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Research on Suspension System Based on Hydroelectric Energy Feed Damper

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ABSTRACT.*In this paper, a seven-degree-of-freedom vehicle dynamics model is built for a suspension equipped with a hydro-electric energy-fed shock absorber. Three ride comfort evaluation indexes of the model vehicle are simulated and analyzed by Matlab and Simulink software.*

KEYWORDS: *Matlab, Car performance, Simulation, Ride comfort design*

1. Introduction

Automobile suspension is a vibration nonlinear system containing elastic and damping elements. The system will generate random vibration under the excitation of vibration sources such as road roughness and engine. The traditional hydraulic shock absorber uses the damping effect of oil to convert the vibrational mechanical energy into heat energy and then dissipate it, and finally realize the damping effect. The energy-fed shock absorber can use the energy recovery device to convert the vibration energy of the suspension into electric energy, realize the recovery and utilization of the vibration energy, and achieve the purpose of reducing the energy consumption of the car. In this paper, by simulating the vibration of the running vehicle, outputting the corresponding results of multiple suspension evaluation indexes in the time domain, it evaluates the suspension system based on the hydroelectric energy feeding type.[1]

2. Hydroelectric Energy-Fed Shock Absorber

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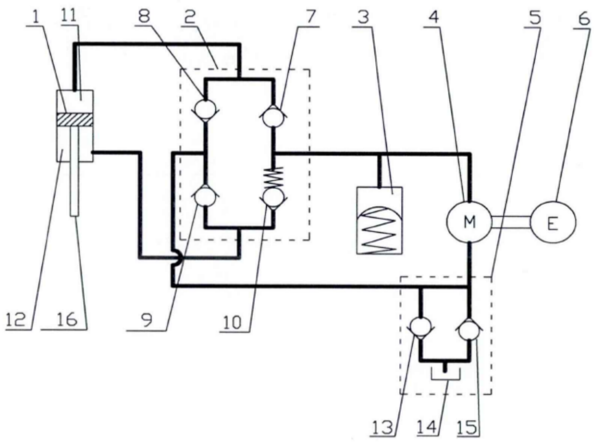

Fig.1 Schematic Diagram of the Structure of the Hydroelectric Energy-Fed Shock Absorber

In the picture: 1. Piston; 2. Hydraulic rectifier bridge; 3. Accumulator; 4. Hydraulic motor; 5. Volume conversion bridge; 6. DC generator; 7. The first one-way valve; 8. The second one-way Valve; 9. The third one-way valve; 10. The fourth one-way valve; 11. rodless cavity; 12. Rod cavity; 13 Fifth one-way valve; 14. Fuel tank; 15. Sixth one-way valve; 16 .Piston push rod.

The working process of the hydroelectric energy-fed shock absorber: when the vehicle body is vertically vibrated due to the uneven road surface during the running of the vehicle, the piston push rod drives the piston to reciprocate. When the piston is in the compression stroke, the hydraulic oil in the rodless cavity pushes open the first one-way valve , after being rectified and filtered by the accumulator, the hydraulic motor is driven to rotate, and the hydraulic motor drives the DC generator to generate electricity. The reaction force generated by the generator during operation causes the hydraulic motor to have a damping effect on the liquid. The hydraulic oil enters the fuel tank through the sixth check valve after passing through the hydraulic motor. At the same time, negative pressure is generated in the rod cavity , respectively open the third one-way valve and the fifth one-way width , the hydraulic oil returns from the fuel tank to the rod cavity . At this time, although the second one-way valve is also affected by the return hydraulic pressure, it is due to the compression stroke of the piston. The inner side is positive pressure, the return hydraulic oil is negative pressure, and the second one-way valve is closed; when the piston is in the stretching stroke, the hydraulic oil in the rod cavity pushes open the fourth one-way valve , hydraulic oil. After passing through the hydraulic motor, it enters the fuel tank through the sixth one-way valve, and then returns to the rodless cavitythrough the second one-way valve and the fifth one-way valve. In this way, no matter whether the piston is in the compression stroke or the extension stroke, the direction of the liquid flow through the hydraulic motor will not change, and the generator will continue to generate electricity stably. In order to ensure that the

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damping force of the shock absorber drawing stroke is greater than the damping force of the compression stroke, the one-way valve with certain opening pressure is selected at the outlet of the rod cavity, and its purpose is the same as setting a small damping hole here.[2]

3. Suspension System Dynamics Model

3.1 Seven-Degree-of-Freedom Vehicle Model

The automobile is a complex vibration system with multiple degrees of freedom. In order to facilitate the study of vehicle vibration characteristics and design control laws, the actual vehicle system needs to be simplified. For four-wheel vehicles, the car model generally includes that the wheels are excited by four unevenness functions, the wheels mainly vibrate in the vertical direction, and the car body mainly exhibits seven degrees of freedom in the vertical direction, pitch angle vibration and roll angle vibration.[3]

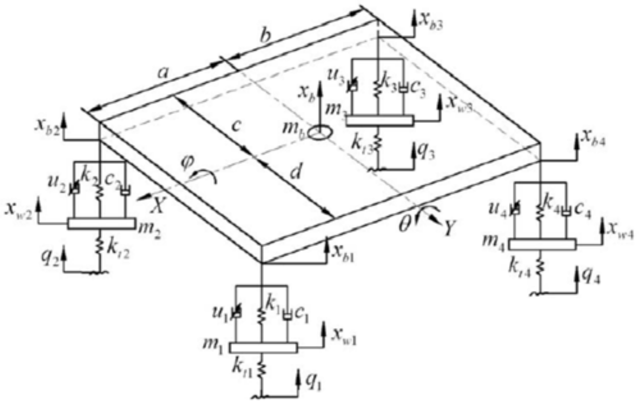

Fig.2 Seven-Degree-of-Freedom Vehicle Model

A total of seven degrees of freedom x_b, θ, φ, x_{w1}, x_{w2}, x_{w3}, x_{w4} are selected as generalized coordinates, and x_{b1}, x_{b2}, x_{b3}, x_{b4} are used as redundant coordinates to establish the variable damping semi-active suspension model shown in the figure above. The relevant parameters of the model vehicle are as follows.

