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Skyhook-based Body-seat System Preview Control for a Semi-active Suspension Tractor

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Abstract: This paper intends to present a method to improve riding comfort of tractor while working. The primary objective is to reduce vibration of the seat in tractor cabin caused by road input, i.e. the performance of tractor suspension. For this purpose, a full-vehicle tractor model was built with wheel and suspension, which includes seven degrees of freedom. Simplified model for seat is put on the tractor model. Then preview control with time-delay consideration was investigated by installing look-ahead sensor on front wheel. On this basis, a semi-active suspension using sky-hook based preview controller is studied. The comfort evaluation parameters about the driver are presented and the mathematical models of passive and sky-hook based preview control suspension are simulated in Simulink.

The comparison of the results of passive suspension and sky-hook based preview control suspension suggests that semi-active controller could significantly improve riding comfort and provide more comfortable working conditions for operators, which can be widely applied on tractor in the future.

Keywords: Preview control, Suspension, Sky-hook control, Ride comfort, Tractor.

1. Introduction

Since vibration applied on the agricultural tractor can significantly influence the ride comfort [1-4], it is widely recognized that driving condition of tractor is poor, especially when driving on the field. ISO 263-1:1997(E) [5] establishes the vibration model of human body and the evaluation method of ride comfort, which can be regarded as investigation reference.

A simplified full-vehicle model with 10-DOF including a suspended seat is built based on available 2-DOF half model of tractor [6], in order to quantify vibration which derives from road input and be transmitted to the seat through suspension.

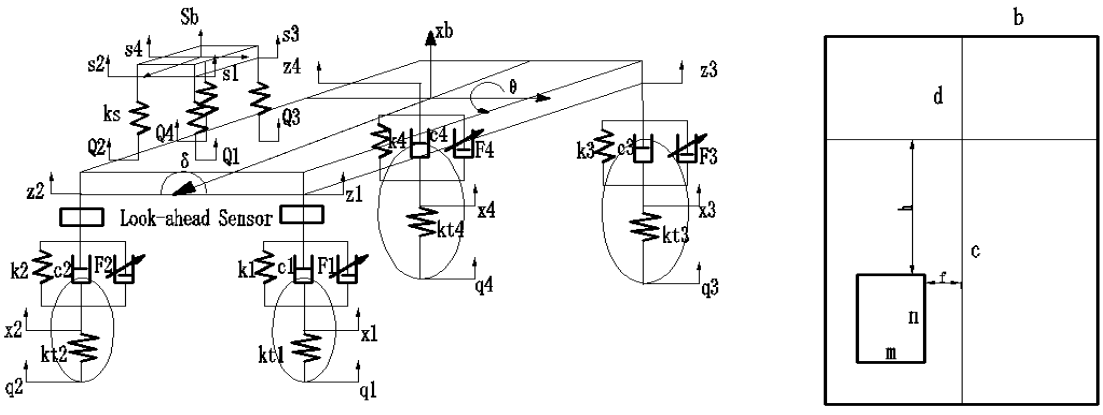
Most traditional tractors using passive suspension cannot effectively reduce the vibration [7-9], and active suspension requires complex structure and high cost. Based on the above condition, an advanced semi-active suspension with sky-hook controller was proposed by Crosby and Karnopp [10], which is adopted by people for the reason of its concision and effectiveness.

However, in terms of time-delay consideration, sky-hook controller couldn't improve suspension performance well. On this basis, preview control [11, 12] is put forward for further optimization about suspension performance, the road profile at some distances in front of the vehicle is measured by the look-ahead sensor.

In this paper, semi-active suspension with skyhook-based preview control strategy is applied on tractor and the ride comfort is evaluated compared with passive suspension.

2. Full-vehicle Dynamical Model

For the purpose of realizing time domain simulation, a 10-DOF model is built in this section. Considering the vibration of each join point, full-body model with semi-active suspension system as well as the seat is described schematically in Fig. 1. The tractor model is divided into three systems including wheel, body and seat, which connect with each other by damper and spring.



