
Method for determining accurate initial air pressure range of air suspension airbag based on vehicle ride comfort simulation analysis

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Abstract. With the rapid development of automobile technology and the improvement of people's quality of life, people put forward higher requirements for vehicle ride comfort. Shock absorption has become an important direction for automobile research, manufacturing and optimization. The traditional air suspension airbag delimits the initial air pressure range to adapt to the bearing capacity of the airbag material so the range of the pressure is inaccurate. Considering optimizing ride comfort of the vehicle, this paper proposes a method to determine the accurate initial air pressure range. In order to determine the accurate initial air pressure range of the airbag, this paper needs to know the vehicle ride comfort under any air pressure. The airbag spring stiffness is calculated using the airbag model in MATLAB environment. A shock absorber with appropriate damping coefficient is selected by using the single mass system model and the airbag spring stiffness. Suspension stiffness is calculated by constructing a single wishbone beam independent suspension model and using the airbag spring stiffness. The damping coefficient and suspension stiffness are introduced into the Simulink five-degree-freedom vehicle model to obtain the acceleration signals of every part including the seat whose RMS value of the acceleration signal is used to judge the ride comfort of the vehicle. Under the specific simulation conditions in this paper, there is an accurate range (14~16kPa) in the rough range (12~20kPa) of the initial air pressure of the airbag to make the vehicle ride smoothly.

1 Introduction

Vehicle ride comfort is an important performance indicator for vehicles competing for advantages in market competition. With the improvement of people's living standards, the problem of structural vibration comfort has attracted more and more researchers' attention. The vehicle ride comfort directly affect the experience of the occupants, and indirectly affect the vehicle's power and economy. The suspension system plays a great role in the shock absorption performance of the vehicle. In practical applications, the air suspension system can meet the various requirements of the suspension design and save energy and material, thus driving many scholars and engineers extensively research and gradually promote it. Air suspension has been widely used in various vehicles. However, for the vast majority of air suspension airbags on the market, only a rough initial air pressure range is given, while the accurate initial air pressure range of various airbags are not given. This paper predicts that there is a certain pressure value or accurate pressure range in the rough initial air pressure range to make the vehicle ride smoothly. This paper intends to find the accurate pressure value or accurate range of the initial air pressure of the airbag by simulation.

The initial air pressure of the airbag is the main factor determining the natural frequency of the air spring, which determines the air spring stiffness, the air suspension

stiffness and the damping coefficient of the shock absorber. Xiong established the vibration model of the air suspension system, and proposed the method to calculate the parameters of the air spring and air suspension and the method to select shock absorber with appropriate parameters.[1] Li proposed the formula for calculating the stiffness of three different shaped air springs and the stiffness of air suspensions matching the springs.[2]

Meanwhile, the rough road surface is the root cause of the vibration of the vehicle, so it is necessary to establish a mathematical model to describe road roughness. Xie used computer simulation of random road surface excitation as input, and established the road surface roughness model by MATLAB/Simulink simulation software for computer simulation.[3] Liu built a Simulink simulation model for Class B Road based on pseudo white noise method.[4] Zheng used the probability and statistics theory and the central limit theorem to establish a mathematical model of the uneven road surface spectrum based on the power spectral density of the principle of harmonic superposition.[5] Zhang's research summarizes the triangular series method and the Fourier inverse transformation method for road roughness.[6]

In general, whole body vibration is the main form of vibration that causes physical injury to the driver so a standard should be established to evaluate the ride comfort. This paper decides to use the impact of the body's vibration to evaluate the ride comfort. In order to evaluate

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the impact of the body's vibration, the International Organization for Standardization (ISO) introduced the international standard "Guidelines for the Evaluation of Human Body's Resistance to Whole Body Vibration" (ISO 2631-1978) [9] in 1978. In order to accurately evaluate the ride comfort of the vehicle, Zhang uses the RMS value of the vertical weighted acceleration of the passenger to evaluate the index of the flatness. [7] Zhang summarized two internationally accepted evaluation criteria for ride comfort and three quantitative calculation methods for passenger comfort.[6]

According to the relationship between weighted RMS acceleration and riding comfort (Table 1), which is related to the relationship between seat acceleration and time, so it is necessary to establish a suitable mathematical model to analyze the vibration of every part of the vehicle. In order to accurately evaluate the ride comfort of the vehicle, Zhang constructed a five-degree-freedom vehicle model of human-vehicle-road, and analyzed the interaction between human and vehicle roads by transfer matrix method.[7] Xie performed mechanical analysis to obtain the system vibration differential equation and built the four-degree-freedom vehicle model by Simulink.[3] Liu, through the dynamic analysis of vehicles, established the eight-degree-freedom vehicle model, calculated the eight-degree-freedom coupled vibration equation of the vehicle four-point random excitation, and used the block matrix method to derive the transfer function of the vehicle vibration system.[8] Zhang's research summarizes the two-degree-freedom, the four-degree-freedom, five-degree-freedom, the seven-degree-freedom, seventeen-degree-freedom vehicle model for vibration analysis of each part.[6]

Table 1. Relationship between weighted RMS acceleration and riding comfort.

