

Analysis of the Transmission Characteristics of Electric Vehicles with Active Suspension under Different Postures

Bin Wang, Zhen Wu^{*}, Zhiqiang Zhao

China Automotive Research Institute Automobile Inspection Center (Tianjin) Co., Ltd. Tianjin 300000, China

^{*}Corresponding author

Abstract: The development of automobile technology has made ride comfort and handling the core of design. The limitation of traditional passive suspension systems is that they cannot be adjusted to adapt to changing driving conditions. The application of air spring suspension technology provides a solution by adjusting the air pressure to change the suspension stiffness and height. The system can maintain a constant bias frequency under different loads, enhance smoothness and stability, automatically adjust to different road conditions, reduce vibration, and improve comfort. This study uses a swept frequency excitation test to measure the acceleration response at different positions of the vehicle and analyze the transfer characteristics. The results show that the air spring suspension can significantly reduce the body acceleration and tire dynamic deformation under various working conditions, confirming its advantages in improving ride comfort and handling stability. These findings provide experimental support for the design of air spring suspension and promote its widespread application in modern automobiles.

Keywords: Air spring suspension, swept frequency excitation test, four poster test rig.

1. Introduction

With the rapid development of economy and the improvement of people's living standards, cars have become an indispensable means of transportation in modern society. In the rapid development of the automobile industry, ride comfort, as one of the important indicators to measure automobile performance, has been increasingly valued by manufacturers and consumers. NVH (Noise, Vibration, Harshness) is a comprehensive indicator reflecting the dynamic characteristics of a car, in which the vibration part directly affects the comfort of the passengers. Therefore, as one of the evaluation indicators of NVH performance, the ride comfort of the car mainly solves the problem of discomfort caused by vibration to the passengers, and its research has important practical significance.

In the field of automobile ride comfort research, domestic and foreign scholars have done a lot of work. For example, Zhang Jianwen et al. reviewed the development status of air suspension systems and pointed out that air suspension has been widely used in high-end buses and trucks due to its excellent vibration reduction performance [1]. Wang Yansong et al. studied the influence of suspension parameters on ride comfort by establishing a nonlinear model of the vehicle vibration system [2]. These studies provide theoretical basis and technical support for the improvement of automobile ride comfort.

This paper aims to analyze the transfer characteristics of the vehicle under different vehicle postures through experimental research methods. The study will use a wheel coupling test bench to sweep the vehicle and measure the sweep signal response of the key parts of the vehicle. By calculating and analyzing these response signals, the transfer characteristic curve is obtained, thereby realizing the quantitative analysis of the vehicle transfer characteristics under different vehicle postures. This study can not only provide important data support for the design and

optimization of the vehicle suspension system, but also provide a theoretical basis for improving the driving safety and ride comfort of the vehicle. Through this study, we hope to have a deep understanding of the changing laws of the dynamic response of the vehicle under different postures, and then provide scientific guidance for the improvement and control of the vehicle dynamic performance.

2. Theoretical Part

2.1. Vehicle frequency sweep test

The vehicle frequency sweep test is a dynamic test method that aims to evaluate the vibration characteristics of the vehicle at different frequencies. The test applies sinusoidal wave excitation to the vehicle within a certain frequency range to stimulate the vehicle's structural mode and obtain the vehicle's dynamic response data. During the test, the vehicle's response data (such as acceleration and displacement) is collected in real time and used to analyze key dynamic parameters such as the vehicle's natural frequency, damping ratio and vibration mode.

The theoretical basis of frequency sweep test is linear or logarithmic frequency sweep control, in which the frequency changes according to a preset rule to cover the possible operating frequency range of the vehicle. The key to the test is to accurately control the excitation signal to ensure that the response of the actuator is consistent with the target excitation signal, which is usually achieved through iteration. By analyzing the frequency response function, the modal parameters of the vehicle can be identified, which are crucial for vehicle design, performance evaluation and fault diagnosis.[3,4,5]

The results of the frequency sweep test can be used to evaluate the ride comfort and ride comfort of the vehicle, optimize the suspension system design, and predict the dynamic behavior of the vehicle in actual driving. This test method has wide applicability in engineering applications and

provides an effective tool for evaluating and optimizing vehicle dynamic performance.

When analyzing the vibration characteristics of a vehicle suspension system and conducting wheel coupling bench tests, a sinusoidal road surface is usually used as an excitation input to examine the suspension response characteristics. [3] There are mainly two types of excitation signals: a sinusoidal fixed-frequency road surface (the frequency of the sinusoidal function does not change with time) and a sinusoidal swept-frequency road surface (the frequency of the sinusoidal

function gradually increases over time).

Sine constant frequency road excitation is mainly used to analyze the response characteristics of the vehicle suspension system at a certain frequency, and can be used to obtain the two resonance frequencies of the vehicle. An example of a time domain curve of sinusoidal constant frequency road excitation is shown in the figure:

$$x_r(t) = A \sin(2\pi ft + \theta)$$

Where: A is the excitation amplitude, f is the excitation frequency, θ and is the initial phase.