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Table 1 Related Parameters of Model Vehicles

Physical meaning	symbol	value
Sprung mass	m_b	745.2 kg
Roll inertia of sprung mass	I_x	375.2 kg* m^2
Pitch moment of inertia of sprung mass	I_y	768.8 kg* m^2
Front suspension left and right unsprung mass	m_1,m_2	25.35 kg
Rear suspension right and left unsprung mass	m_3,m_4	68.8 kg
Front suspension left and right suspension spring stiffness coefficient	k_1 ,k_2	30000 N/m
Rear suspension right and left suspension spring stiffness coefficient	k_3 ,k_4	32500 N/m
Front suspension left and right shock absorber base value damping coefficient	c1 ,c2	1000 N/m
Rear suspension right and left shock absorber base value damping coefficient	c3 ,c4	1000 N/m
Front suspension left and right tire stiffness coefficient	k_{t1} ,k_{t2}	181000 N/m
Rear suspension left and right tire stiffness coefficient	k_{t3} ,k_{t4}	181000 N/m
Distance from the center of the front axis to the center of mass	a	1.1161 m
Distance from the center line of the rear axle to the center of mass	b	1.2319 m
To the right is the distance from the center of mass	c	0.6280 m
Distance from the left wheel to the center of mass	d	0.6490 m

Table 2 Unknown Parameter Table

Physical meaning	symbol	value
Vertical displacement of sprung mass center of mass	x_b	
Sprung mass roll angle displacement	φ	
Sprung mass pitch angle displacement	θ	
Vertical displacement of left and right unsprung mass of front suspension	x_{w1} , x_{w2}	
Vertical displacement of right and left unsprung mass of rear suspension	x_{w3} , x_{w4}	

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Vertical displacement of the left and right sprung mass of the front suspension	x_{b1} , x_{b2}	
Vertical displacement of the right and left sprung mass of the rear suspension	x_{b3} , x_{b4}	
Wheel vertical input excitation	q_1 , q_2 , q_3 , q_4	
Damping force provided by variable damper	u_1 , u_2 , u_3 , u_4	

3.2 Differential Equation of Motion of Vibration System

Ignoring the influencing factors of the vehicle seat, the vehicle model generally includes seven degrees of freedom, which are the vertical movement of the vehicle body, the roll movement of the vehicle body, the pitch movement of the vehicle body and the vertical movement of the four wheels.

Movement displacement of sprung mass:

$$x_{b1} = x_b - a\theta + d\varphi$$

$$x_{b2} = x_b - a\theta - c\varphi$$

$$x_{b3} = x_b + b\theta - c\varphi$$

$$x_{b4} = x_b + b\theta + d\varphi$$

Movement speed of sprung mass:

$$\dot{x}_{b1} = \dot{x}_b - a\dot{\theta} + d\dot{\varphi}$$

$$\dot{x}_{b2} = \dot{x}_b - a\dot{\theta} - c\dot{\varphi}$$

$$\dot{x}_{b3} = \dot{x}_b + b\dot{\theta} - c\dot{\varphi}$$

$$\dot{x}_{b4} = \dot{x}_b + b\dot{\theta} + d\dot{\varphi}$$

Because all the parameters of the model vehicle passive suspension model and the variable damping semi-active suspension model are different only in the expression of the damping force of the shock absorber [4] [5]. The model can be simplified according to Newton's second law of motion, and its dynamic equation is:

$$m_b\ddot{x}_b = k_1(x_{w1} - x_{b1}) + k_2(x_{w2} - x_{b2}) + k_3(x_{w3} - x_{b3}) + k_4(x_{w4} - x_{b4})$$

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$$+c_1(\dot{x}_{w1}-\dot{x}_{b1})+c_2(\dot{x}_{w2}-\dot{x}_{b2})+c_3(\dot{x}_{w3}-\dot{x}_{b3})$$
$$+c_4(\dot{x}_{w4}-\dot{x}_{b4})-u_1-u_2-u_3-u_4$$

The rolling motion equation of sprung mass:

$$Ix\ddot{\varphi}=d\cdot[k_1(x_{w1}-x_{b1})+k_4(x_{w4}-x_{b4})$$
$$+c_1(\dot{x}_{w1}-\dot{x}_{b1})+c_4(\dot{x}_{w4}-\dot{x}_{b4})-u_1-u_4]$$
$$-c\cdot[k_2(x_{w2}-x_{b2})+k_3(x_{w3}-x_{b3})$$
$$+c_2(\dot{x}_{w2}-\dot{x}_{b2})+c_3(\dot{x}_{w3}-\dot{x}_{b3})-u_2-u_3]$$