Weighted Acceleration RMS Value/ ($\text{m} \cdot \text{s}^{-2}$)	People's feeling
0.315	Comfortable
0.315 ~ 0.63	Slightly Uncomfortable
0.5 ~ 1.0	A Little uncomfortable
0.8 ~ 1.6	Uncomfortable
1.25 ~ 2.5	Very uncomfortable
2.0	Particularly Uncomfortable

In order to ensure the best ride comfort of a vehicle under a specific road roughness level, this paper proposes a method to determine the accurate initial air pressure range of the air suspension airbag. For a certain type of vehicle using air suspension, the control variable method is used to change the initial air pressure of the air suspension airbag, thereby changing the suspension stiffness and suspension damping coefficient. Vehicle parameters and the road roughness excitation derived from the Simulink road roughness model and vehicle

parameters are introduced to five-degree-freedom vehicle Simulink model. Using the transfer matrix method to solve the vibration equation, the acceleration signal of the vehicle seat under each initial air pressure of airbag can be obtained. Then use the acceleration signal of the vehicle seat to find the seat acceleration RMS value. The RMS value of the seat acceleration at each initial air pressure is compared to find an accurate range of the initial airbag pressure that optimizes ride comfort. The method can be used to determine the optimal initial air pressure range of the air suspension airbag of the vehicle under various road conditions and the vehicle can adjust the initial air pressure of the air suspension in real time according to the road condition; The method can also be used to initialize the air suspension airbag gas pressure during maintenance.

2 System description

The working process of the optimal initial air pressure optimization system for airbags proposed in this paper is shown in the figure 1. First, an initial air pressure is required to set the air suspension airbag. Next, the suspension stiffness and suspension damping coefficient can be calculated by inputting the initial air pressure of the airbag and the parameters related to airbag and air suspension into the single mass system model and the airbag model. Then, the suspension stiffness damping coefficient, vehicle parameters and road roughness excitation obtained from the road model are input into the five-degree-freedom vehicle Simulink model to obtain the signals of the vibration displacement, velocity and acceleration of each part of the vehicle. Then, the RMS value of the existing seat acceleration signal is obtained to measure the ride comfort of the vehicle as an output and recorded. Finally, change the initial air pressure of the airbag and repeat the above steps to find the initial air pressure of the airbag with the optimal ride comfort.

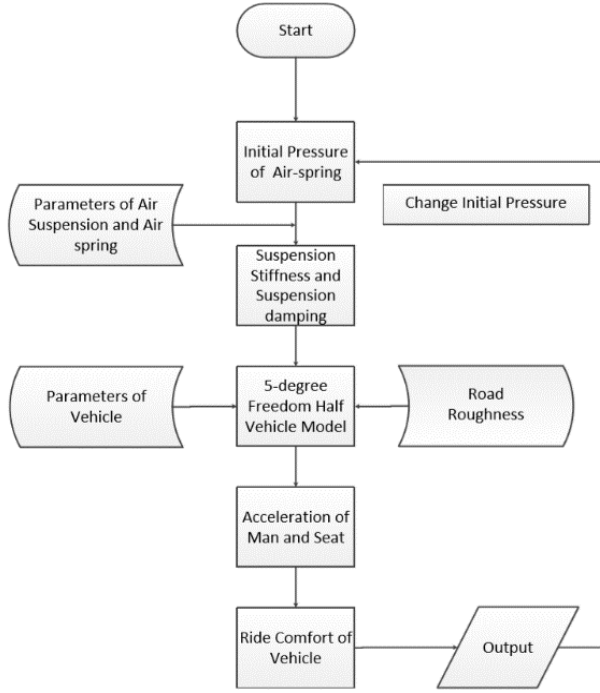


Figure 1. System model of optimal initial air pressure optimization method for airbags.

3 Mathematical model

In this paper, a five-degree-freedom vehicle model is built in the Simulink environment, and the ride comfort simulation analysis of the model's vibration differential equation is carried out. In order to obtain the input parameters of the model, the road roughness excitation $q(t)$ is obtained through the simulation of the road roughness model. The second is to obtain the front air suspension stiffness and rear air suspension stiffness k_{cf}, k_{cr} and front suspension damping coefficient and rear suspension damping coefficient c_{cf}, c_{cr} through the airbag model, the single mass system model and the single wishbone beam independent suspension model. The road roughness excitation $q(t)$, the suspension stiffness k_{cf}, k_{cr} , the suspension damping coefficient c_{cf}, c_{cr} and the vehicle parameters are input to the five-degree-freedom vehicle model to obtain the seat acceleration $a_w(t)$.

3.1 Road roughness model

The input of the five-degree-freedom vehicle model is mainly the road roughness excitation $q(t)$ and parameters of the vehicle, so establishing a reasonable road model helps to obtain accurate simulation results. Through a large number of literatures[3,4], the white noise method has the advantages of small calculation, fast running speed and high calculation accuracy. Therefore, this paper chooses the white noise method to simulate the road model.

Road roughness refers to the deviation of the road surface from the ideal plane. It affects the power, comfort and safety of the vehicle. The power spectral density of the road is often used to describe the statistical characteristics

of road roughness. The international standard ISO8608[9] and the national standard GB7031-86[5] suggest that the fitting expression of the road power spectral density $G_q(n)$ is:

$$G_q(n) = G_q(n_0) \left(\frac{n}{n_0} \right)^{-W} \quad (1)$$

Where: $G_q(n_0)$ is the road surface roughness coefficient, which is the value of the road surface power spectral density at the reference spatial frequency n_0 , in m^3 ; n represents the spatial frequency of several wavelengths per m length m^{-1} ; n_0 is the reference spatial frequency.

According to the road power spectrum density, the road roughness is divided into 8 levels, as shown in the following table, and the geometry mean of the corresponding root mean square value q_{rms} (σ_q) of the road roughness in the range of $0.011m^{-1} < n < 2.83m^{-1}$ is listed.

Under normal circumstances, the numerical range of road roughness is: wavelength $\lambda = 0.1 \sim 100m$, amplitude $A = 1 \sim 200mm$ road roughness classification as shown in the table 2.

Table 2. 8-level-classification of road roughness.