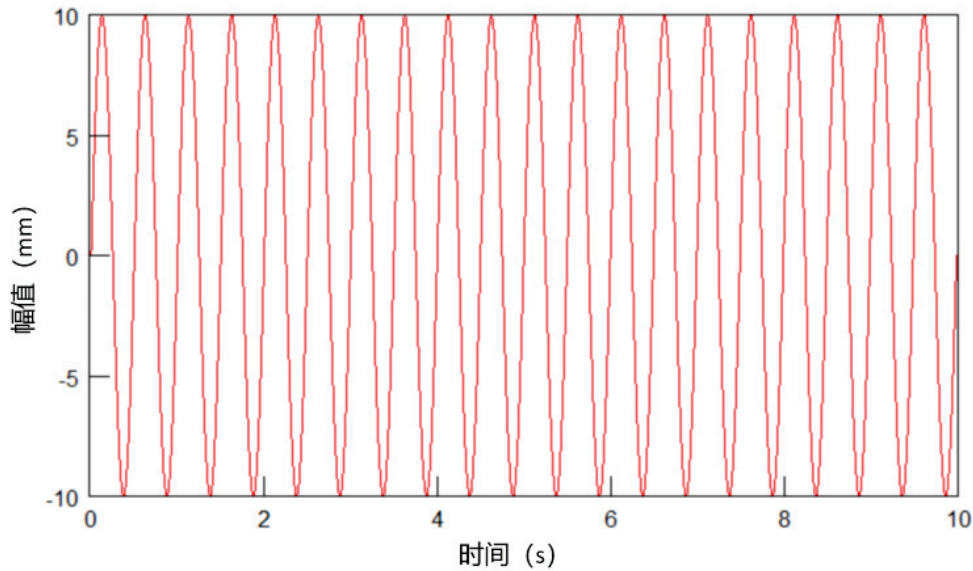


Figure 2.1 Time domain curve of constant frequency sinusoidal road excitation

Sine swept road excitation can be used to analyze the vibration frequency response characteristics of the vehicle suspension system.

$$x_r(t) = A \sin(2\pi\lambda t^2 + \theta)$$

Where: λ is the sweep rate, $f = \lambda t$, indicating that the frequency of the sinusoidal road excitation increases linearly with time. An example of a time domain curve of a sinusoidal swept-frequency road excitation is shown in the figure:

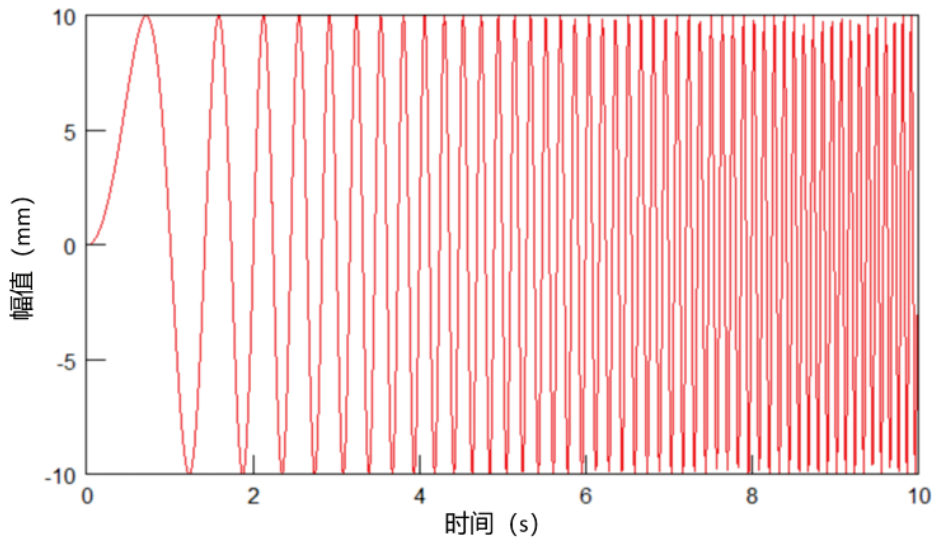


Figure 2.2 Time domain curve of frequency sweep sinusoidal road excitation

According to the frequency change law, the sine sweep test is divided into a linear sine sweep test and a logarithmic sine sweep test. This paper adopts the linear sine sweep test, so a brief introduction to the linear sweep is given. The linear sine sweep test refers to a sweep test in which the frequency of the excitation signal changes linearly. It is mainly used in the sine

slow sweep test for accurate identification of product modal parameters. For a system component such as a complete vehicle composed of complex parts, the sine slow sweep modal test is mainly used to analyze the vibration isolation characteristics of the suspension system [4,5].

This paper uses a constant-speed sweep frequency signal as

the excitation signal for the experiment [6]. The constant-speed sweep frequency input speed curve is shown in the

figure:

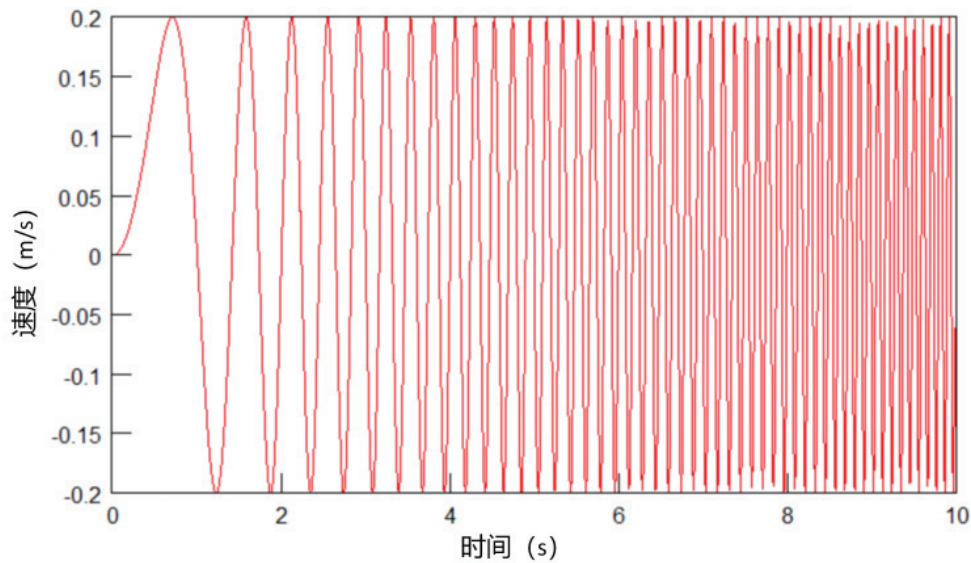


Figure 2.3 Constant speed sweep speed curve

2.2. Introduction and principle of four-poster test rig

The four-post bench test, also known as the four-post road simulation bench test, is a test method that simulates the impact of road loads on vehicles in an indoor environment. It is widely used in the automotive development process to evaluate the fatigue damage and durability of vehicle components. This test method can simulate the main road loads efficiently and at a low cost. There is a certain proportional relationship between the load pressure and the input load amount of each component of the vehicle. Therefore, by accurately obtaining the input signals and reproducing these signals on the bench, key control of the vehicle fatigue test can be achieved.[6,7]