(a) (b)

Fig. 1. Full-vehicle model with semi-active suspension. (a) 3D view, (b) Top view.

In Fig. 1(a), *b*, *c*, *d* represent distances from the center of the body to the left and right, as well as the front and rear wheels respectively. x_b, θ, δ are vertical displacement, pitch and roll angles of the body. q_i, x_i, z_i are displacements of road, un-sprung mass and sprung mass. kt_i, k_i, c_i, k_s are tire stiffness coefficients, suspension stiffness coefficients, damping coefficients of body suspension and spring stiffness coefficient of seat. F_i is variable damping force according to variable damping coefficient attached to c_i, Q_i, s_i are vertical displacements of the junction of body and seat while s_b is vertical displacement of the center of seat (i=1, 2, 3, 4). In Fig. 1(b), m, n represent the size of seat and h, t represent the horizontal position of seat relative to center of the body.

2.1. Dynamical Equation of Suspension

Considering the delay time τ, variable damping force shall be $F_i(t-\tau)$ correspondingly. Then the generalized dynamical equation of suspension system can be described as follows neglecting the influence of the seat temporarily:

$$I_x\ddot{\delta}=+[k_1(x_1-z_1)+c_1(\dot{x}_1-\dot{z}_1)-k_2(x_2-z_2)-c_2(\dot{x}_2-\dot{z}_2)-F_3+F_2]^a$$
$$a+[k_1(x_1-z_1)+c_1(\dot{x}_1-\dot{z}_1)-k_4(x_4-z_4)-c_4(\dot{x}_4-\dot{z}_4)-F_3+F_4]b \quad (1)$$

$$I_y\ddot{\theta}=-[k_3(x_3-z_3)+c_3(\dot{x}_3-\dot{z}_3)+k_2(x_2-z_2)+c_2(\dot{x}_2-\dot{z}_2)-F_3-F_2],$$
$$c+[k_3(x_3-z_3)+c_3(\dot{x}_3-\dot{z}_3)+k_4(x_4-z_4)+c_4(\dot{x}_4-\dot{z}_4)-F_3-F_4]a \quad (2)$$

$$m_b\ddot{x}_b=k_3(x_3-z_3)+c_3(\dot{x}_3-\dot{z}_3)+k_2(x_2-z_2)+c_2(\dot{x}_2-\dot{z}_2)+$$
$$k_3(x_3-z_3)+c_3(\dot{x}_3-\dot{z}_3)+k_4(x_4-z_4)+c_4(\dot{x}_4-\dot{z}_4)-F_1-F_2-F_3-F_4, \quad (3)$$

$$m_i\ddot{z}_i(t)+c_i(\dot{z}_i(t)-\dot{x}_i(t))+k_i(z_i(t)-x_i(t))-F_i(t-\tau)=0, \quad (4)$$

$$m_{wi}\ddot{x}_i(t)+c_i(\dot{x}_i(t)-\dot{z}_i(t))+k_i(x_i(t)-z_i(t))+$$
$$kt_i(x_i(t)-q_i(t))=0, \quad (5)$$

where m_i represents sprung mass and m_{wi} is the un-sprung mass (*i*=1, 2, 3, 4). I_x, I_y are the rotary inertia of roll and pitch of the body. m_b is the sprung mass of the whole body.