Road Level	Roughness Level			
	$n_0 = 0.1m^{-1}, 0.011m^{-1} < n < 2.83m^{-1}$			
	$G_q(n_0)/10^{-6}m^3$			
	Lower Limit	Geometric Mean	Upper Limit	Geometric Mean
A	8	16	32	3.81
B	32	64	128	7.61
C	128	256	512	15.23
D	512	1024	2048	30.45
E	2048	4096	8192	60.9
F	8192	16384	32768	121.8
G	32768	65536	131072	243.61
H	131072	262144	524288	487.22

The method proposed in this paper takes B-level road as an example. For reference to the literature [4], using the pseudo white noise method, the mathematical model of a single wheel subjected to road roughness excitation in the time domain can be described by (2) :

$$\dot{q}(t) = 2\pi f_0 \sqrt{G_q(n_0)} uW(t) - 2\pi f_0 q(t) \quad (2)$$

In equation (2), $q(t)$ is the road roughness excitation; $G_q(n_0)$ is the road surface roughness coefficient; $W(t)$ is the random simulated white noise; f_0 is the cut-off frequency; u is the vehicle speed.

Because the probability of a passenger car driving on a highway or a road with good road conditions is high, here is a B-level road as an example:

$$\begin{cases} G_q(n_0) = 64 \times 10^{-6}m^{-3} \\ f_0 = 0.1Hz \end{cases}$$

According to the road roughness model and the initially set parameters, the road roughness excitation $q(t)$ can be obtained in the Simulink environment.

3.2 Airbag model

Filled with compressed gas (this paper takes the rough pressure range 12kpa ~ 20kpa), the airbag (figure 2 and figure 3) uses the compressibility of the gas to achieve the spring action.



Figure 2. Airbag physical map.

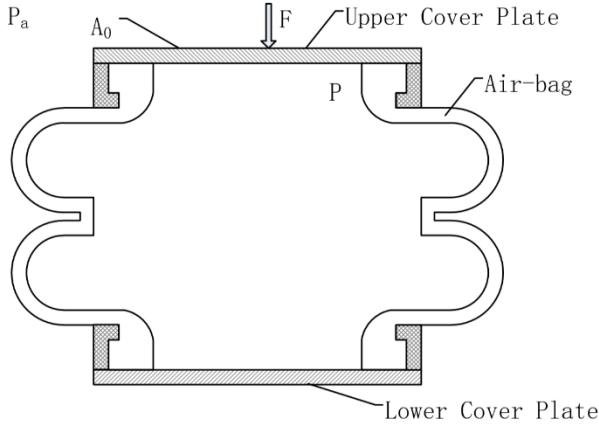


Figure 3. Airbag structure diagram.

The relationship between the load F on the air spring, the absolute pressure P of the air inside the airbag, the atmospheric pressure P_a , and the effective area A_0 is:

$$F = (P - P_a) \times A_0 \quad (3)$$

When the load causes the height of the airbag to change, the volume and internal pressure of the airbag also change, and the variation law satisfies the gas state equation:

$$P = P_0 \left(\frac{V_0}{V} \right)^n \quad (4)$$

Where: V represents the volume within the airbag at any position; P_0 represents the absolute pressure of the volume within the airbag at the static equilibrium position; V_0 represents the volume within the airbag at the static equilibrium position; n represents the variable index. When the vehicle speed is slow, $n = 1$; when the road condition is poor, the gas state changes close to the adiabatic process, then $n = 1.4$; in general, take $n = 1.33$, so in this paper $n = 1.33$. The vehicle simulation speed is 41km/h.

The vertical stiffness k of the air spring is:

$$k = \frac{dF}{dx} = A_0 \frac{d(P - P_a)}{dx} + (P - P_a) \frac{dA_0}{dx} = (P - P_a) \frac{dA_0}{dx} - A_0 n P_0 \frac{V_0^n dV}{V^{n+1} dx} \quad (5)$$

Where: $\frac{dA_0}{dx} = 0$, $\frac{dV}{dx} = -A_0$

Consider $V = V_0$ when the airbag is in static equilibrium position. Spring stiffness at static equilibrium position can be obtained:

$$k_0 = \frac{n P_0 A_0^2}{V_0} \quad (6)$$

From equation (6), the static equilibrium spring stiffness of the front suspension airbag is:

$$k_{0f} = \frac{n P_0 A_{0f}^2}{V_{0f}} \quad (7)$$

the static equilibrium spring stiffness of the rear suspension airbag is:

$$k_{0r} = \frac{n P_0 A_{0r}^2}{V_{0r}} \quad (8)$$

The static equilibrium spring stiffness k_{0f} of the front suspension airbag and the static equilibrium spring stiffness k_{0r} of the rear suspension airbag can be obtained by the airbag model. With the values of k_{0f}, k_{0r} , The front suspension damping coefficient c_{cf} and the rear suspension damping coefficient c_{cr} can be obtained by the single mass system model. The front suspension stiffness k_{cf} and the rear suspension stiffness k_{cr} can be obtained by the single wishbone beam independent suspension model.

3.3 Single mass system model

In general, the suspension damping coefficient matching the stiffness of airbag can be obtained from the single mass system model shown in Figure 4. m is the suspension mass of the vehicle. It consists of the body, the frame and the assembly on it. k is the stiffness of the airbag, c is the damping coefficient of the shock absorber, and the three constitute the suspension system of the car. q is the input road roughness excitation.

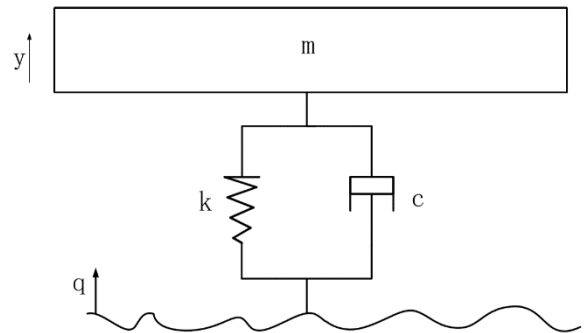


Figure 4. Single mass system model.