The working principle of the four-column bench test mainly includes the following steps:

a) Road load spectrum collection: Acceleration sensors are placed at the four wheel centers of the test vehicle to collect the target road load value. The vehicle drives on the specified test road surface, and the acceleration sensors record the road load data.

b) Edit road spectra: Use technologies such as RPC (remote parameter control) to edit the collected road spectra, remove abnormal signals and time periods with minimal fatigue damage to improve test efficiency.

c) Test system modeling and inversion: After the system generates a random signal X and the hydraulic cylinder is executed, the data acquisition equipment recovers the wheel center acceleration signal Y. The transfer function of the test system is determined by X and Y, and the inverse function is calculated, so that the drive signal X can be generated by the target signal Y.

d) Iteration: The inverse function of the transfer function of the target signal is used to obtain the first drive signal of the test system. After the drive signal is executed, the real-time wheel center acceleration signal is compared with the road spectrum, and the difference is used to correct the drive signal. Repeat the iterative process until the acceleration signal can reproduce the road spectrum well, that is, the iterative process

is completed.

e) Output signal: The test bench system outputs the vehicle wheel center acceleration signal, the actuator cylinder displacement drive signal and the actuator cylinder's actual displacement response signal .

2.3. Vehicle sweep frequency test

The vehicle sweep frequency test is an experimental method used to evaluate the dynamic characteristics of a vehicle. Its core principle is to apply a sinusoidal excitation force to the vehicle within a certain frequency range to stimulate the various modes of the vehicle, thereby obtaining the dynamic response data of the vehicle. These data can be used to analyze the vibration characteristics of the vehicle, such as natural frequency, damping ratio, vibration mode, etc. The following are several key steps and principles of the vehicle sweep frequency test:

a) Test preparation: Determine the test object, that is, the vehicle that needs to be subjected to the sweep test ; select appropriate measurement points, usually including key structural parts of the vehicle, such as the suspension system, body, chassis, etc. Install necessary sensors, such as accelerometers, displacement meters, force sensors, etc., to measure the vehicle's response.

b) Excitation signal generation: Generates a sinusoidal excitation signal whose frequency changes at a certain rate within a preset range (usually the frequency range of interest of the vehicle). This process is called frequency sweep.

c)Excitation application: The excitation signal is applied to the vehicle through an actuator (such as an electric or hydraulic vibration table), which can be a single-axis or multi-axis simultaneous excitation ;

d) Data collection: During the excitation process, the vehicle's response data is collected in real time, including acceleration, displacement, speed, etc.

e) Frequency Response Function (FRF) Analysis: Use the acquired data to calculate the frequency response function, which is the relationship between the vehicle response and the excitation, usually expressed as a function of amplitude and phase as a function of frequency.

f) Modal parameter identification: By analyzing the frequency response function, the modal parameters such as the vehicle's natural frequency, damping ratio and vibration mode are identified.

g) Data processing and analysis: Further process the collected data, such as Fourier transform, to obtain information in the frequency domain ; analyze the dynamic response of the vehicle at different frequencies and evaluate the dynamic performance of the vehicle.

The purpose of the vehicle sweep frequency test is to simulate the vibrations of various frequencies that the vehicle may encounter during actual driving. By analyzing these vibration responses, the dynamic performance of the vehicle can be evaluated and optimized, such as comfort, handling stability, and structural safety. In addition, the results of the sweep frequency test can also be used for modal analysis in the vehicle design stage to avoid structural resonance and improve the overall performance of the vehicle.

3. Test Verification

3.1. Test setup

This study selected a vehicle model equipped with air spring suspension from a certain independent brand car company, placed the whole vehicle on a four-post test bench, and pasted acceleration sensors on the four-post tray, vehicle axle head, wheel arch, and seat rail. Table 3.1 shows examples of sensor pasting locations. An eDAQ data acquisition device was selected and connected to collect data from the acceleration sensor. Table 3.2 shows a schematic diagram of the data collection results of the acceleration of some installation positions under the same-direction excitation of the front axle in comfort mode. The four-post test bench provides a 0.5-40Hz constant-speed sweep frequency excitation signal. The operating condition setting combination is shown in Table 3.3.