The pitch motion equation of sprung mass:

$$Iy\ddot{\theta}=b\cdot[k_3(x_{w3}-x_{b3})+k_4(x_{w4}-x_{b4})$$
$$+c_3(\dot{x}_{w3}-\dot{x}_{b3})+c_4(\dot{x}_{w4}-\dot{x}_{b4})-u_3-u_4]$$
$$-a\cdot[k_1(x_{w1}-x_{b1})+k_2(x_{w2}-x_{b2})$$
$$+c_1(\dot{x}_{w1}-\dot{x}_{b1})+c_2(\dot{x}_{w2}-\dot{x}_{b2})-u_1-u_2]$$

The differential equation of the front left unsprung mass motion:

$$m_1\ddot{x}_{w1}=k_{t1}(q_1-x_{w1})-k_1(x_{w1}-x_{b1})-c_1(\dot{x}_{w1}-\dot{x}_{b1})+u_1$$

The differential equation of the front right unsprung mass motion:

$$m_2\ddot{x}_{w2}=k_{t2}(q_2-x_{w2})-k_2(x_{w2}-x_{b2})-c_2(\dot{x}_{w2}-\dot{x}_{b2})+u_2$$

The differential equation of the rear right unsprung mass motion:

$$m_3\ddot{x}_{w3}=k_{t3}(q_3-x_{w3})-k_3(x_{w3}-x_{b3})-c_3(\dot{x}_{w3}-\dot{x}_{b3})+u_3$$

The differential equation of the rear left unsprung mass motion:

$$m_4\ddot{x}_{w4}=k_{t4}(q_4-x_{w4})-k_4(x_{w4}-x_{b4})-c_4(\dot{x}_{w4}-\dot{x}_{b4})+u_4$$

After substitution, the following equations can be solved:

$$m_b\ddot{x}_b=k_1(x_{w1}-x_{b1})+k_2(x_{w2}-x_{b2})+k_3(x_{w3}-x_{b3})+k_4(x_{w4}-x_{b4})$$
$$+c_1[\dot{x}_{w1}-(\dot{x}_b-a\dot{\theta}+d\dot{\varphi})]+c_2[\dot{x}_{w2}-(\dot{x}_b-a\dot{\theta}-c\dot{\varphi})]$$
$$+c_3[\dot{x}_{w3}-(\dot{x}_b+b\dot{\theta}-c\dot{\varphi})]$$
$$+c_4[\dot{x}_{w4}-(\dot{x}_b+b\dot{\theta}+d\dot{\varphi})]-u_1-u_2-u_3-u_4$$

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$$Ix\ddot{\varphi}=d\cdot[k_1(x_{w1}-x_{b1})+k_4(x_{w4}-x_{b4})+c_1[\dot{x}_{w1}-(\dot{x}_b-a\dot{\theta}+d\dot{\varphi})]$$
$$+c_4[\dot{x}_{w4}-(\dot{x}_b+b\dot{\theta}+d\dot{\varphi})]-u_1-u_4]-c\cdot[k_2(x_{w2}-x_{b2})+k_3(x_{w3}-x_{b3})$$
$$+c_2[\dot{x}_{w2}-(\dot{x}_b-a\dot{\theta}-c\dot{\varphi})]+c_3[\dot{x}_{w3}-(\dot{x}_b+b\dot{\theta}-c\dot{\varphi})]-u_2-u_3]$$
$$Iy\ddot{\theta}=b\cdot[k_3(x_{w3}-x_{b3})+k_4(x_{w4}-x_{b4})+c_3[\dot{x}_{w3}-(\dot{x}_b+b\dot{\theta}-c\dot{\varphi})]$$
$$+c_4[\dot{x}_{w4}-(\dot{x}_b+b\dot{\theta}+d\dot{\varphi})]-u_3-u_4]-a\cdot[k_1(x_{w1}-x_{b1})+k_2(x_{w2}-x_{b2})$$
$$+c_1[\dot{x}_{w1}-(\dot{x}_b-a\dot{\theta}+d\dot{\varphi})]+c_2[\dot{x}_{w2}-(\dot{x}_b-a\dot{\theta}-c\dot{\varphi})]-u_1-u_2]$$
$$m_1\ddot{x}_{w1}=k_{t1}(q_1-x_{w1})-k_1(x_{w1}-x_{b1})-c_1[\dot{x}_{w1}-(\dot{x}_b-a\dot{\theta}+d\dot{\varphi})]+u_1$$
$$m_2\ddot{x}_{w2}=k_{t2}(q_2-x_{w2})-k_2(x_{w2}-x_{b2})-c_2[\dot{x}_{w2}-(\dot{x}_b-a\dot{\theta}-c\dot{\varphi})]+u_2$$
$$m_3\ddot{x}_{w3}=k_{t3}(q_3-x_{w3})-k_3(x_{w3}-x_{b3})-c_3[\dot{x}_{w3}-(\dot{x}_b+b\dot{\theta}-c\dot{\varphi})]+u_3$$
$$m_4\ddot{x}_{w4}=k_{t4}(q_4-x_{w4})-k_4(x_{w4}-x_{b4})-c_4[\dot{x}_{w4}-(\dot{x}_b+b\dot{\theta}+d\dot{\varphi})]+u_4$$

3.3 State Space Model of Vibration System

As the whole vehicle is symmetrical, there are:

m1= m2= mf, mf is the unsprung mass of front suspension;

m3= m4= mr, mr is the unsprung mass of rear suspension;

k1= k2= kf, kf is the front Suspension spring stiffness coefficient;

k3= k4= kr, kr is the rear Suspension spring stiffness coefficient;

c1= c2= cf, cf is the base value damping coefficient of front suspension shock absorber;

c3= c4= cr, cr is the base value damping coefficient of rear suspension shock absorber;

kt1= kt2= ktf, ktf is the front suspension tire spring stiffness;

kt3= kt4= ktr, ktr is the rear suspension tire spring stiffness;