Apply Newton's second law to the entire system:

$$m\ddot{y} + c(\dot{y} - \dot{q}) + k(y - q) = 0 \quad (9)$$

The solution of this equation consists of the sum of the solution of the free vibration homogeneous equation and the special solution of the nonhomogeneous equation.

Let $2a = c/m$, $w_0^2 = k/m$

Where: w_0 is the natural circular frequency of the system. The influence of damping on the motion depends on the ratio ζ of a and w_0 . ζ is called the damping ratio.

$$\zeta = \frac{a}{w_0} = \frac{c}{2\sqrt{km}} \quad (10)$$

So:

$$c = 2\zeta\sqrt{km} \quad (11)$$

According to the equation (11), suspension damping coefficient c can be obtained.

The front suspension damping coefficient c_{cf} is:

$$c_{cf} = 2\zeta\sqrt{k_{of}M_f} \quad (12)$$

The rear suspension damping coefficient c_{cr} is:

$$c_{cr} = 2\zeta\sqrt{k_{or}M_r} \quad (13)$$

Where: M_f is the front suspension mass. M_r is the rear suspension mass. k_{of} is the stiffness of front airbag. k_{or} is the stiffness of rear airbag.

3.4 Single wishbone beam independent suspension model

If the car does not move, the car is in a static stress state, that is, the ground normal reaction force on a tire is $\frac{(G_s+G_u)}{2}$, G_s is the suspension mass gravity, G_u is Non-suspension mass gravity; then add an upward micro-element force $\Delta F'_z$ on the tire, thereby causing the micro-component displacement Δs_t of the wheel in the vertical direction and the micro-element displacement Δs_s of the spring along its center. The spring force also increases ΔQ , $\Delta Q = k_s\Delta s_s$, k_s is the spring stiffness.

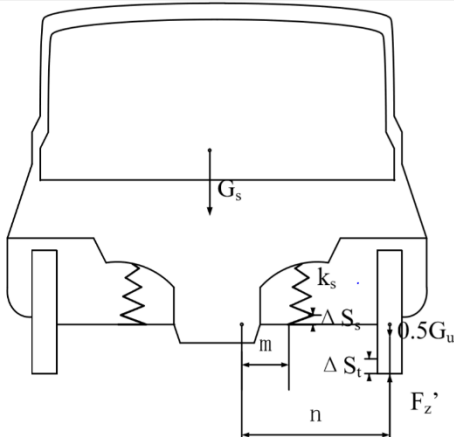


Figure 5. Single wishbone beam independent suspension model.

As can be seen in figure 5:

$$\frac{\Delta s_s}{m} = \frac{\Delta s_t}{n} \quad (14)$$

Where m is the distance from the center of the spring to the hinge point of the wishbone beam; n is the length of the wishbone beam.

In addition, according to the torque balance:

$$\Delta F'_z n = \Delta Q m = k_s \Delta s_s m \quad (15)$$

According to (14)(15):

$$\Delta F'_z = k_s \frac{m}{n} \Delta s_s = k_s \left(\frac{m}{n}\right)^2 \Delta s_t \quad (16)$$

One side suspension stiffness is:

$$\frac{\Delta F'_z}{\Delta s_t} = k_s \left(\frac{m}{n}\right)^2 \quad (17)$$

The whole suspension stiffness is:

$$k_c = 2k_s \left(\frac{m}{n}\right)^2 \quad (18)$$

According to (18), the front suspension stiffness is:

$$k_{cf} = 2k_{of} \left(\frac{m_f}{n_f}\right)^2 \quad (19)$$

The rear suspension stiffness is:

$$k_{cr} = 2k_{or} \left(\frac{m_r}{n_r}\right)^2 \quad (20)$$

Road roughness excitation $q(t)$, the stiffness of vehicle front suspension and rear suspension k_{cf}, k_{cr} , the damping coefficient of front and rear suspension c_{cf}, c_{cr} and vehicle parameters are available. These parameters are input together to the five-degree-freedom vehicle model and the seat acceleration signal $a_w(t)$ is obtained.

3.5 Five-degree-freedom vehicle model

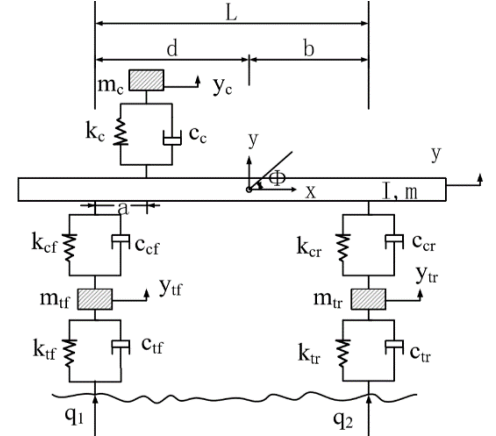


Figure 6. Five-degree-freedom vehicle model.

As is shown in figure 6, the displacements of the seat, the front suspension system and the rear suspension system are $y - a\Phi$, $y - d\Phi$ and $y + b\Phi$. The vibration equation is established by using Newton's second law.