Table 3.1 Schematic diagram of sensor layout

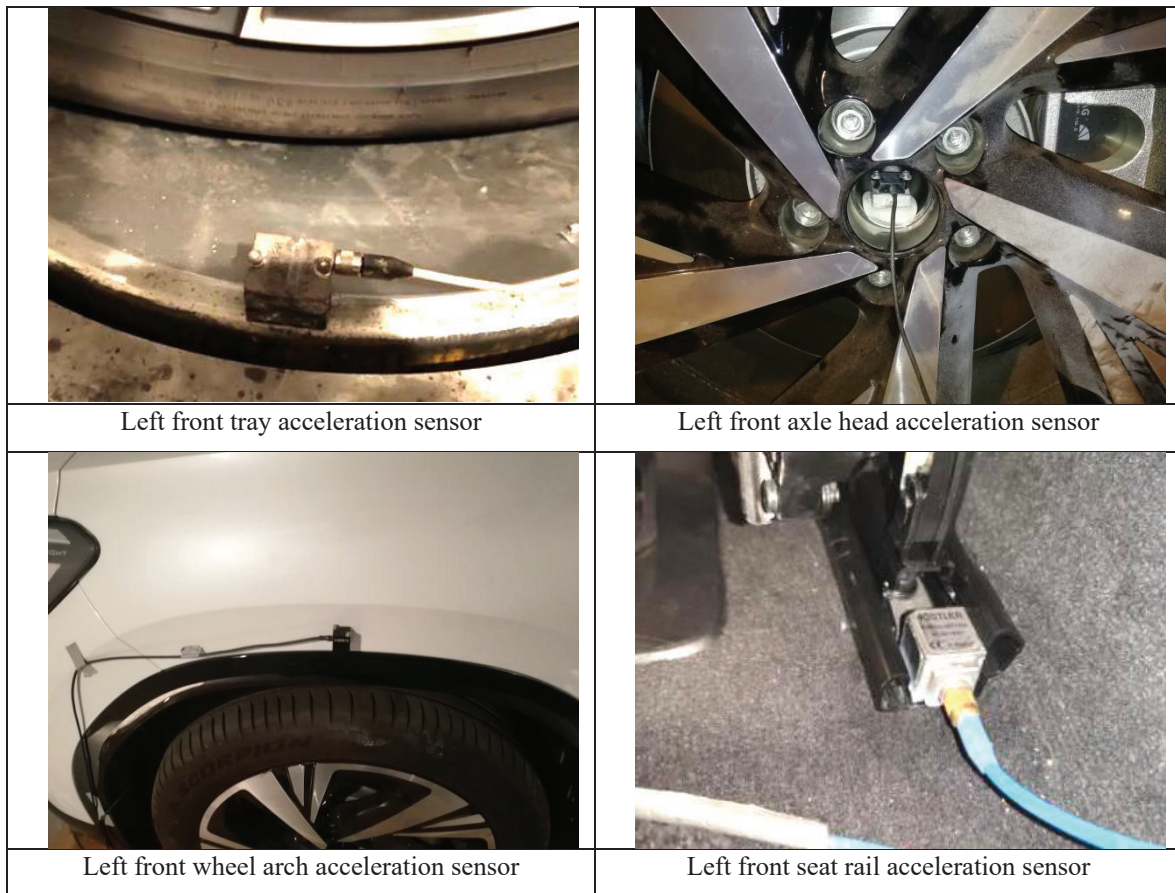
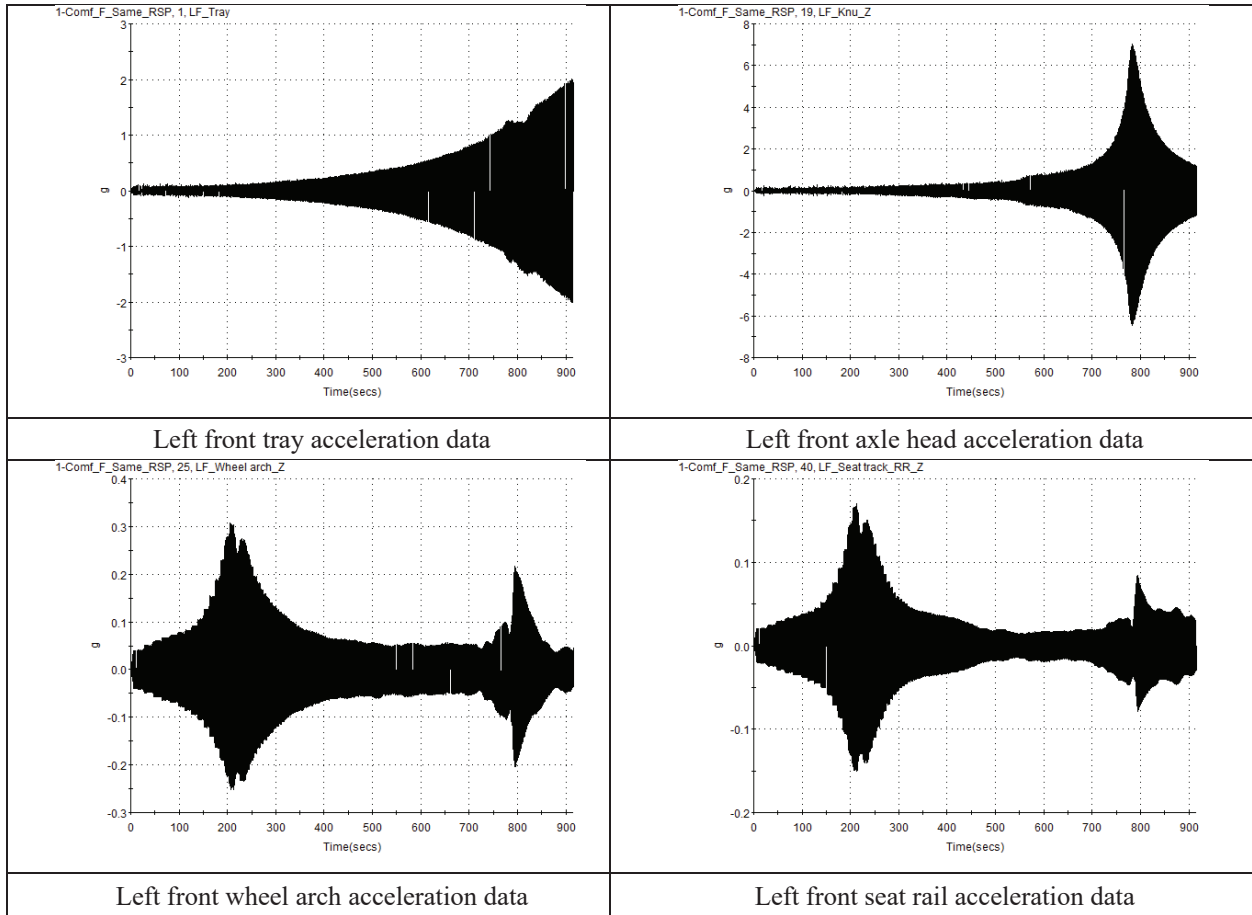


Table 2.3 Working condition setting combinations

| Incentive method Vehicle status | Comfort Mode | Sport Mode |
|------------------------------------|-------------------|--------------------|
| Front axle same direction | Comf F Same RSP | Sport F Same RSP |
| Rear axle same direction | Comf R Same RSP | Sport R Same RSP |
| Front axle reverse | Comf F Invert RSP | Sport F Invert RSP |
| Rear axle reverse | Comf R Invert RSP | Sport R Invert RSP |

Table 3.2 Partial position acceleration sensor data



3.2. Data processing and analysis

The data of different channels in the acceleration data are processed to obtain the transfer function between channels. The acceleration data of the four-post pallet and the data of

the axle head are processed to obtain the transfer characteristics of the tire. If the transfer characteristics under different states have good consistency, it means that the data is valid. The above conclusion can be clearly drawn from the transfer characteristic diagram in Figure 3.1.