The state space parameter table and physical meaning are as follows:

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Table 3 State Space Parameter Table

Parameter	Expression	Physical meaning
x_1	$x_1=x_{w1}-x_{b1}$	Deformation of front left suspension
x_2	$x_2=x_{w2}-x_{b2}$	Deformation of front right suspension
x_3	$x_3=x_{w3}-x_{b3}$	Deformation of rearright suspension
x_4	$x_4=x_{w4}-x_{b4}$	Deformation of rear left suspension
x_5	$x_5=x_{w1}$	Vertical movement displacement of front left unsprung mass
x_6	$x_6=x_{w2}$	Vertical movement displacement of front right unsprung mass
x_7	$x_7=x_{w3}$	Vertical movement displacement of rearright unsprung mass
x_8	$x_8=x_{w4}$	Vertical movement displacement of rear left unsprung mass
x_9	$x_9=\dot{x}_{w1}=\dot{x}_5$	Vertical movement speed of front left unsprung mass
x_{10}	$x_{10}=\dot{x}_{w2}=\dot{x}_6$	Vertical movement speed of front right unsprung mass
x_{11}	$x_{11}=\dot{x}_{w3}=\dot{x}_7$	Vertical movement speed of rearright unsprung mass
x_{12}	$x_{12}=\dot{x}_{w4}=\dot{x}_8$	Vertical movement speed of rear left unsprung mass
x_{13}	$\dot{x}_b$	Vertical speed of sprung mass
x_{14}	$\dot{\varphi}$	Angular velocity of rolling motion of sprung mass
x_{15}	$\dot{\theta}$	Angular velocity of pitching motion of sprung mass

Substituting parameter variables into the equations listed above:

$$\dot{x}_1=\dot{x}_{w1}-\dot{x}_{b1}=\dot{x}_{w1}-(\dot{x}_b-a\dot{\theta}+d\dot{\varphi})=x_9-(x_{13}-ax_{15}+dx_{14})$$

$$\dot{x}_2=\dot{x}_{w2}-\dot{x}_{b2}=\dot{x}_{w2}-(\dot{x}_b-a\dot{\theta}-c\dot{\varphi})=x_{10}-(x_{13}-ax_{15}-cx_{14})$$

$$\dot{x}_3=\dot{x}_{w3}-\dot{x}_{b3}=\dot{x}_{w3}-(\dot{x}_b+b\dot{\theta}-c\dot{\varphi})=x_{11}-(x_{13}+bx_{15}-cx_{14})$$

$$\dot{x}_4=\dot{x}_{w4}-\dot{x}_{b4}=\dot{x}_{w3}-(\dot{x}_b+b\dot{\theta}+d\dot{\varphi})=x_{12}-(x_{13}+bx_{15}+dx_{14})$$

$$\dot{x}_5=\dot{x}_{w1}=x_9$$

$$\dot{x}_6=\dot{x}_{w2}=x_{10}$$

$$\dot{x}_7=\dot{x}_{w3}=x_{11}$$

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$$\dot{x}_8 = \dot{x}_{w4} = x_{12}$$

$$m_f \dot{x}_9 = k_{tf}(q_1 - x_5) - k_f x_1 - c_f[x_9 - (x_{13} - ax_{15} + dx_{14})] + u_1$$

$$m_f \dot{x}_{10} = k_{tf}(q_2 - x_6) - k_f x_2 - c_f[x_{10} - (x_{13} - ax_{15} - cx_{14})] + u_2$$

$$m_r \dot{x}_{11} = k_{tr}(q_3 - x_7) - k_r x_3 - c_r[x_{11} - (x_{13} + bx_{15} - cx_{14})] + u_3$$

$$m_r \dot{x}_{12} = k_{tr}(q_4 - x_8) - k_r x_4 - c_r[x_{12} - (x_{13} + bx_{15} + dx_{14})] + u_4$$

$$m_b \dot{x}_{13} = k_f x_1 + k_f x_2 + k_r x_3 + k_r x_4 + c_f[x_9 - (x_{13} - ax_{15} + dx_{14})]$$

$$+c_f[x_{10} - (x_{13} - ax_{15} - cx_{14})] + c_r[x_{11} - (x_{13} + bx_{15} - cx_{14})]$$

$$+c_r[x_{12} - (x_{13} + bx_{15} + dx_{14})] - u_1 - u_2 - u_3 - u_4$$

$$I_x \dot{x}_{14} = d\{k_f x_1 + k_r x_4 + c_f[x_9 - (x_{13} - ax_{15} + dx_{14})]$$

$$+c_r[x_{12} - (x_{13} + bx_{15} + dx_{14})] - u_1 - u_4\}$$

$$-c\{k_f x_2 + k_r x_3 + c_f[x_{10} - (x_{13} - ax_{15} - cx_{14})]$$

$$+c_r[x_{11} - (x_{13} + bx_{15} - cx_{14})] - u_2 - u_3\}$$

$$I_y \dot{x}_{15} = b\{k_r x_3 + k_r x_4 + c_r[x_{11} - (x_{13} + bx_{15} - cx_{14})]$$

