Method for Determining Accurate Initial Air Pressure Range of Air Suspension Airbag Based on Vehicle Ride Comfort Simulation Analysis

Quan Zhou¹,a, Puguang Yuan¹, Tim Tudor², Xudong Wang¹, Zhangwei Guo¹, Yihui Huang¹, Jingfeng Sun¹, Boyun Wang³

¹Institute of vehicle suspension, Automotive Engineering Department, Wuhan University of Technology, China
²School of Engineering, University of Wales Trinity Saint David, Swansea, UK
³Bellevue College, Bellevue, Washington, US

Corresponding author: 1805150@student.uwtsd.ac.uk

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 based on 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 a significant performance indicator to compete 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 significant 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 specific pressure value or accurate pressure range in the rough initial air pressure range to maximize the vehicle ride comfort. This paper intends to find the accurate pressure value or an 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 to calculate the stiffness of three different shaped air springs and the stiffness of air suspensions matching different shaped 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].

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 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].

| Weighted Acceleration RMS Value/ (m • 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 |

The weighted RMS acceleration is related to seat acceleration signal. According to the relationship between weighted RMS acceleration and riding comfort (Table 1), it is necessary to establish a suitable mathematical model to analyze the vibration of every part of the vehicle to get seat acceleration signal. 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].

The above literatures provide a theoretical basis and modeling basis for studying the relationship between initial air pressure and vehicle ride comfort of air suspension airbags, but none of these literatures study the initial air pressure of air suspension airbags for the purpose of maximizing vehicle ride comfort. Therefore, the purpose of this paper is to find a method for determining accurate initial air pressure range of air suspension airbag based on vehicle ride comfort simulation analysis.

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 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.

![System model of optimal initial air pressure optimization method for airbags.](image)

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

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 evaluate 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.

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. First, 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:

\[
G_q(n) = G_q(n_0) \left( \frac{n}{n_0} \right)^{-W}
\]  

(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 \( q_{rms} (\sigma_q) \) 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 \( \lambda = 0.1\sim100m \),
amplitude \( A = 1\sim200mm \) road roughness classification as shown in the table 2.

| Road Level | Roughness Level | \( n_0 = 0.1m^{-1}, 0.011m^{-1} < n < 2.83m^{-1} \) |
|------------|-----------------|-------------------------------------------------|
| 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):

\[ q(t) = 2\pi f_0 \sqrt{G_q(n_0)} u W(t) - 2\pi f_0 q(t) \]  

(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:

\[ \begin{align*}
G_q(n_0) &= 64 \times 10^{-6} \text{ m}^{-3} \\
 f_0 &= 0.1 \text{Hz}
\end{align*} \]

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.

![Airbag physical map](image2)

**Figure 2.** Airbag physical map.

![Airbag structure diagram](image3)

**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:

\[ F = (P - P_a) \times A_0 \]  

(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:

\[ P = P_0 \left( \frac{V}{V_0} \right)^n \]  

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 polytropic 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 41 km/h.

The vertical stiffness \( k \) of the air spring is:

\[
k = \frac{dF}{dx} = A_0 \frac{d(P - P_a)}{dx} + (P - P_a) \frac{dA_0}{dx} = (P - P_a) \frac{dA_0}{dx} - A_0 n P_0 \frac{V_0 \, dV}{V_0^{n+1}} \frac{dx}{dx} \]  

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:

\[
k_0 = \frac{n P_0 A_0^2}{V_0} \]  

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

\[
k_{0f} = \frac{n P_0 A_0^2}{V_{0f}} \]  

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

\[
k_{0r} = \frac{n P_0 A_0^2}{V_{0r}} \]  

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 single mass system model, the front suspension damping coefficient \( c_{cf} \) and the rear suspension damping coefficient \( c_{cr} \) can be calculated from the values of \( k_{0f}, k_{0r} \). The front suspension stiffness \( k_{cf} \) and the rear suspension stiffness \( k_{cr} \) can be obtained by the single wishbone beam independent suspension model.