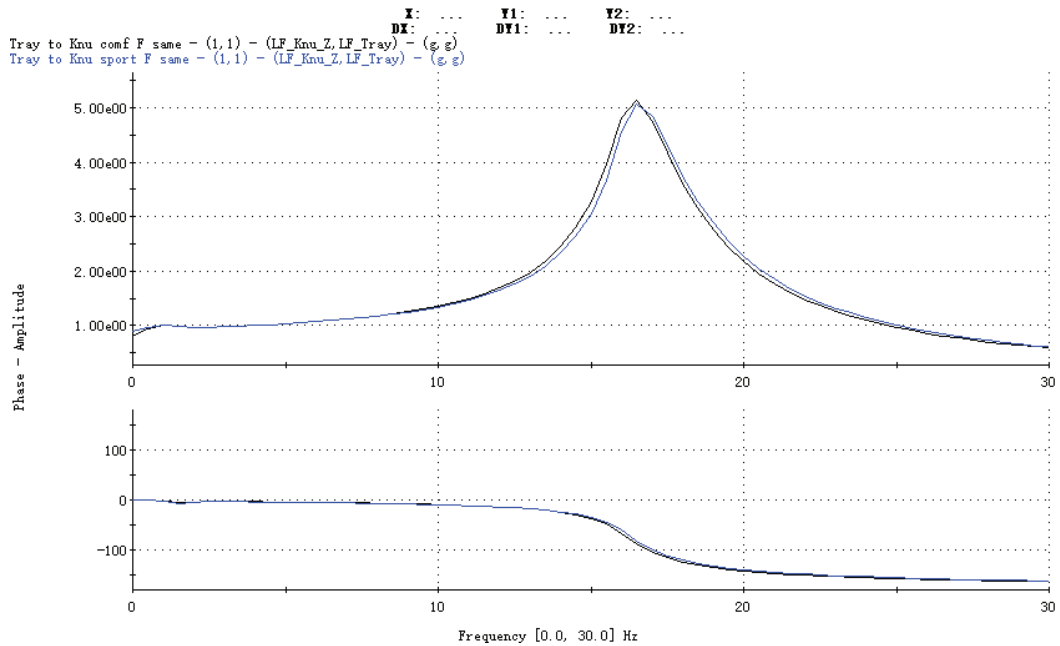


Figure 3.1 Transfer characteristics of tires under different vehicle conditions

3.2.1. Comparison of transfer characteristics of vehicles in different states under front axle co-directional excitation conditions.