2.2. Dynamical Equation of Seat

Since the seat model is connected with the body only by spring and horizontally placed on body, the movement of seat should be related to dynamical equation of body as shown in Eq. (1-3). Based on Fig. 1(a), the dynamic equation of seat can be expressed as follows:

$$I_{sx}\ddot{\delta}_s\left[k_s(Q_1-s_1)-k_s(Q_2-s_2)+k_s(Q_3-s_3)-k_s(Q_4-s_4)\right]\frac{m}{2}, \quad (6)$$

$$I_{sy}\ddot{\theta}_s \left[k_s(Q_3 - s_3) + k_s(Q_4 - s_4)k_s(Q_1 - s_1) - k_s(Q_2 - s_2) \right] \frac{m}{2} \quad (7)$$

$$I_{sy}\ddot{\theta}_s \left[k_s(Q_3 - s_3) + k_s(Q_4 - s_4)k_s(Q_1 - s_1) - k_s(Q_2 - s_2) \right] \frac{m}{2}, \quad (8)$$

where m_s represents seat mass. δ_s, θ_s are the roll and pitch angles of seat. I_{sx}, I_{sy} are the rotary inertia of roll and pitch of seat. Once the relative position of seat and the body is located as Fig. 1(b) shows, Q_i can be achieved by compositing vertical displacement, pitch and roll angles of the body as well.

$$Q_1 = x_b - \delta_s f - \theta_s(n+h), \quad (9)$$

$$Q_2 = x_b - \delta_s(f+m) - \theta_s(n+h), \quad (10)$$

$$Q_3 = x_b - \delta_s f - \theta_s h, \quad (11)$$

$$Q_4 = x_b - \delta_s(f+m) - \theta_s h, \quad (12)$$

The parameters of the tractor are listed in Table 1.

Table 1. Parameters of the tractor.

Parameter	**Notation**	**Value**
Distances from the center of sprung mass to the left and right wheels/(m)	b	0.6280
Distances from the center of sprung mass to the front and rear wheels/(m)	c	1.1219
Distances from the center of sprung mass to the front and rear wheels/(m)	d	1.1161
Sprung mass of the body/(kg)	m_b	745.2
Front unsprung mass/(kg)	m_{w1}, m_{w2}	25.35
Rear unsprung mass/(kg)	m_{w3}, m_{w4}	68.8
Seat mass/(kg)	m_s	100
Inertia of pitching motion of body/(kg·m^2)	m_b I_y	768.8
Inertia of rolling motion of body/(kg·m^2)	m_b I_x	375.2
Inertia of pitching motion of seat/(kg·m^2)	I_{sy}	95
Inertia of rolling motion of seat/(kg·m^2)	I_{sx}	48
Front suspension stiffness coefficient/(N/m)	k_1, k_2	300860
Rear suspension stiffness coefficient/(N/m)	k_3, k_4	349790
Front tire stiffness coefficient/(N/m)	kt_1, kt_2	326200
Rear tire stiffness coefficient/(N/m)	kt_3, kt_4	437300
Spring stiffness coefficient of seat/(N/m)	k_s	100000
Front suspension damping coefficient/(N·s·m^{-1})	c_1, c_2	3554.7
Rear suspension damping coefficient/(N·s·m^{-1})	c_3, c_4	2059.3
The size of seat/(m×m)	$m \times n$	0.3×0.5
Distance from seat to the center of the body/(m×m)	$h \times f$	0.3×0.1

3. Sky-hook Based Preview Controller Design

Preview control strategy is generally used for time-delay correction. In this model, the road input of front wheel could be regarded as future input signal of rear wheel. 1/2 model with preview control is shown in Fig. 2. The look-ahead sensor installed on front wheel perceives the road input in front of the front wheel and passes the signal to controller, and then send a command to the actuator to adjust the damping coefficient of shock absorber.

According to Fig. 2, dynamical equation (4), (5) can be rewritten as follows like Eq. (13) and (14).

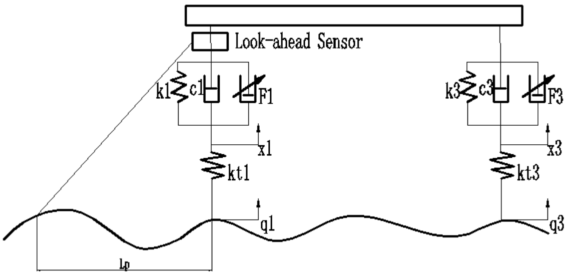


Fig. 2. 1/2 model with preview control.

