (b) Suspension dynamic displacement; (c) Tire dynamic deformation.

According to the Fourier transformation, the time domain signals are transformed as the frequency domain signals, which obtained the amplitude-frequency characteristics of ride comfort and driving safety. Figure. 20(a) illustrates that amplitude-frequency characteristic of body acceleration with sky-hook control and extension control is relatively close. However, sky-hook control and extension control are better than the passive suspension; From Figure. 20(b), suspension dynamic displacement amplitude-frequency characteristic among all controls is closed; From Figure. 20(c), tire dynamic deformation response at low range (0~5 Hz) with extension control is between that of the passive control and sky-hook control, at the middle and high frequency range (5~12 Hz), the extension control performs better than the passive control and sky-hook control. The above results show that extension control can change the tire dynamic deformation amplitude-frequency characteristic under random excitation, and improve amplitude-frequency characteristic effectively at the middle and high frequency range.

However, the difference of suspension dynamic displacement and tire dynamic deformation among the passive suspension, sky-hook control and extension control are difficult to distinguish. Therefore, the RMS of ride comfort and driving safety and frequency responses are represented as follow:

Table.2 Results of response in different control

RMS	Passive suspension	Sky-hook control	Extension control
Body acceleration ($m{\cdot}s^{-2}$)	2.63	1.88	1.90
Suspension dynamic displacement (m)	0.0535	0.0511	0.0534
Tire dynamic deformation (m)	0.0079	0.0071	0.0065

Table 2 shows the RMS of body acceleration, suspension dynamic displacement, and tire dynamic deformation in detail. Comparing the data in Table 2, it can be seen that body acceleration under passive suspension is higher 20% than that of extension control, which increases only 1% from the sky-hook control. The RMS of the suspension dynamic displacement is similar among all control methods. However, the RMS of tire dynamic deformation with extension control is better than sky-hook control, which decreases 9.2% from sky-hook control. Based on the information from Table. 2, extension control can adjust the performance of body acceleration and tire dynamic deformation.

4. Conclusion

In this paper, the weight of Sky-Ground hook control method under various road excitation was studied based on 2-DOF suspension model. Then, with proposed extension controller, the effect of 2-DOF suspension system on ride comfort indexes was studied.

The following main conclusions can be drawn:

(1) Based on the 2-DOF suspension model, sky-hook, ground-hook and S-GH control model are established. The frequency responses are analyzed the influence of S-GH weight.

(2) Based on the extension theory, the hybrid damping extension control is established under the simulation. The optimal weight of S-GH control is conducted by correlation function.

(3) Compared to sky-hook control algorithm and the passive suspension, the proposed hybrid damping extension control is simulated based on MATLAB/Simulink simulation. Notably, control effectiveness of the hybrid controller is highlighted under complicated conditions.