![Figure 4. Single mass system model.](image-url)
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.
Apply Newton’s second law to the entire system:
\[
m\ddot{y} + c(\dot{y} - \dot{q}) + k(y - q) = 0
\]
(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 \( 2a = c/m, \quad w_0^2 = k/m \)
where: \( w_0 \) is the natural circular frequency of the system. The influence of damping on the motion
depends on the ratio \( \zeta \) of \( a \) and \( w_0, \zeta \) is called the damping ratio.

\[
\zeta = \frac{a}{w_0} = \frac{c}{2\sqrt{km}}
\]
(10)
So:
\[
c = 2\zeta \sqrt{km}
\]
(11)
According to the equation (11), suspension damping coefficient \( c \) can be obtained.
The front suspension damping coefficient \( c_{cf} \) is:
\[
c_{cf} = 2\zeta \sqrt{k_{cf}M_f}
\]
(12)
The rear suspension damping coefficient \( c_{cr} \) is:
\[
c_{cr} = 2\zeta \sqrt{k_{cr}M_r}
\]
(13)
where: \( M_f \) is the front suspension mass. \( M_r \) is the rear suspension mass. \( k_{cf} \) is the stiffness of front
airbag. \( k_{cr} \) 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 \( \Delta F' \) on the tire, thereby causing the micro-component displacement
\( \Delta s' \) of the wheel in the vertical direction and the micro-element displacement \( \Delta s_s \) of the spring along
its center. The spring force also increases \( \Delta Q, \Delta Q = k_s \Delta s_s \), \( k_s \) is the spring stiffness.

![Figure 5. Single wishbone beam independent suspension model.](image)
As can be seen in figure 5:

$$\frac{\Delta s}{m} = \frac{\Delta s_t}{n}$$  \hspace{1cm} (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:

$$\Delta F'_zn = \Delta Qm = k_s\Delta s_m$$  \hspace{1cm} (15)

According to (14)(15):

$$\Delta F'_z = k_s\frac{m}{n}\Delta s_s = k_s \left(\frac{m}{n}\right)^2 \Delta s_t$$  \hspace{1cm} (16)

One side suspension stiffness is:

$$\frac{\Delta F_{iz}}{\Delta s_t} = k_s \left(\frac{m}{n}\right)^2$$  \hspace{1cm} (17)

The whole suspension stiffness is:

$$k_c = 2k_s \left(\frac{m}{n}\right)^2$$  \hspace{1cm} (18)

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

$$k_{cf} = 2k_{0f} \left(\frac{m_f}{n_f}\right)^2$$  \hspace{1cm} (19)

The rear suspension stiffness is:

$$k_{cr} = 2k_{0r} \left(\frac{m_r}{n_r}\right)^2$$  \hspace{1cm} (20)

Road roughness excitation \((t)\), 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. Road roughness 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.

![Figure 6. Five-degree-freedom vehicle model.](image-url)
For seat:

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

For front wheel:

$$m_{tf} \ddot{y}_{tf} + c_{cf} [\dot{y}_{tf} - (\dot{y} - d \Phi)] + c_{tf} (\dot{y}_{tf} - \dot{q}_1) + k_{cf} [y_{tf} - (y - d \Phi)] + k_{tf} (y_{tf} - q_1) = 0 \quad (22)$$

For rear wheel:

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

For the vehicle body:

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

For the torque balance of vehicle body:

$$1 \ddot{\Phi} + a c_c [\dot{y}_c - (\dot{y} - a \Phi)] + d c_{cf} [\dot{y}_{tf} - (\dot{y} - d \Phi)] - b c_{cr} [\dot{y}_{tr} - (\dot{y} + b \Phi)] +$$

$$a k_c [y_c - (y - a \Phi)] + d k_{cf} [y_{tf} - (y - d \Phi)] - b k_{cr} [y_{tr} - (y + b \Phi)] = 0 \quad (25)$$

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

$$\frac{d\mathbf{q}}{dt} = \mathbf{XQ} + \mathbf{Y}_1 \mathbf{q}_1 + \mathbf{Y}_2 \mathbf{q}_2 + \mathbf{Y}_3 \mathbf{q}_3 + \mathbf{Y}_4 \mathbf{q}_4 \quad (26)$$

where:

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

$$\mathbf{Y}_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$\mathbf{Y}_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$\mathbf{Y}_3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$\mathbf{Y}_4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

The elements in \( \mathbf{X} \) that are not 0 are as follows:
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 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:

$$a_w = \left( \frac{\int_0^T a^2_w(t) \, dt}{T} \right)^{\frac{1}{2}}$$

(27)

4.1. 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 $\Delta t$, where $\Delta t = L/v$, $v$ is the vehicle speed. The hysteresis function can be implemented using the Transport Delay module.

