The Comfort Simulation of Double-wheel Intelligent Vehicles Considering Human Bodys

Zhendong Gao¹³, Xin Chen¹, Jing Hou¹³, Zhangxi Lin¹, Shunya Lv¹³ and Bin Hong²*

¹ School of Mechanical Engineering, Tianjin University, Tianjin, China
² Internal Combustion Engine Research Institute, Tianjin University, Tianjin, China
³ Tianjin Tianbo Science & Technology Co., Ltd., Tianjin, China

*Corresponding author email: hongbin@tju.edu.cn

Abstract. In this paper, aiming at the self-developed double-wheel intelligent vehicle, a comfort simulation considering the human two-DOF (degree-of-freedom) model was conducted. Based on the analysis of the human body response to the vibration, the dynamic model of vehicle random vibration is used to establish a five-DOF human-seating-road ride dynamic model combined with MATLAB/Simulink software. Through the simulation of the road comfort test under the excitation of filtered white noise, the ride comfort analysis of the intelligent vehicle was realized.

1. Introduction

Comprehensive performance of the vehicle, including ride qualities, is essential of great value in practice. Electric vehicles in the process of riding caused by the vibration, the road uneven internal motor, the existence of the drive train and the wheel rotating parts also will arouse the vibration of the vehicle, the significance of comfort is to keep vibration and impact within certain boundaries. How to control the vibration of the automobile and improve comfort have become the focus of designers and manufacturers. Meanwhile, the development of virtual prototype technology and modern control technology can accurately predict and evaluate the ride of the automobile in the design stage, shortening the design cycle and reducing the production cost.

Based on the vibration source of the vehicle, the human body is combined with 1/4 vehicle model in such aspects as the suspension performance parameters, achieving a lot of beneficial results. Many scholars discuss that in the single-wheel model considering human factors, the human body can be simplified into a single degree of freedom model [1]. However, the human body, as a multi-degree of freedom mode, not only has the quality but also has certain damping and stiffness.

Aiming at the field of vehicle ride comfort simulation, passengers are rarely taken into account in the past vehicle ride comfort simulation of road surface model, a dynamic simulation model can be built to simulate the ride comfort of wheels, suspension system, seats, and human body under the excitation of different speeds and road surfaces. Meanwhile, the simulation results are analyzed. MATLAB software is used to develop a set of vehicle ride comfort simulation software, which can accurately analyze the vehicle ride comfort.

2. Vibration Source Analysis

As the main excitation of the vibration, pavement excitation is used to describe the degree of road surface fluctuation, it directly affects the accuracy of automobile vibration analysis results. As a time-
domain analysis method, the filtered white noise numerical simulation method overcomes the limitation that the frequency-domain analysis is suitable for a linear system, it is more suitable for the actual situation of automobile. It is a kind of pavement roughness simulation method commonly used in the time-domain modeling field.

However, previous studies [2-4] only changed the speed and amplitude of the road surface model, without changing the frequency of the road surface input signal. Therefore, the road surface model generated by the filtered white noise cannot reflect the natural frequency characteristics of the vehicle vibration system. For this, literature [5] proposed that in the application of the pavement white noise formula, the noise power, sampling frequency, and seeds of the band-limited white noise module should be set when the speed is changed.

3. Human Body's Response to Vibration

The ultimate purpose is to obtain good comfort performance of passengers. Therefore, it is necessary to understand the vibration characteristics of the human body and its physiological response to vibration. According to the study, the vibration common point of the human body is close to 4-6Hz, and the vibration point before and after is about 2Hz.

Meanwhile, when conducting the vehicle's comfort modeling, it should consider the influence of the human biology model. Aiming at the biological mechanics model, western scholars conducted a lot of beneficial attempts, including establishing the biological model of different degrees of freedom. We realize that Chinese and Westerners have an obvious difference in body weight and body size, their dynamic parameters of the body are not identical, therefore set up our own physical biology model appears more important.

The parallel 2-DOF Chinese human body biological model (figure. 1) has been verified to conform to Chinese’s physique, and this model is adopted for human body modeling in this paper.