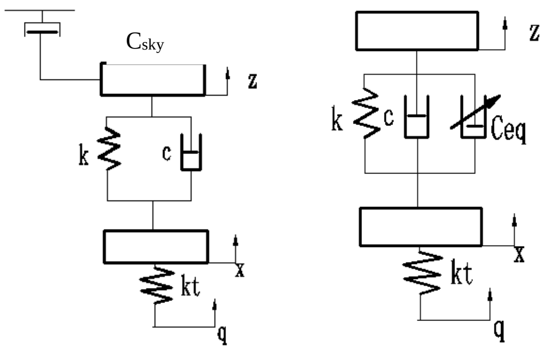
$$m_1\ddot{z}_1(t+T_p)+c_1(\dot{z}_1(t+T_p)-\dot{x}_1(t+T_p))+ \\ k_1(z_1(t+T_p)-x_1(t+T_p))-F_1(t+T_p)=0, \quad (13)$$

$$m_{w1}\ddot{x}_1(t+T_p)+c_1(\dot{x}_1(t+T_p)-\dot{z}_1(t+T_p))+ \\ k_1(x_1(t+T_p)-z_1(t+T_p))+kt_1(x_1(t+T_p)-(q_1(t+T_p))=0, \quad (14)$$

$$T_p=\frac{L_p}{V}, \quad (15)$$

where T_p is the preview time, L_p represents preview distance, V is the tractor speed.

As one of the most classical semi-active suspension control strategies, sky-hook control strategy can be intuitively designed and learned by people, for it applies feedback control to the suspension just according to the vertical velocity of sprung mass. The model of sky-hook control can be shown in Fig. 3.



(a) (b)

Fig. 3. Sky-hook control model. (a) Ideal model, (b) Equivalent model.

Sky-hook control is designed to suppress vibration acceleration of sprung mass by switching the suspension damping coefficients according to the signs of suspension relative velocity $(\dot{z}-\dot{x})$ and body absolute velocity $\dot{z}$.

The control strategy can be described as follows: only when the two signs are the same does the suspension switches to harder damping, otherwise the damping force is set to 0 and we can get F_i formula like Eq. (16).

$$F_i=\begin{cases} C_{sky}\dot{z}_i, & (\dot{z}_i-\dot{x}_i)\dot{z}_i\geq 0, \\ 0, & (\dot{z}_i-\dot{x}_i)\dot{z}_i<0, \end{cases} \quad i=1,2,3,4, \quad (16)$$

where C_{sky} is the damping coefficient of the sky-hook controller. By considering ride comfort and handling stability of the tractor, C_{sky} is the set to 2000 Ns/m for ease of simulation in next section.

4. Modeling and Simulation

4.1. Full-vehicle Passive Suspension Modeling and Simulation

Road input q_i is simulated by integral random white noise in Simulink, on this basis, Eq. (1-5) can be integrated and described as Simulink model in Fig. 4.

By substituting parameters in Table 1, The simulation results can be shown in Fig. 5.

4.2. Sky-hook Based Preview Control of Body-seat System Modeling and Simulation

Based on Eq. (6-15), the model of seat can be described in Fig. 6.

By substituting parameters in Table 1, the simulation results of seat under passive and semi-active based preview control can be shown as Fig. 7.

According to Fig. 7, the root-mean-square values of pitch, roll angles and vertical acceleration of seat in passive suspension are 0.0016/(rad), 0.0025/(rad), 7.8916/(m/s^2). Under sky-hook based preview control, the root-mean-square values of pitch, roll angles and vertical acceleration of seat are 0.0011/(rad), 0.0018/(rad), 4.0777/(m/s^2).

5. Conclusion

The simulation results shows that compared to passive suspension, the root-mean-square values of pitch, roll angle and vertical acceleration of seat reduced by 31.25 %, 28 %, 48.32 % respectively under sky-hook based preview controlling, which means that the tractor with semi-active suspension achieves better ride comfort significantly. This paper acquired satisfactory simulation results and proved the effectiveness when taking time-delay of damping force into consideration.