For seat:

$$m_c \ddot{y}_c + c_c [\dot{y}_c - (\dot{y} - a\dot{\Phi})] + k_c [y_c - (y - a\Phi)] = 0 \quad (21)$$

For front wheel:

$$m_{tf} \ddot{y}_{tf} + c_{cf} [\dot{y}_{tf} - (\dot{y} - d\dot{\Phi})] + c_{tf} (y_{tf} - q_1) + k_{cf} [y_{tf} - (y - d\Phi)] + k_{tf} (y_{tf} - q_1) = 0 \quad (22)$$

For rear wheel:

$$\begin{aligned} m_{tr}\ddot{y}_{tr} + c_{cr}[\dot{y}_{tr} - (\dot{y} + b\dot{\Phi})] \\ + c_{tr}(\dot{y}_{tr} - \dot{q}_2) \\ + k_{cr}[y_{tr} - (y + b\Phi)] \\ + k_{tr}(y_{tr} - q_2) = 0 \end{aligned} \quad (23)$$

For the vehicle body:

$$\begin{aligned} m\ddot{y} - c_c[\dot{y}_c - (\dot{y} - a\dot{\Phi})] \\ - c_{cf}[\dot{y}_{tf} - (\dot{y} - d\dot{\Phi})] \\ - c_{cr}[\dot{y}_{tr} - (\dot{y} + b\dot{\Phi})] \\ - k_c[y_c - (y - a\Phi)] \\ - k_{cf}[y_{tf} - (y - d\Phi)] \\ - k_{cr}[y_{tr} - (y + b\Phi)] = 0 \end{aligned} \quad (24)$$

For the torque balance of vehicle body:

$$\begin{aligned} I\ddot{\Phi} + ac_c[\dot{y}_c - (\dot{y} - a\dot{\Phi})] \\ + dc_{cf}[\dot{y}_{tf} - (\dot{y} - d\dot{\Phi})] \\ - bc_{cr}[\dot{y}_{tr} - (\dot{y} + b\dot{\Phi})] \\ + ak_c[y_c - (y - a\Phi)] \\ + dk_{cf}[y_{tf} - (y - d\Phi)] \\ - bk_{cr}[y_{tr} - (y + b\Phi)] = 0 \end{aligned} \quad (25)$$

Using the transfer matrix method to solve the vibration equation of a five-degree-freedom vehicle model, (21)~(25) can be written as:

$$\frac{dQ}{dt} = XQ + Y_1q_1 + Y_2q_2 + Y_3q_1 + Y_4q_2 \quad (26)$$

Where:

$$Q = [y_c \quad \dot{y}_c \quad y_{tf} \quad \dot{y}_{tf} \quad y_{tr} \quad \dot{y}_{tr} \quad y \quad \dot{y} \quad \Phi \quad \dot{\Phi}]^T$$

$$Y_1 = \begin{bmatrix} 0 & 0 & 0 & \frac{k_{tf}}{m_{tf}} & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$Y_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \frac{k_{tr}}{m_{tr}} & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$Y_3 = \begin{bmatrix} 0 & 0 & 0 & \frac{c_{tf}}{m_{tr}} & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$Y_4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \frac{c_{tr}}{m_{tr}} & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$X =$

$$\begin{bmatrix} 0 & x_{1.2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ x_{2.1} & x_{2.2} & 0 & 0 & 0 & 0 & x_{2.7} & x_{2.8} & x_{2.9} & x_{2.10} \\ 0 & 0 & 0 & x_{3.4} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & x_{4.3} & x_{4.4} & 0 & 0 & x_{4.7} & x_{4.8} & x_{4.9} & x_{4.10} \\ 0 & 0 & 0 & 0 & 0 & x_{5.6} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & x_{6.5} & x_{6.6} & x_{6.7} & x_{6.8} & x_{6.9} & x_{6.10} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_{7.8} & 0 & 0 \\ x_{8.1} & x_{8.2} & x_{8.3} & x_{8.4} & x_{8.5} & x_{8.6} & x_{8.7} & x_{8.8} & x_{8.9} & x_{8.10} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_{9.10} \\ x_{10.1} & x_{10.2} & x_{10.3} & x_{10.4} & x_{10.5} & x_{10.6} & x_{10.7} & x_{10.8} & x_{10.9} & x_{10.10} \end{bmatrix}$$

The elements in X that are not 0 are as follows:

$$x_{1.2} = 1, x_{2.1} = -\frac{k_c}{m_c}, x_{2.2} = -\frac{c_c}{m_c}, x_{2.7} = \frac{k_c}{m_c}$$

$$\begin{aligned} x_{2.8} &= \frac{c_c}{m_c}, x_{2.9} = -\frac{k_c a}{m_c}, x_{2.10} = -\frac{c_c a}{m_c}, x_{3.4} = 1 \\ x_{4.3} &= -\frac{k_{cf} + k_{tf}}{m_{tf}}, x_{4.4} = -\frac{c_{cf} + c_{tf}}{m_{tf}}, x_{4.7} = \frac{k_{cf}}{m_{tf}} \\ x_{4.8} &= \frac{c_{cf}}{m_{tf}}, x_{4.9} = -\frac{k_{cf} d}{m_{tf}}, x_{4.10} = -\frac{c_{cf} d}{m_{tf}}, x_{5.6} = 1 \\ x_{6.5} &= -\frac{k_{cr} + k_{tr}}{m_{tr}}, x_{6.6} = -\frac{c_{cr} + c_{tr}}{m_{tr}}, x_{6.7} = \frac{k_{cr}}{m_{tr}} \\ x_{6.8} &= \frac{c_{cr}}{m_{tr}}, x_{6.9} = \frac{k_{cr} b}{m_{tr}}, x_{6.10} = -\frac{c_{cr} b}{m_{tr}}, x_{7.8} = 1 \\ x_{8.1} &= \frac{k_c}{m}, x_{8.2} = \frac{c_c}{m}, x_{8.3} = \frac{k_{cf}}{m}, x_{8.4} = \frac{c_{cf}}{m} \\ x_{8.5} &= \frac{k_{cr}}{m}, x_{8.6} = \frac{c_{cr}}{m}, x_{8.7} = -\frac{k_c + k_{cf} + k_{cr}}{m} \\ x_{8.8} &= -\frac{c_c + c_{cf} + c_{cr}}{m}, x_{8.9} = \frac{k_c a + k_{cf} d + k_{cr} b}{m} \\ x_{8.10} &= \frac{c_c a + c_{cf} d - c_{cr} b}{m}, x_{9.10} = 1, x_{10.1} = -\frac{k_c a}{I} \\ x_{10.2} &= -\frac{c_c a}{I}, x_{10.3} = -\frac{k_{cf} d}{I}, x_{10.4} = -\frac{c_{cf} d}{I} \\ x_{10.5} &= -\frac{k_{cr} b}{I}, x_{10.6} = -\frac{c_{cr} b}{I} \\ x_{10.7} &= \frac{k_c a - k_{cf} d - k_{cr} b}{I} \\ x_{10.8} &= \frac{c_c a - c_{cf} d - c_{cr} b}{I} \\ x_{10.9} &= -\frac{k_c a^2 + k_{cf} d^2 + k_{cr} b^2}{I} \\ x_{10.10} &= -\frac{c_c a^2 + c_{cf} d^2 + c_{cr} b^2}{I} \end{aligned}$$