$$+c_r[x_{12} - (x_{13} + bx_{15} + dx_{14})] - u_3 - u_4\}$$

$$-a\{k_f x_1 + k_f x_2 + c_f[x_9 - (x_{13} - ax_{15} + dx_{14})]$$

$$+c_f[x_{10} - (x_{13} - ax_{15} - cx_{14})] - u_1 - u_2\}$$

Take the system state variables as:

$$X =$$

$$\begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 & x_{10} & x_{11} & x_{12} & x_{13} & x_{14} & x_{15} \end{bmatrix}^T$$

$$= \begin{bmatrix} x_{w1} - x_{b1} & x_{w2} - x_{b2} & x_{w3} - x_{b3} & x_{w4} - x_{b4} & x_{w1} & x_{w2} & x_{w3} & x_{w4} & \dot{x}_{w1} & \dot{x}_{w2} & \dot{x}_{w3} & \dot{x}_{w4} & \dot{x}_b & \dot{\varphi} & \dot{\theta} \end{bmatrix}^T$$

Take the system input variables as:

$$U = \begin{bmatrix} q_1 & q_2 & q_3 & q_4 & u_1 & u_2 & u_3 & u_4 \end{bmatrix}^T$$

Take the system output variable as:

$$Y = \begin{bmatrix} y_1 & y_2 & y_3 & y_4 & y_5 & y_6 & y_7 & y_8 & y_9 & y_{10} & y_{11} \end{bmatrix}^T$$

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$$=\begin{bmatrix}\dot{x}_{13} & \dot{x}_{14} & \dot{x}_{15} & x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 & x_{10} & x_{11} & x_{12}\end{bmatrix}^T$$

Then the state space equation of the system is:

$$\begin{cases}\dot{X} = AX + BU \\ Y = CX + DU\end{cases}$$

The equation coefficients A, B, C, D are:

$$A=\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & -d & -a \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & c & a \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & c & -b \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & -d & -b \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
-\frac{k_f}{m_f} & 0 & 0 & 0 & -\frac{k_{tf}}{m_f} & 0 & 0 & 0 & -\frac{c_f}{m_f} & 0 & 0 & 0 & \frac{c_f}{m_f} & \frac{dc_f}{m_f} & -\frac{ac_f}{m_f} \\
0 & -\frac{k_f}{m_f} & 0 & 0 & 0 & -\frac{k_{tf}}{m_f} & 0 & 0 & 0 & -\frac{c_f}{m_f} & 0 & 0 & \frac{c_f}{m_f} & -\frac{cc_f}{m_f} & -\frac{ac_f}{m_f} \\
0 & 0 & -\frac{k_r}{m_r} & 0 & 0 & 0 & -\frac{k_{tr}}{m_r} & 0 & 0 & 0 & -\frac{c_r}{m_r} & 0 & \frac{c_r}{m_r} & -\frac{cc_r}{m_r} & \frac{bc_r}{m_r} \\
0 & 0 & 0 & -\frac{k_r}{m_r} & 0 & 0 & 0 & -\frac{k_{tr}}{m_r} & 0 & 0 & 0 & -\frac{c_r}{m_r} & \frac{c_r}{m_r} & \frac{dc_r}{m_r} & \frac{bc_r}{m_r} \\
\frac{k_f}{m_b} & \frac{k_f}{m_b} & \frac{k_r}{m_b} & \frac{k_r}{m_b} & 0 & 0 & 0 & 0 & \frac{c_f}{m_b} & \frac{c_f}{m_b} & \frac{c_r}{m_b} & \frac{c_r}{m_b} & a_{1313} & a_{1314} & a_{1315} \\
\frac{dk_f}{I_x} & -\frac{ck_f}{I_x} & -\frac{ck_r}{I_x} & \frac{dk_r}{I_x} & 0 & 0 & 0 & 0 & \frac{dc_f}{I_x} & -\frac{cc_f}{I_x} & -\frac{cc_r}{I_x} & \frac{dc_r}{I_x} & a_{1413} & a_{1414} & a_{1415} \\
-\frac{ak_f}{I_y} & -\frac{ak_f}{I_y} & \frac{bk_r}{I_y} & \frac{bk_r}{I_y} & 0 & 0 & 0 & 0 & -\frac{ac_f}{I_y} & -\frac{ac_f}{I_y} & \frac{bc_r}{I_y} & \frac{bc_r}{I_y} & a_{1513} & a_{1514} & a_{1515}
\end{bmatrix}$$

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$$B=\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
\frac{k_{tf}}{m_f} & 0 & 0 & 0 & \frac{1}{m_f} & 0 & 0 & 0\\
0 & \frac{k_{tf}}{m_f} & 0 & 0 & 0 & \frac{1}{m_f} & 0 & 0\\
0 & 0 & \frac{k_{tr}}{m_r} & 0 & 0 & 0 & \frac{1}{m_r} & 0\\
0 & 0 & 0 & \frac{k_{tr}}{m_r} & 0 & 0 & 0 & \frac{1}{m_r}\\
0 & 0 & 0 & 0 & -\frac{1}{m_b} & -\frac{1}{m_b} & -\frac{1}{m_b} & -\frac{1}{m_b}\\
0 & 0 & 0 & 0 & -\frac{d}{I_x} & \frac{c}{I_x} & \frac{c}{I_x} & -\frac{d}{I_x}\\
0 & 0 & 0 & 0 & \frac{a}{I_y} & \frac{a}{I_y} & -\frac{b}{I_y} & -\frac{b}{I_y}
\end{bmatrix}$$