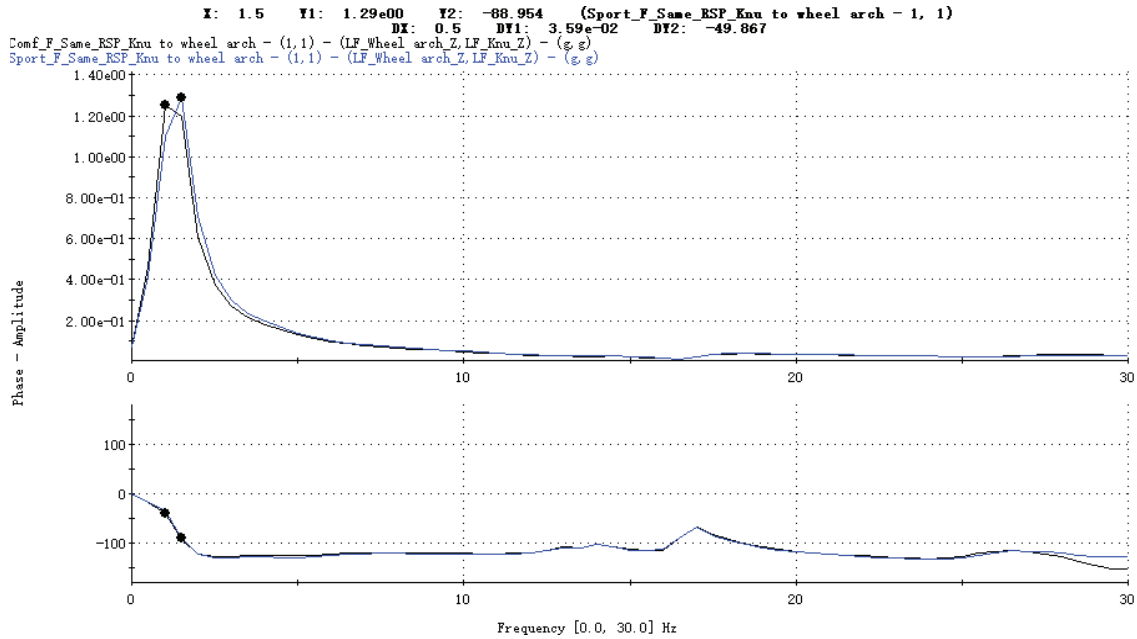


Figure 3.2 Transfer characteristics from axle head to wheel arch

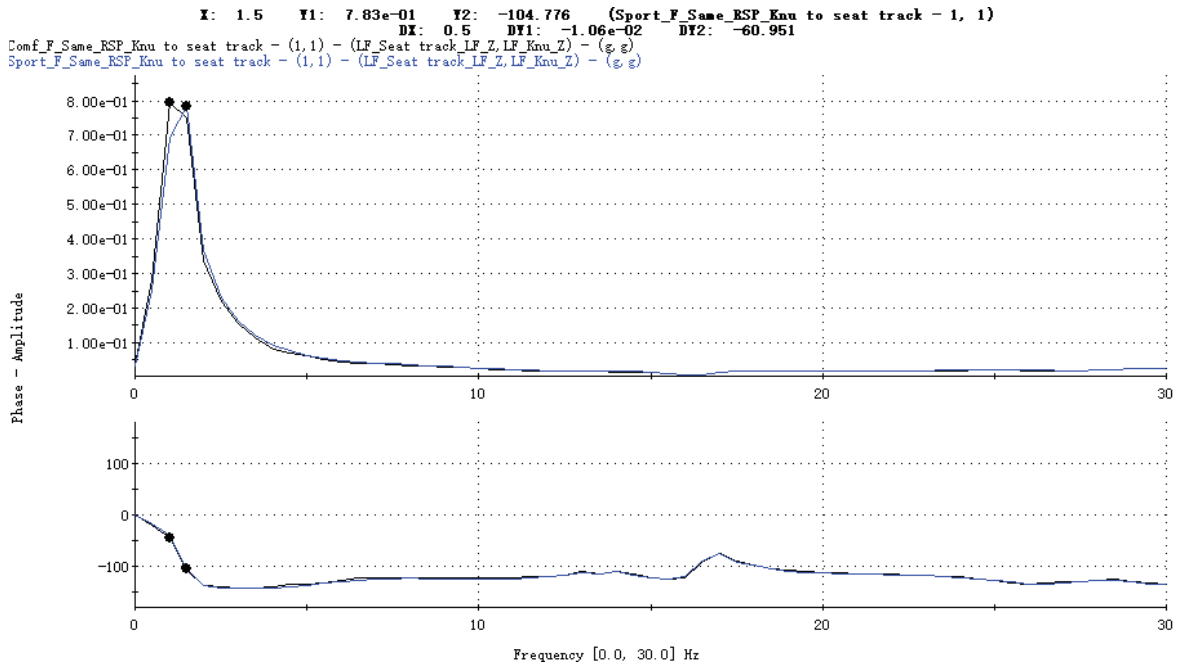


Figure 3.3 Transfer characteristics from axle head to seat rail

Since the energy is small when the frequency is higher than 30Hz, in the actual test data analysis, only the transfer characteristics within the range of 0-30Hz are analyzed. It can be clearly seen from Fig. 3.2 that for the front axle, in the comfort mode, the resonance point from the axle head to the wheel arch is low frequency, which is caused by the lower rigidity of the system. A similar conclusion can be drawn from Fig. 3.3, indicating that after the mode is changed, the whole

vehicle is not only changed in the height of the suspension, but also in the rigidity of the body, but from a quantitative perspective, the change is not significant.

3.2.2. Comparison of transfer characteristics of vehicles in different states under the same-direction excitation condition of the rear axle

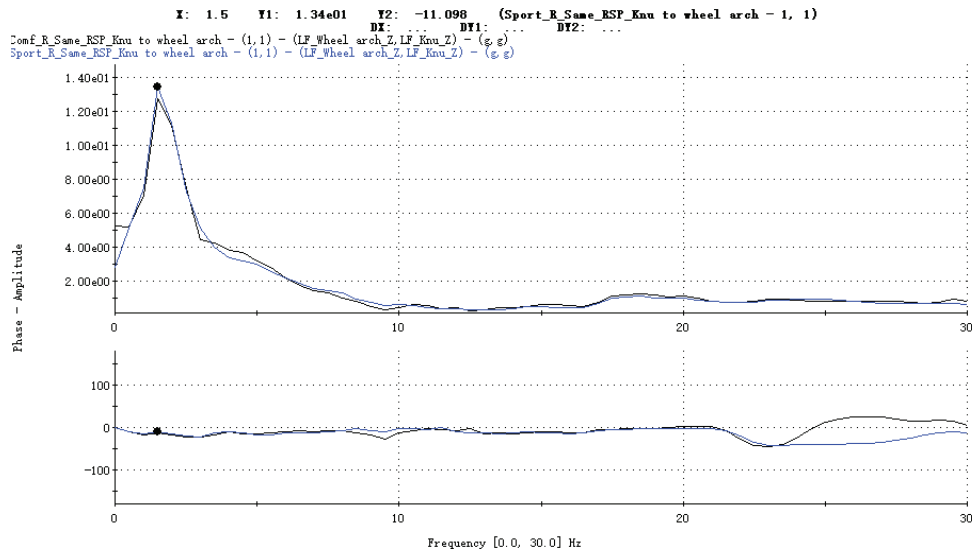


Figure 3.4 Transfer characteristics from axle head to wheel arch

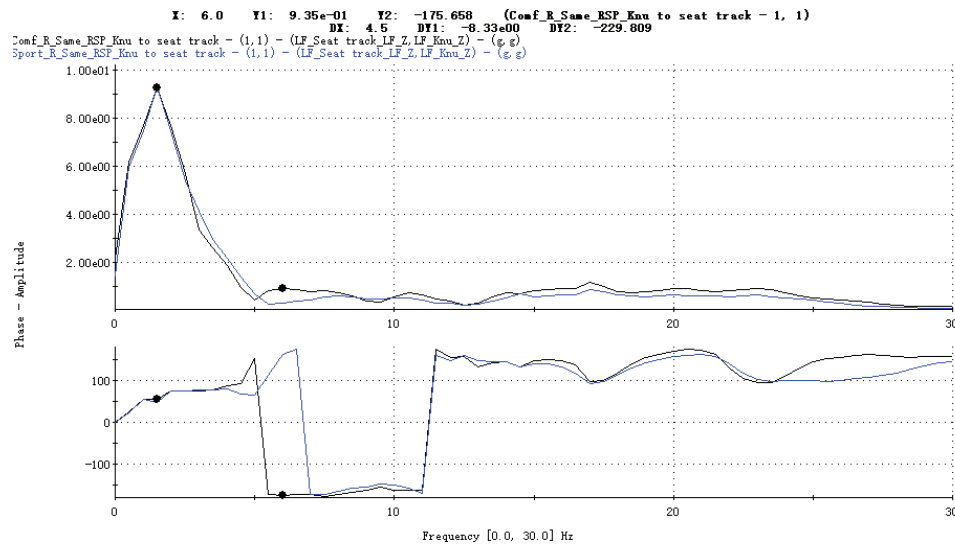


Figure 3.5 Transfer characteristics from axle head to seat rail

As can be seen from Fig. 3.4 and Fig.3.5, for the rear axle, the resonance points from the axle head to the wheel arch and seat rail are relatively consistent in different vehicle modes, indicating that the body rigidity has basically not changed. However, at around 5.5Hz, the transfer characteristics in the

sports mode show obvious lag in phase.