![Figure 7. Road roughness Simulink model.](image)

4.2. Five-degree-freedom vehicle 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 $Q$.

![Figure 8. Road roughness Simulink model.](image)

5. Simulation results

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

| Parameter                                                                 | Value     |
|---------------------------------------------------------------------------|-----------|
| Front suspension airbag static balance volume \( V_{of} \)/cm\(^3\)        | 13650     |
| Effective area of front suspension airbag \( A_{of} \)/m\(^2\)             | 0.286     |
| Rear suspension airbag static balance volume \( V_{or} \)/cm\(^3\)        | 13650     |
| Effective area of rear suspension airbag \( A_{or} \)/m\(^2\)              | 0.0905    |
| Polytropic index \( n \)                                                  | 1.33      |
| Vehicle speed \( v \)/km • h\(^{-1}\)                                     | 41        |
| Front suspension mass \( M_f \)/kg                                        | 594.8     |
| Rear suspension mass \( M_r \)/kg                                         | 290.2     |
| Relative damping ratio \( \zeta \)                                        | 0.3       |
| People and seat mass \( m_{c} \)/kg                                       | 53        |
| Stiffness of the seat \( k_{c} \)/N • m\(^{-1}\)                          | 19030     |
| Damping coefficient of the seat \( c_{c} \)/N • s • m\(^{-1}\)            | 170       |
| Rear wheel mass \( m_{tr} \)/kg                                           | 210       |
| Stiffness of rear wheel \( k_{tr} \)/N • m\(^{-1}\)                       | 571420    |
| Rear wheel damping coefficient \( c_{tr} \)/N • s • m\(^{-1}\)            | 0         |
| Front wheel mass \( m_{tf} \)/kg                                          | 180       |
| Stiffness of front wheel \( k_{tf} \)/N • m\(^{-1}\)                      | 571420    |
| Front wheel damping coefficient \( c_{tf} \)/N • s • 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 • 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 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 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.

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

| \( P_0 \) / Pa | \( a_w \) / (m/s²) |
|-------------|------------------|
| 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          |
Table 4 reflects the relationship between the seat acceleration RMS value $a_{w}$ and the initial air pressure $P_0$ of airbag. 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, in order to optimize the ride comfort of the vehicle, this paper proposes a Method for determining accurate initial air pressure range of air suspension airbag based on vehicle ride comfort simulation analysis. Through simulation and calculation, the main conclusions are as follows:

The five-degree-freedom vehicle model established in this paper can fully reflect the vibration characteristics of the vehicle. Using random road excitation, air suspension parameters and other relevant vehicle parameters as inputs, the five-degree-freedom vehicle Simulink model can simulate the road roughness excitation (Figure 9) and the vibration displacement signal, speed signal and acceleration signal of each part of the vehicle. As is shown in Figure 8, the Simulink model can still output displacement, velocity and acceleration signals of other parts such as body, wheel and centroid. This paper only selects the person and the seat acceleration signal to analyse and research. Displacement signal, velocity signal and acceleration signal of other parts can also be used as research objects in other fields.

There is an optimal initial air pressure of the airbag to maximize the vehicle ride comfort. 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 maximizing the vehicle ride comfort, which is consistent with the expected result of this paper.

The method proposed in this paper can obtain a more accurate initial air pressure range of the airbag. The optimal initial air pressure range of the vehicle airbag is between 14–16kPa (Figure 19). 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 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.

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. However, if the selected pressure gradient is too small, the workload simulated and calculated using the method proposed in this paper will be too large. So the models and method of this paper need to be optimized.

References

[1] S Xiong, W Bao, Calculation and Selection of Air Suspension System Parameters. Mechanical Manufacturing, Page 8-10, 07(2008).

[2] X Li, Research and Simulation Analysis of Dynamic Characteristics of Single Air Chamber Air Spring, Northeastern University, Page 89(2013).

[3] J Xie, Q Zhang, Simulation Analysis of Vehicle Ride Comfort Based on Simulink, Electromechanical Technology, Page 14-18, 01(2013).

[4] H Liu, W Zhou, J Chen, Vehicle Ride Simulation and Optimization Based on Five-degree-freedom Vehicle Model, 33rd China Control Conference, Page 5(2014)

[5] H Zheng, Standard Road Surface Reconstruction Based on Harmonic Superposition Method, Mechanical Research and Application, 06(2014).

[6] B Zhang, Vehicle-Road System Coupling Vibration Analysis and Ride Comfort Evaluation, Central South University, Page 156(2013).

[7] H Zhang, W Yang, Evaluation Method of Road Flatness Based on Human-vehicle-road Five-degree-freedom Vibration Model, Journal of Transportation Engineering, Page 16-22, 04(2010).

[8] C Liu, Study on The Transfer Function of Eight-degree-freedom Vehicle Model, Journal of Gansu Agricultural University, Page 113-117, 03(2006).

[9] Z Yu, Automotive Theory, Mechanical Industry Press(2000).