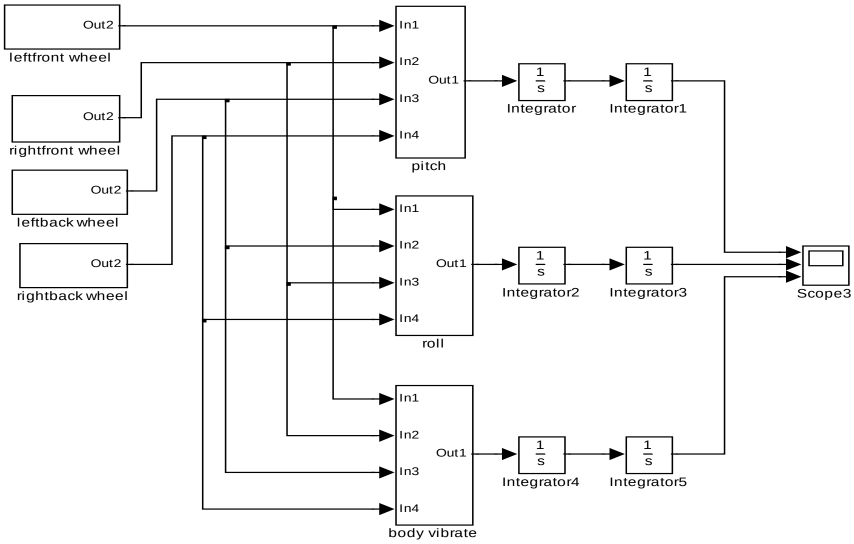


Fig. 4. Passive suspension Simulink model.

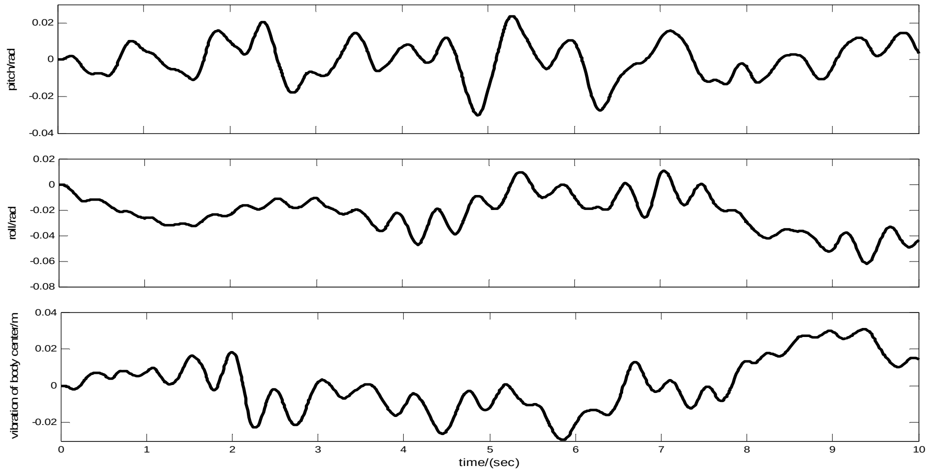


Fig. 5. Movements of body under passive control.