3.2.3. Comparison of transfer characteristics of vehicles in different states under front axle reverse excitation conditions

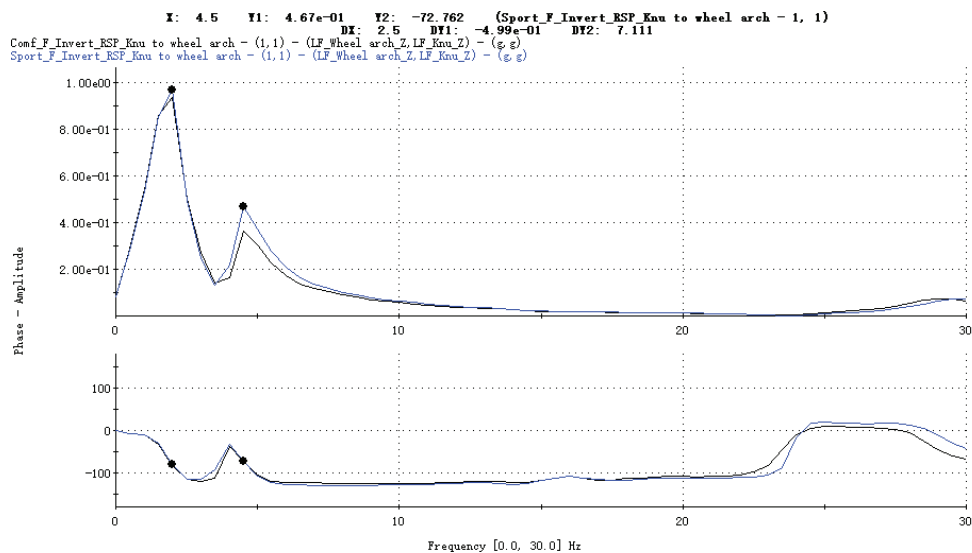


Figure 3.6 Transfer characteristics from axle head to wheel arch

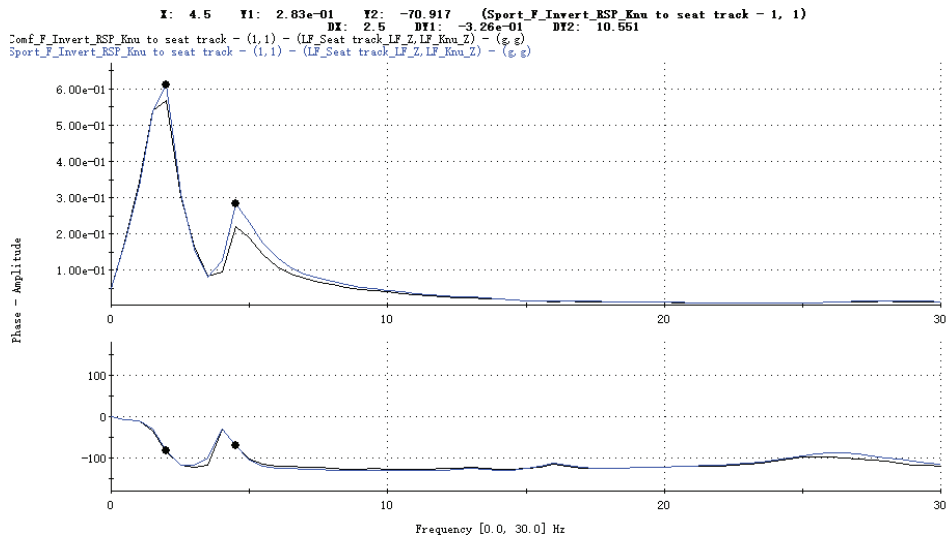


Figure 3.7 Transfer characteristics from axle head to seat rail

As can be seen from Figures 2.6 and 2.7, for the front axle, when the vehicle is in sport mode, the resonance points from the axle head to the wheel arch and seat rail are relatively consistent, indicating that the body rigidity at around 2 Hz has basically not changed. However, at around 5 Hz, the transfer characteristics in sport mode are significantly greater in amplitude than in comfort mode, indicating that the body

rigidity is enhanced in this mode and the high-frequency response of the chassis is strengthened.

3.2.4. 3 Comparison of transfer characteristics of vehicles in different states under rear axle reverse excitation conditions