4 Simulation model

In order to determine the optimal initial air pressure of the suspension airbag under the B-level road surface, the paper first gives an arbitrary initial air pressure, and calculates the suspension stiffness and suspension damping coefficient through the initial air pressure in the MATLAB environment. Then, the vehicle parameters and the road roughness excitation are introduced to five-degree-freedom vehicle model to obtain the acceleration signal of seat whose RMS value a_w can be an evaluation index of the ride comfort of the vehicle. The simulation of this paper consists of two parts. The first part is the road surface roughness excitation measured by the road roughness Simulink simulation model. The second part is the five-degree-freedom Simulink model to measure the acceleration signal of the seat and find its RMS value. The vehicle parameters are derived from the bus of the literature [7]. The airbag parameters are the airbag parameters that are reasonably matched according to the vehicle parameters of the bus. The most widely used vibration comfort standards in the world are BS 6841-1987 and ISO 2631-1-1997[9], both of which use the weighted acceleration of seat RMS as the basic evaluation index.[7]

At present, when studying the ride comfort of a vehicle, the human comfort index is generally based on the weighted acceleration RMS a_w , and the calculation formula is as follows:

$$a_w = \left[\frac{\int_0^T a_w^2(t) dt}{T} \right]^{\frac{1}{2}} \quad (27)$$

4.1 Road roughness Simulink model

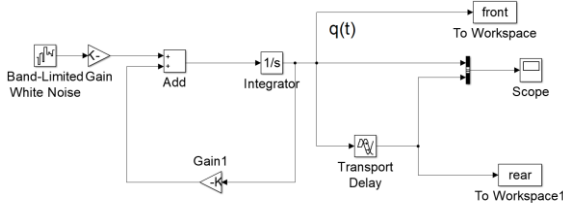


Figure 7. Road roughness Simulink model.

According to (2), this paper chooses to simulate road roughness excitation based on Simulink environment. There are two main outputs for road roughness, the front wheel road roughness excitation $q(t)$ and the rear wheel road roughness excitation $q(t + T)$. Rear wheel output lags front wheel output for T . Assuming that the front and rear wheel axles are on the same rut, the front and rear road roughness displacement outputs q_1 and q_2 are only one time lag in time Δt , where $\Delta t = L/v$, v is the vehicle speed. The hysteresis function can be implemented using the Transport Delay module.

4.2 Five-degree-freedom vehicle Simulink model

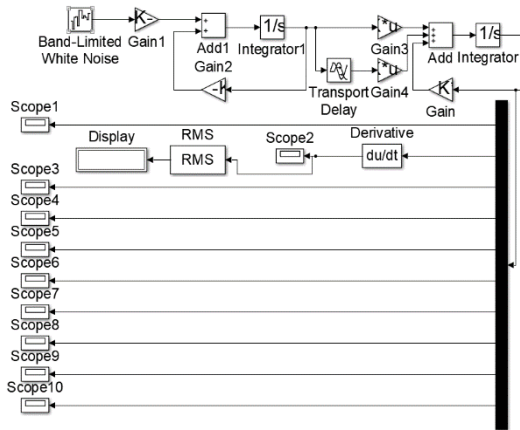


Figure 8. Road roughness Simulink model.

According to (26), a five-degree-freedom vehicle model can be constructed in the Simulink environment. The q_1 and q_2 obtained from the road roughness Simulink simulation model and the X, Y_1, Y_2, Y_3, Y_4 matrices composed of vehicle parameters are introduced into the five-degree-freedom vehicle Simulink simulation model to obtain the output matrix Q .

5 Simulation results

The parameters introduced in this paper are shown in the table 3.

Table 3. The table of vehicle parameters.

Front suspension airbag static balance volume V_{0f}/cm^3	13650
Effective area of front suspension airbag A_{0f}/m^2	0.286
Rear suspension airbag static balance volume V_{0r}/cm^3	13650
Effective area of rear suspension airbag A_{0r}/m^2	0.0905
Variable index n	1.33
Vehicle speed $v/km \cdot h^{-1}$	41
Front suspension mass M_f/kg	594.8
Rear suspension mass M_r/kg	290.2
Relative damping ratio ζ	0.3
People and seat mass m_c/kg	53
Stiffness of the seat $k_c/N \cdot m^{-1}$	19030
Damping coefficient of the seat $c_c/N \cdot s \cdot m^{-1}$	170
Rear wheel mass m_{tr}/kg	210
Stiffness of rear wheel $k_{tr}/N \cdot m^{-1}$	571420
Rear wheel damping coefficient $c_{tf}/N \cdot s \cdot m^{-1}$	0
Front wheel mass m_{tf}/kg	180
Stiffness of front wheel $k_{tf}/N \cdot m^{-1}$	571420
Front wheel damping coefficient $c_{tf}/N \cdot s \cdot m^{-1}$	0
Seat center and centroid distance a/m	0.183
Front wheel center and centroid distance d/m	1.353
Distance from the center of the front suspension spring to the hinge point of the wishbone beam m_f/m	1.2
Distance from the center of the rear suspension spring to the hinge point of the wishbone beam m_r/m	1.59
Front suspension wishbone beam length n_f/m	0.5
Rear suspension wishbone beam length n_r/m	0.5
Vehicle body mass m/kg	1770
Moment of inertia of the frame around the center of mass $I/kg \cdot m^2$	1988
Rear wheel center and centroid distance b/m	0.947
Front and rear wheel center distance L/m	2.3