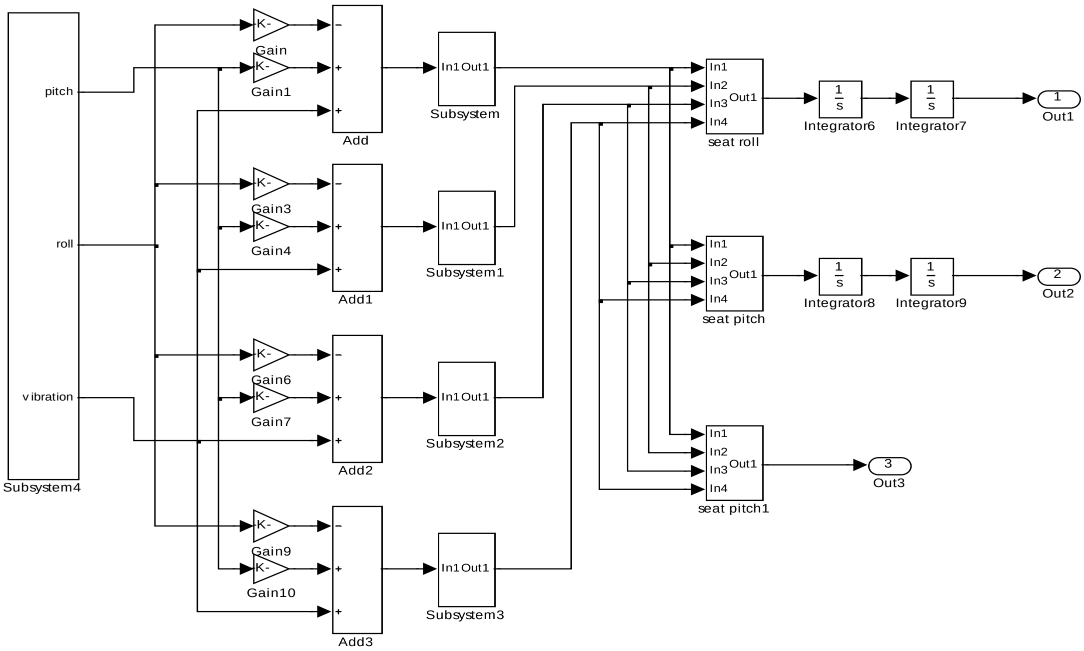


Fig. 6. Simulink model of seat.

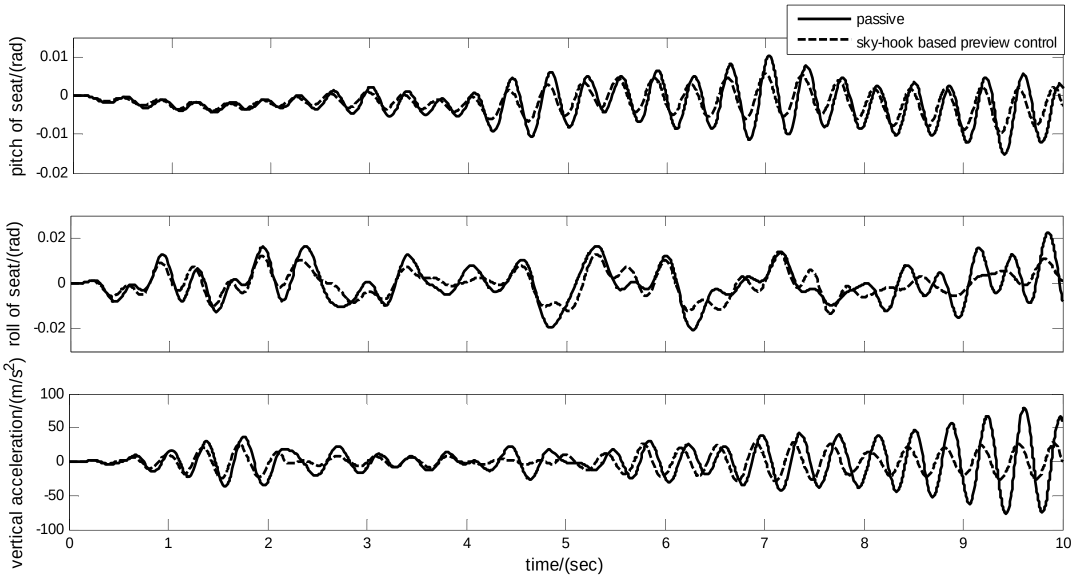


Fig. 7. Movements of seat under passive and sky-hook control.

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