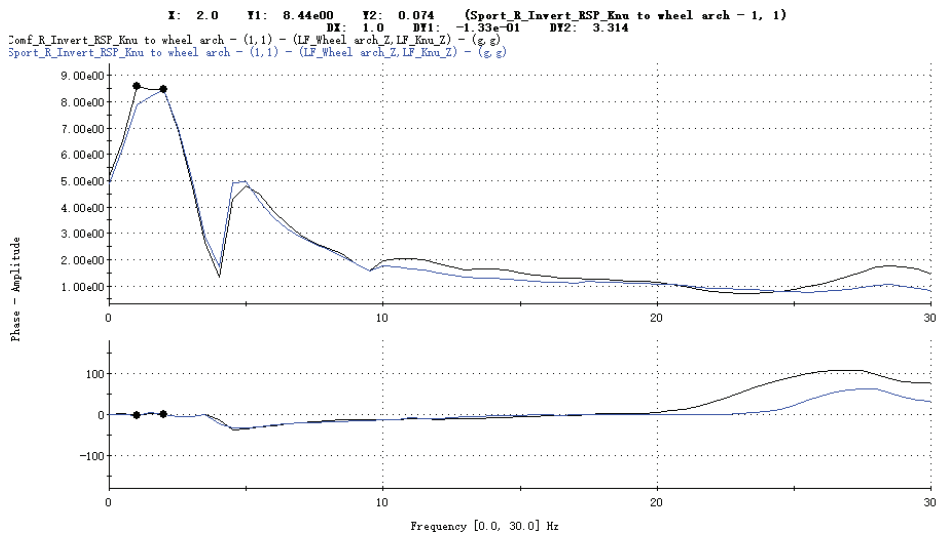


Figure 3.8 Transfer characteristics from axle head to wheel arch

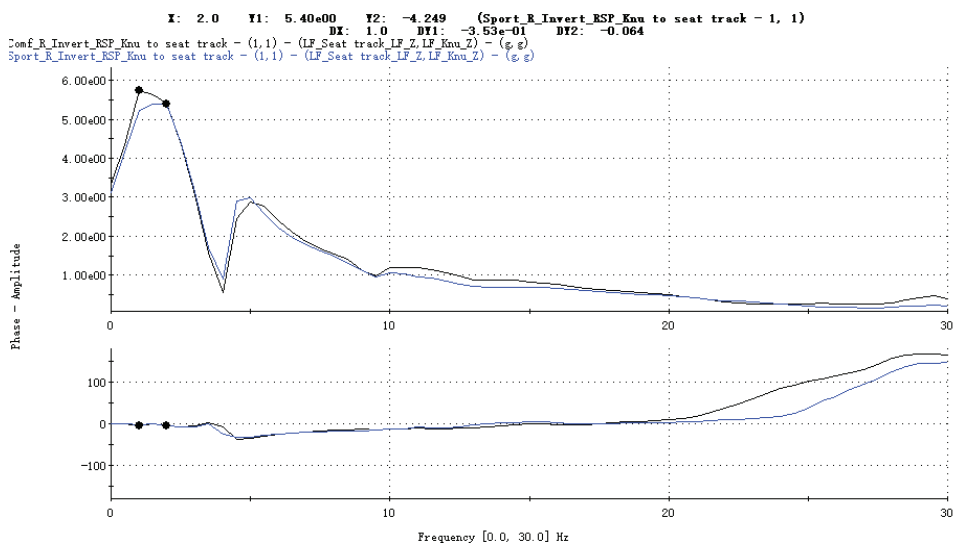


Figure 3.9 Transfer characteristics from axle head to seat rail

It can be seen from Fig. 3.8 and Fig.3.9 that for the rear axle, when the vehicle is in sport mode, the resonance points from the axle head to the wheel arch and seat rail are relatively consistent.

In summary, the transfer characteristics of the front axle change relatively obviously in both comfort mode and sport mode, while the rear axle data does not change obviously. After checking the vehicle structure, it is found that this is a rear-wheel drive model, and the rear suspension is structurally stiffer than the front axle. Therefore, switching vehicle modes has little effect on the vehicle's transfer characteristics.

4. Conclusion

Effect of suspension system on vehicle dynamic response: The study found that the transfer characteristics of the front axle changed significantly in comfort mode and sport mode, while the rear axle did not change much. This shows that the design and adjustment of the suspension system have a significant impact on the dynamic response of the vehicle, especially in different driving modes. The experimental results of this study provide experimental support for the design and optimization of air spring suspension, and also provide a theoretical basis for improving the driving safety and ride comfort of the vehicle.

a) Changes in body rigidity: In different modes, the vehicle's body rigidity also shows a certain degree of change, especially at the front axle. This change involves not only the adjustment of the suspension height, but also the change of the body rigidity, although from a quantitative point of view, this change is not significant.

b) Suspension characteristics of rear-wheel drive models: For rear-wheel drive models, due to the strong rigidity of the rear suspension structure, the switching of vehicle modes has

little effect on the transfer characteristics. This shows that the vehicle's driving mode and suspension structure design have a direct impact on suspension performance.

References

- [1] Bao Weining. Research on the Dynamic Simulation Analysis of Automotive Air Suspension and Its Control System [D]. Huazhong University of Science and Technology, 2011. DOI: 10.7666/d.d201528.
- [2] Wang Anzhu. Analysis and Improvement of Car Ride Comfort Based on Virtual Prototyping Technology [D]. Suzhou University, 2011. DOI:10.7666/d.y1909649.
- [3] Wang Bin, Zhan Yongxiao, Li Yao, et al. Research on the Influence of Sensor Position in Sweep Frequency Test on the Evaluation of Vehicle Ride Comfort [J]. Sensor Technology and Application, 2022, 10(2):9. DOI:10.12677/JSTA.2022.102031.
- [4] Wang Yingying, Bai Yang, Xu Xiaohui, et al. High-Precision Spectral Analysis Method for Structural Response in Sine Sweep Frequency Vibration Tests[J]. Spacecraft Environment Engineering, 2020, 37(6):9.
- [5] Pan Peng, Liu Jie, Dong Shuai, et al. Research on Vehicle Frequency Response Characteristics and Test Evaluation Indicators[J]. Automotive Science and Technology, 2023(6):6-10. DOI:10.3969/j.issn.1005-2550.2023.06.002.
- [6] Guan Ping, Yin Fenggen, Yao Lie. Feasibility Study on the Standard Spectrum of Four-Post Rig Test[J]. Shanghai Automobile, 2020. DOI:10.3969/j.issn.1007-4554.2020.10.13.
- [7] Zhao Lihui, Yang Peng, Weng Shuo, et al. Research on Standardization Method of Load Spectrum for Reliability Tests of Four-Poster[J]. Vibration and Shock, 2022(005):041. DOI:10.13465/j.cnki.jvs.2022.05.033.