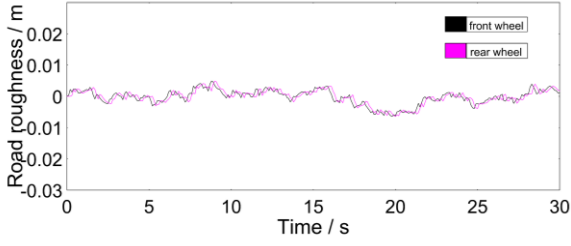


Figure 9. Front wheel and rear wheel road roughness excitation q_1, q_2 .

Figure 9 shows the road roughness excitation to the front wheel and the rear wheel.

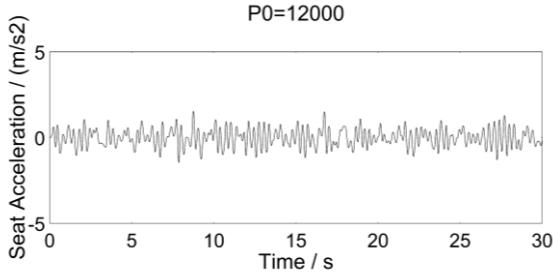


Figure 10. Seat acceleration signal when $P_0 = 12000$.

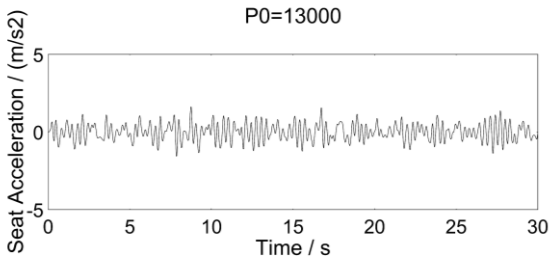


Figure 11. Seat acceleration signal when $P_0 = 13000$.

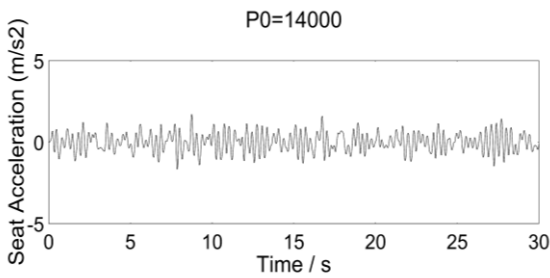


Figure 12. Seat acceleration signal when $P_0 = 14000$.

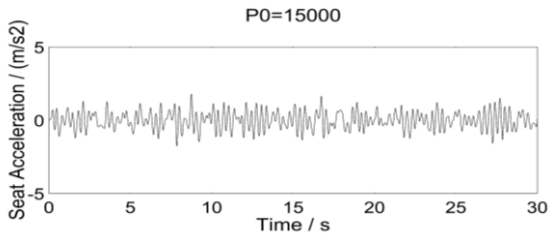


Figure 13. Seat acceleration signal when $P_0 = 15000$.

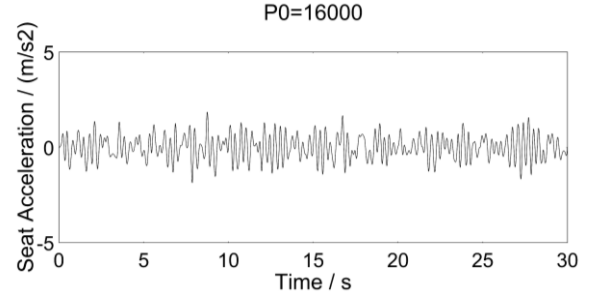


Figure 14. Seat acceleration signal when $P_0 = 16000$.

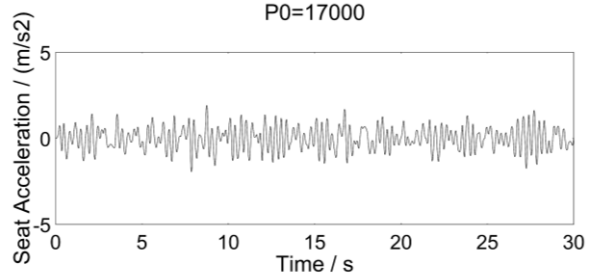


Figure 15. Seat acceleration signal when $P_0 = 17000$.

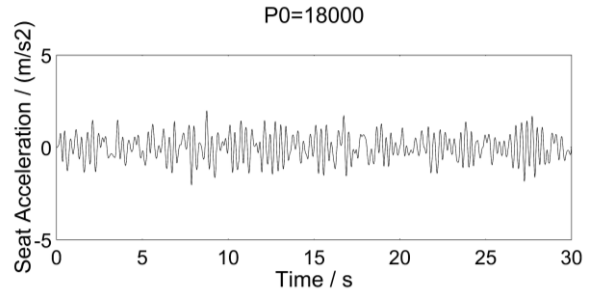


Figure 16. Seat acceleration signal when $P_0 = 18000$.