$$C=\begin{bmatrix}
\frac{k_f}{m_b} & \frac{k_f}{m_b} & \frac{k_r}{m_b} & \frac{k_r}{m_b} & 0 & 0 & 0 & 0 & \frac{c_f}{m_b} & \frac{c_f}{m_b} & \frac{c_r}{m_b} & \frac{c_r}{m_b} & a_{1313} & a_{1314} & a_{1315}\\
\frac{dk_f}{I_x} & -\frac{ck_f}{I_x} & -\frac{ck_r}{I_x} & \frac{dk_r}{I_x} & 0 & 0 & 0 & 0 & \frac{dc_f}{I_x} & -\frac{cc_f}{I_x} & -\frac{cc_r}{I_x} & \frac{dc_r}{I_x} & a_{1413} & a_{1414} & a_{1415}\\
-\frac{ak_f}{I_y} & -\frac{ak_f}{I_y} & \frac{bk_r}{I_y} & \frac{bk_r}{I_y} & 0 & 0 & 0 & 0 & -\frac{ac_f}{I_y} & -\frac{ac_f}{I_y} & \frac{bc_r}{I_y} & \frac{bc_r}{I_y} & a_{1513} & a_{1514} & a_{1515}\\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

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$$D=\begin{bmatrix} 0 & 0 & 0 & 0 & -\frac{1}{m_b} & -\frac{1}{m_b} & -\frac{1}{m_b} & -\frac{1}{m_b} \\ 0 & 0 & 0 & 0 & -\frac{d}{I_x} & \frac{c}{I_x} & \frac{c}{I_x} & -\frac{d}{I_x} \\ 0 & 0 & 0 & 0 & \frac{a}{I_y} & \frac{a}{I_y} & -\frac{b}{I_y} & -\frac{b}{I_y} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$a_{1313}=-\frac{2(c_f+c_r)}{m_b};$$

$$a_{1314}=\frac{(c-d)(c_f+c_r)}{m_b};$$

$$a_{1315}=\frac{2(ac_f-bc_r)}{m_b}$$

$$a_{1413}=\frac{(c-d)(c_f+c_r)}{I_x};$$

$$a_{1414}=-\frac{(c^2+d^2)(c_f+c_r)}{I_x};$$

$$a_{1415}=\frac{(ad-ac)c_f-(bd-bc)c_r}{I_x}$$

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$$a_{1513}=\frac{2ac_f-2bc_r}{I_y};$$

$$a_{1414}=\frac{(ad-ac)c_f+(bc-bd)c_r}{I_y};$$

$$a_{1415}=\frac{-2a^2c_f-2b^2c_r}{I_y}$$

4. Road Surface Incentives

According to the national standard, the highway grades are divided into 8 types, and it is difficult to obtain two identical road contour curves when measured on different road sections. Usually, a large amount of random data of road surface roughness obtained by measurement is processed to obtain the road surface power spectrum density. Random road input is the most basic situation encountered in vehicle driving. Refer to GB4970-85 “Automobile Ride Comfort Random Input Driving Test Method”, introduce the road surface spectral density unevenness coefficient G0, and the road surface excitation power spectral density formula:Gq(n)=G0(n)-w.

Using an integrator or shaping filter to generate white noise, after corresponding calculations, the expression of the road surface excitation time domain model:[6]

$$\dot{q}(t)=-2\pi f_0 q(t)+2\pi\sqrt{G_q V}w(t)$$

Among them, q(t) is the random road surface excitation received by the wheels, v is the driving speed of the car, w(t) is the white noise, and f0 is the cutoff frequency. Consider that in actual driving, there is a relative delay in the time when the front and rear wheels receive the road surface excitation. Therefore, a time delay input is added to the rear wheels, and the delay time t is related to vehicle speed and displacement.[7]

When using simulink for simulation, the input source of the simulation module is Band-Limited White Noise. The time-domain simulation model ofroad random excitation is established as shown in the figure below:

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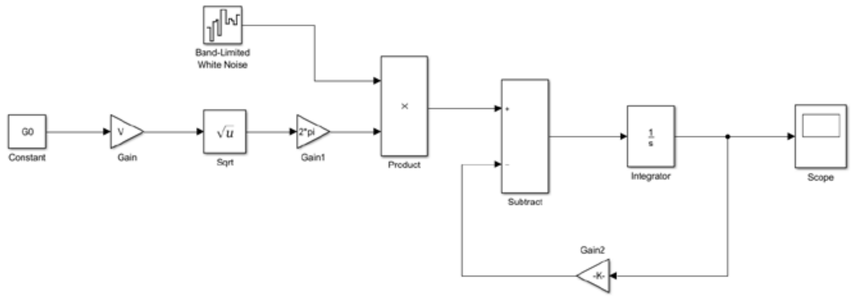

Fig.3 Time Domain Simulation Model of Road Excitation

In the case of inputting road flatness coefficient G0=6e-6, vehicle speed V=20km/h, f0=0.06Hz, the simulation diagram is as follows:

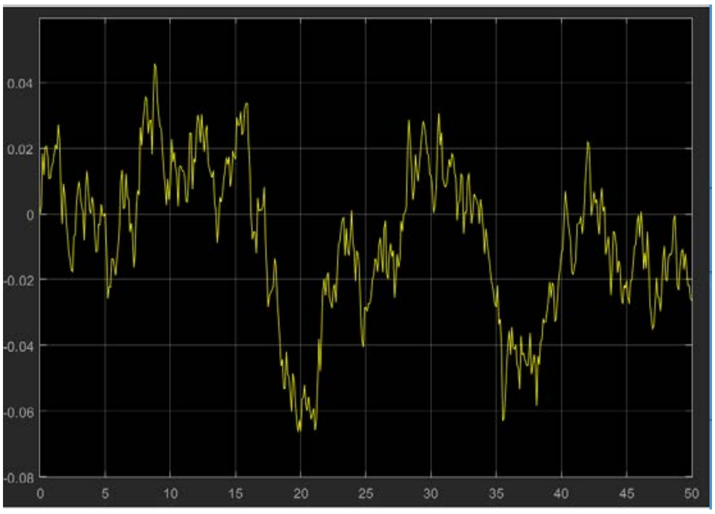

Fig.4 Time Domain Response of Road Excitation

Based on the above vehicle dynamics model, use Matlab\Simulink software to establish a simulation model[8], as shown in the figure:

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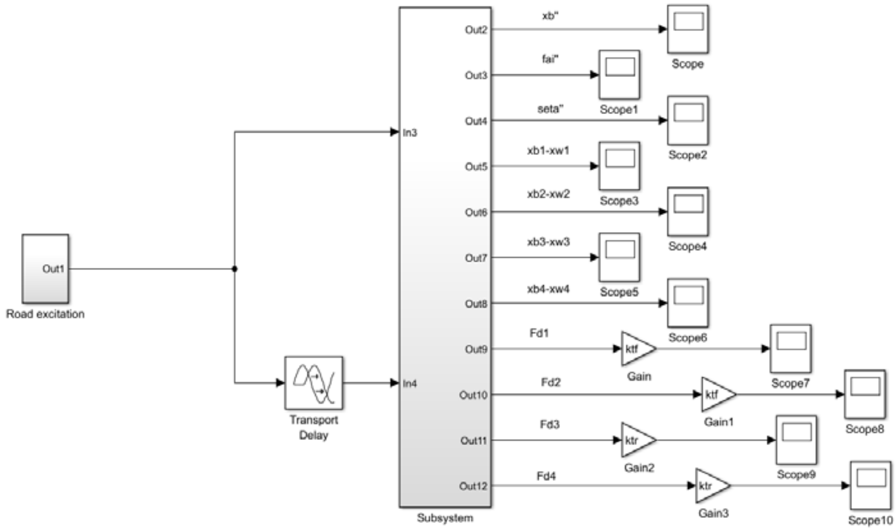

Fig.5 Simulation Model of the Whole Vehicle System

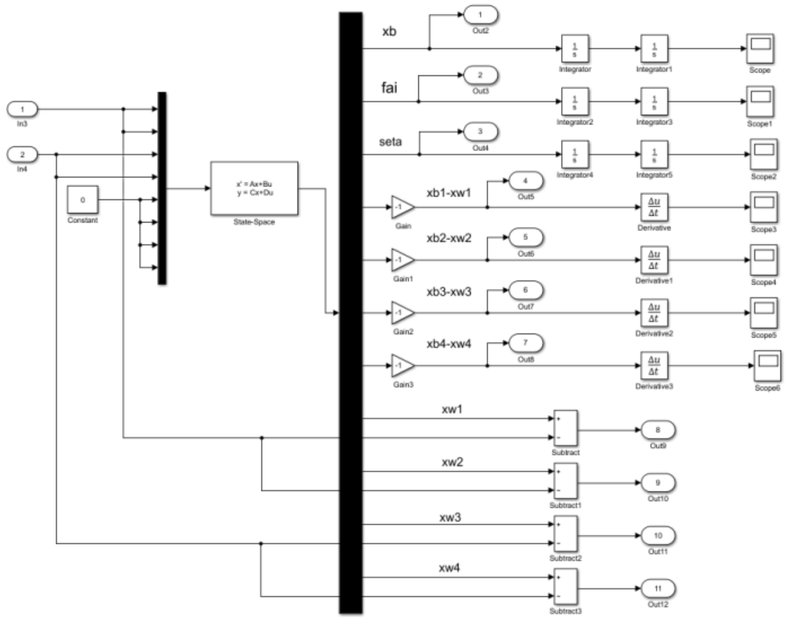

Fig.6 Suspension System Simulation Sub-Model

Figure7 shows the time-domain simulation response of the model vehicle on the

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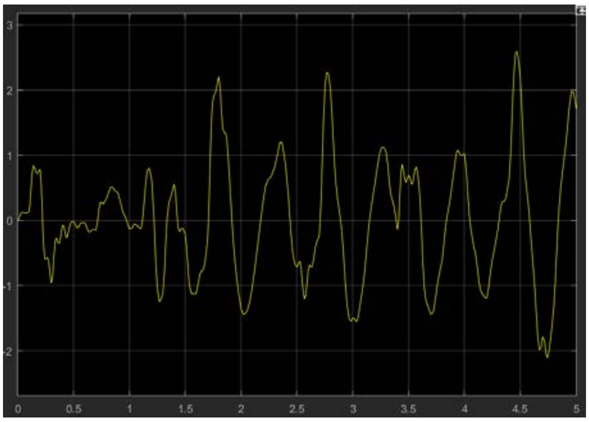
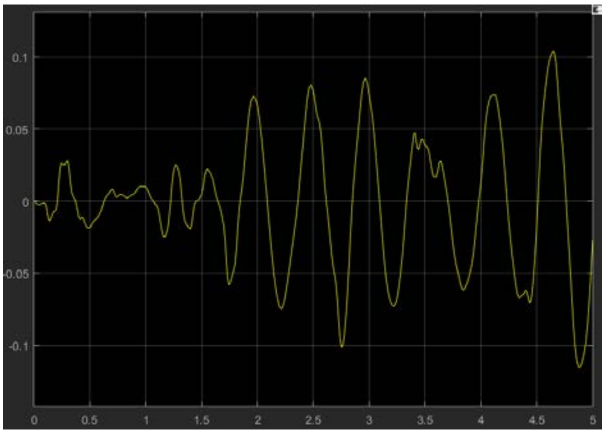
b-class road with a road roughness coefficient of 6E-6 and a vehicle speed of 20km/h, including vertical acceleration, lateral inclination acceleration, pitch Angle acceleration, dynamic travel of front and rear suspension, and dynamic load of front and rear wheels:





(left) Acceleration time domain response (right) Roll angular acceleration time domain response

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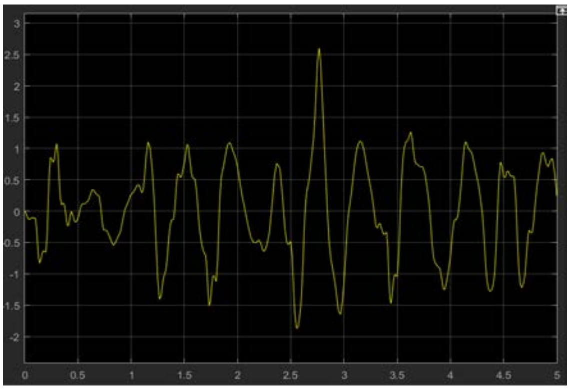
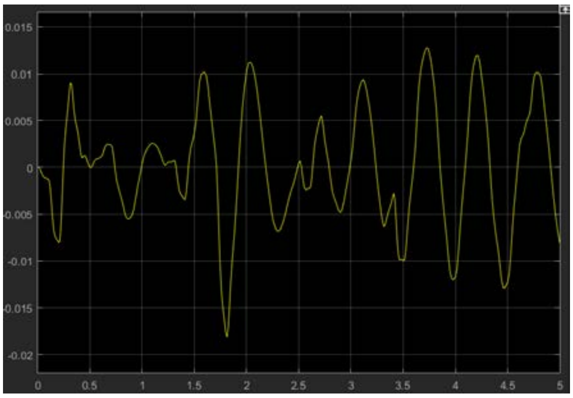
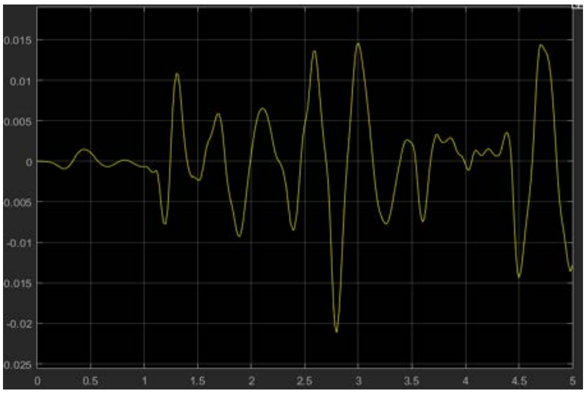




(left) Time domain response of pitch angular acceleration

(right) Time domain response of front suspension dynamic deflection



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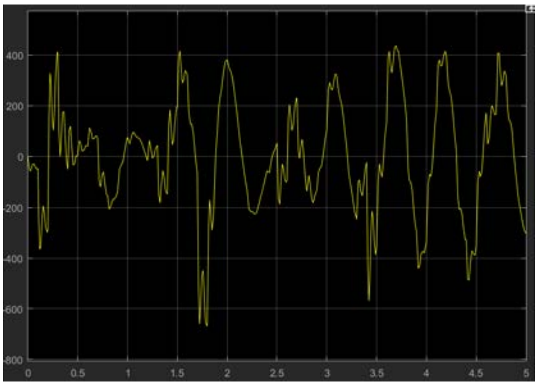

(left) Time domain response of rear suspension dynamic deflection

(right) Time domain response of front wheel dynamic load

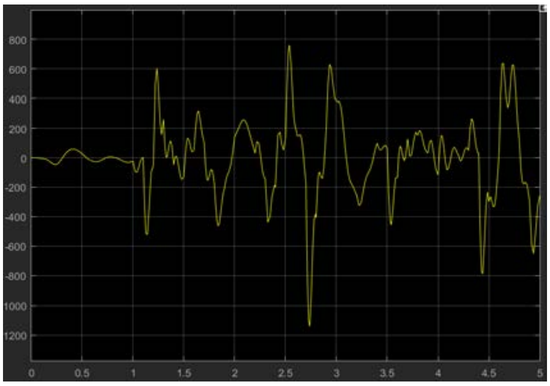

Fig.7 Time domain response of rear wheel dynamic load

5. Conclusion

This paper establishes a road surface excitation model and a vehicle suspension system simulation model based on the model vehicle. By inputting relevant vehicle parameters and road surface information, it outputs time-domain response diagrams of three evaluation indicators for ride comfort. The simulation graphics can be used to evaluate vehicle ride comfort. The performance is evaluated, and the results show that the simulation model can correctly reflect the performance of the vehicle, and has a certain reference for the evaluation, optimization and improvement of the vehicle design.

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