![Figure 1. Two-degree-of-freedom Chinese human biomechanical vibration model](image)

4. Establishment of Vehicle Model

In comfort research of vehicle, what people are concerned about is the acceleration of each point on the auto body. It usually includes the x, y, z value of three directions. One of the most important issues- the z-direction is perpendicular to the direction of the acceleration value. To the developed intelligent vehicle, the analysis found that the quality of the vehicle body distribution coefficient is near to 1. With independent suspension units in the body, the vibration is independent of each other. In the ultra-low weight design, the quality of the automobile main distribution of 90% in the backseat, and left and right sides are symmetrical. It will be a good solution to solve the concerned vehicle ride comfort by using a quarter car body modeling variable.

Ultra-lightweight technology makes the seat, the human body account for a large part of the car quality, so we have to consider the human body-seat. To sum up, the four mass-five degrees of freedom single-wheel vehicle model established includes body parallel and two degrees of freedom, vertical degrees of freedom of seat, vertical degrees of freedom of car body, and vertical degrees of freedom of wheel.

Meanwhile, the corresponding simplification is made for the vehicle model:

- Symmetrical automobile structure and symmetrical mass distribution;
• Mechanical properties of tires are simplified to general springs;
• The automobile vibration system is linear;
• Front and rear suspension shock absorbers and spring stiffness are taken as constants;
• The simplified structure is shown in figure 2 (right).

Figure 2. 3D model of vehicle (left) and 1/4 vehicle model considering human and seats (right).
In Figure 2, the non-spring load mass (wheel) is described by \( m_1 \), the spring-load mass (vehicle body) is described by the motor mass and the 1/4 body mass. The rear suspension is described by the spring of stiffness \( k_2 \) and the rear damper with damping coefficient \( c_2 \). The rear tire is described by the spring of stiffness \( k_1 \). The seat is described by the spring with stiffness \( k_3 \) and damping coefficient \( c_3 \). The human body is described by a two-DOF human model where parameters include \( m_5, m_4, k_5, k_4 \) and \( c_5, c_4 \). The system is driven by the road incentive \( q(t) \) of the rear wheel. The vibration freedom of the system is 5, which composes of the vertical displacement \( z_1 \) of the non-spring load mass center, the vertical displacement \( z_2 \) of spring-load mass, the vertical displacement \( z_3 \) of the seat and the vertical displacement \( z_4, z_5 \) of the human body mass.

5. The Differential Equation Solution of Vehicle Vibration
According to the above mechanical model, the differential equation of vehicle vibration is established as follows:

\[
m_i \ddot{z}_i = -k_i(z_i - z_3) - c_i(\dot{z}_i - \dot{z}_3), i = 4,5
\]

\[
m_3 \ddot{z}_3 = \sum_{i=4}^{5}(k_i(z_i - z_3) + c_i(\dot{z}_i - \dot{z}_3) - k_2(z_2 - z_3) - c_2(\dot{z}_2 - \dot{z}_3)), i = 4,5
\]

\[
m_2 \ddot{z}_2 = k_2(z_3 - z_2) + c_2(\dot{z}_3 - \dot{z}_2) - k_1(z_2 - z_1) - c_1(\dot{z}_2 - \dot{z}_1)
\]

\[
m_1 \ddot{z}_1 = k_1(z_2 - z_1) + c_1(\dot{z}_2 - \dot{z}_1) - k_1(z_1 - q)
\]

Table 1. Vehicle simulation parameters

| Rear wheel \( m_1 \) (kg) | Vehicle body \( m_2 \) (kg) | Seat mass \( m_3 \) (kg) | Human parameter \( m_4 \) (kg) | Human parameter \( m_5 \) (kg) | Tire stiffness \( k_1 \) (N.m\(^{-1}\)) | Vehicle stiffness \( k_2 \) (N.m\(^{-1}\)) |
|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 5.4                      | 42.4                     | 22                       | 11.1                     | 33.7                     | 200000                   | 200000                   |
| Seat stiffness \( K_3 \) (N.m\(^{-1}\)) | Human parameter \( K_4 \) (N.m\(^{-1}\)) | Human parameter \( K_5 \) (N.m\(^{-1}\)) | Vehicle damping \( c_2 \) (Ns.m\(^{-1}\)) | Seat damping \( c_3 \) (Ns.m\(^{-1}\)) | Human damping \( c_4 \) (Ns.m\(^{-1}\)) | Human damping \( c_5 \) (Ns.m\(^{-1}\)) |
| 100                      | 50514                    | 32718                    | 1500                     | 7500                     | 543                      | 714                      |