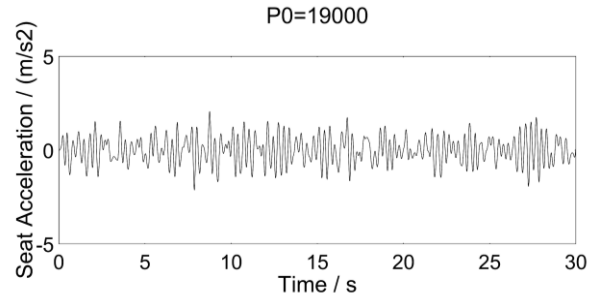


Figure 17. Seat acceleration signal when $P_0 = 19000$.

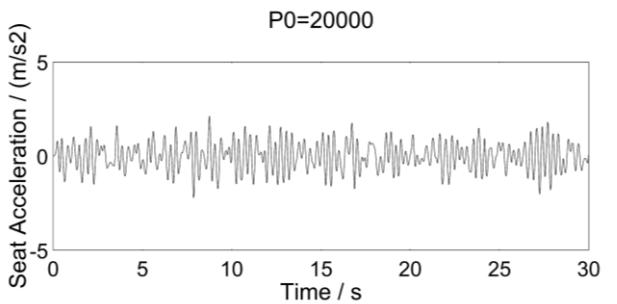


Figure 18. Seat acceleration signal when $P_0 = 20000$.

Figure 10 to Figure 18 show the relationship between the acceleration of the seat $a_w(t)$ with time t when P_0 takes different values. It can be seen that the difference between the maximum and minimum values of

the acceleration of the person and the seat increases as the initial air pressure of the airbag increases, indicating that the greater the initial air pressure of the airbag, the greater the change in acceleration of the seat.

Table 4. The table of a_w value corresponding to any P_0 .

P_0 / Pa	$a_w = \left[\frac{\int_0^T a_w^2(t) dt}{T} \right]^{\frac{1}{2}} / (\text{m/s}^2)$
12000	0.08882
13000	0.06459
14000	0.03773
15000	0.009946
16000	0.01768
17000	0.04326
18000	0.06132
19000	0.0707
20000	0.09029

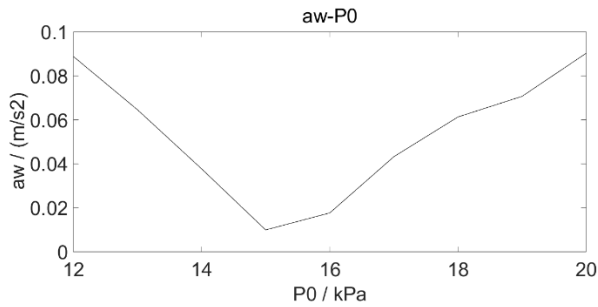


Figure 19. The line diagram of a_w value corresponding to any P_0 .

Table 4 reflects the relationship between the seat acceleration RMS value a_w value corresponding to the initial air pressure P_0 of airbag, and Figure 19 is a line diagram drawn based on the data of Table 4. It can be seen from the line diagram that as the initial air pressure P_0 of the airbag increases, the acceleration RMS value a_w of the seat decreases first and then increases while the ride comfort of the vehicle increases first and then decreases. This reflects the existence of an accurate initial air pressure of airbag with optimum vehicle ride comfort and the initial air pressure ranges between 14kPa and 16kPa.

6 Conclusion

Taking the B-level road as an example, this paper establishes a five-degree-freedom vehicle model. With the random road excitation, air suspension parameters and other relevant vehicle parameters as input, a simulation model is established, and the RMS value of vertical weighted acceleration of the seat is used to analyse the ride comfort of the vehicle corresponding to the initial air pressure of any air suspension airbag.

It can be seen from Figure 19 that under the B-level road surface, as the initial air pressure of the airbag increases, the ride comfort of the vehicle increases first

and then decreases. Obviously, there is an accurate initial air pressure making the vehicle ride smooth, which is consistent with the expected result of this paper. The optimal initial air pressure range of the vehicle airbag is between 14~16kPa. The rough range given in this paper is 12~20kPa. The length of the range is reduced from 8kPa to 2kPa, and the length of the accurate range is reduced to 1/4.

Here are a few innovative points:

(1) Using the airbag model, the single mass system model and the single wishbone beam independent suspension model can determine the specific values of the suspension stiffness and suspension damping coefficient corresponding to any initial air pressure of airbag.

(2) The five-degree-freedom vehicle model established in this paper can comprehensively reflect the vibration characteristics of every part of the vehicle under the condition of rough road surface. This model is the basis for studying the ride comfort of vehicles and analysing the vibration state of vehicles.

(3) When analysing the ride comfort of a rough road surface, it is not appropriate to use the vehicle vibration acceleration to evaluate the ride comfort of the human body. Therefore, the vibration condition of the seat is particularly important and can be directly used to measure the ride comfort of the vehicle.

(4) The initial air pressure of the air suspension airbag has a great influence on the ride comfort of the vehicle. Under the B-level road surface, as the initial air pressure of the airbag increases, the ride comfort of the vehicle increases first and then decreases, so there is an initial air pressure. Therefore there is an accurate initial air pressure makes the vehicle ride smoother. In this paper, the method of finding the accurate range of the initial air pressure of the airbag can be used as the initial air pressure reference value for air suspension production and can also be used as an important reference for airbag maintenance.

7 Prospective

The rough range given in this paper is 12~20kPa, and the accurate range found in this paper is 14~16kPa. In theory, if the selected pressure gradient is smaller, a more accurate initial pressure range or even an accurate initial pressure value can be obtained.

The five-degree-freedom vehicle model constructed in this paper can reflect the vibration characteristics of every part of the vehicle more comprehensively, so it can be used to study the influence of other vehicle parameter changes on vehicle ride comfort.

This paper provides a method to determine the optimal initial air pressure range of air suspension airbags. It can be used as a reference for the study of shock absorption. It can also be used as a method to determine the precise initial air pressure range of airbags during airbag maintenance. It can also be used as the basis for producing variable stiffness air suspension.

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