The simulation is based on the parameters shown in table 1. Meanwhile, the input mathematical model of filtered Gaussian white noise pavement is established:
\[ \dot{q} = -w_0 q(t) + 2\pi n_0 \sqrt{G_0(n_0)} u W(t) = -2\pi n_0 w_0 q(t) + 2\pi n_0 \sqrt{G_0(n_0)} u W(t) \tag{5} \]

Where \( n_0 \) is the lower cutoff spatial frequency with a value of 0.11 m\(^{-1}\), \( W(t) \) is the Guass white noise with zero mean value, \( q(t) \) is the road random uneven displacement, \( G_0(n_0) \) refers to using C level road roughness coefficient with value \( 256 \times 10^{-6} \).

It is worth noting that the three settings (noise power, sampling frequency and seed) of the bandlimited white noise module had a great influence on the simulation results. Since the time-domain simulation model needs unilateral power spectral density for a bandlimited white noise output, the noise power spectrum density is set to 0.5. The sampling time of the bandlimited white noise module is set to 1/10 u.

For the road surface generated by this method, the amplitude of the height course is exactly the same under different speeds. Additionally, the space state of the road surface height course is independent of the speed, and the time-frequency component of the road surface input is also proportional to the speed under different speeds, which conforms to the real situation.

The road white noise simulation model is established in Simulink, and the simulation graph of 10s is carried out, as shown in figure. 3. The simulation results show that the vibration amplitude of the intelligent vehicle under the C-level national standard road is less than 0.01m at the speed of 20km/h in Fig. 4, which is in line with the reality and standard.

6. Vehicle Vibration Dynamics Simulation Model
According to the differential equation form of the single-wheel 5-DOF vehicle dynamics model established in the previous section, the simulation model as shown in figure. 5 below is established in Simulink.

---

**Figure 3.** Time-domain simulation model of road roughness.

**Figure 4.** Simulation result of road roughness.
Figure 5. Vehicle vibration dynamic simulation model. After the input of various mass parameters, damping and stiffness coefficients, 10s simulation analysis was carried out. The figures of acceleration and displacement of human body, seat and car body were selected as shown in figure 6 and figure 7 below.

It can be seen from the analysis that after the two-stage damping system, the time-domain simulation acceleration peak of human body parameters is controlled between 6-8.2, the vibration acceleration at the seat is controlled between -5.2 and 7.4, and the time-domain simulation acceleration of the car body is controlled between -6.7 and 8.5.

The vertical displacements of the colleagues have played a good shock absorption effect, and the displacement is controlled between -0.05 and 0.08. Therefore, the design of the intelligent vehicle basically meets the requirements of human comfort in the time domain.

Figure 6. Time-domain simulation results (a-b represents the acceleration human body parameter 1 and 2, seat and car body respectively).
Figure 7. Time-domain simulation results (a-b represents the displacement of human body parameter 1 and 2, seat and car body of respectively).

7. Conclusion
Combined with the comprehensive analysis of intelligent vehicle smoothness, a 5-DOF single-wheel vehicle dynamics model was established. By applying the parallel 2-DOF model, the vertical displacement acceleration of the system model was obtained by simulation. From the simulation results, it can be seen that the vibration frequency of the car in the figure indicates that the subjective feeling of the intelligent car is comfortable, that is, the parameters such as the suspension seat adopted show good comfort.

References
[1] Yin, J. , Chen, X. , Lixin, W. U. , & Liu, Y. .(2017). Simulation method of road excitation in time domain using filtered white noise and dynamic analysis of suspension. Tongji Daxue Xuebao/Journal of Tongji University, 45(3), 398-407.
[2] Duan Huming;Shi Feng;Xie Fei;Zhang Kaibin. Review on research of road roughness. , 2009, 28(9): 95-101.
[3] Gao, J. H. , Hou, Z. C. , & Amp, H. L. . (2011). Vertical vibration characteristics of seated human bodies and a biodynamic model with two degrees of freedom. Science China Technological Sciences, 54(10), 2776-2784.
[4] Ye Dong. Study on Vehicle Suspension System and Vehicle Ride Comfort [D]. Shanxi: Shanxi University of Science&Technology, 2017.
[5] Yu Zhisheng. (2009). Automobile theory. 5th edition. China+ Machine Press.