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Comparative Study on the Transmission Characteristics of CDC Suspension under Different Damping Modes and Excitation Amplitudes

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Abstract

At present, Continuous Damping Control (CDC) suspension has been increasingly adopted in passenger vehicles to balance ride comfort and handling stability. However, most existing studies focus on control algorithm design rather than quantifying how adjustable damping alters the vehicle's vertical vibration transmission behavior, especially under varying excitation amplitudes. This article takes a production vehicle equipped with CDC dampers as the research object, and conducts sine sweep excitation tests on a four-channel road simulation test bench. Acceleration signals at the axle head (input) and the shock absorber tower top (output) are measured simultaneously. The suspension transfer function is calculated under three damping modes (comfort, normal, sport) and three excitation amplitude levels. By analyzing the transfer characteristics, the difference in transmission characteristics among different damping modes can be quantitatively analyzed, and the amplitude-dependent nonlinearity of CDC suspension can be revealed. The conclusion of this study can provide a basis for CDC calibration optimization and NVH problem diagnosis of different vehicle models.

Keywords

CDC Suspension; Transfer Function; Four Poster; Sweep Excitation; Amplitude Nonlinearity.

1. Introduction

With the development of automobile electrification, intelligence and connectivity, products are rapidly iterated, and the comfort of automobiles has become the focus of product competition. As a better solution, Continuous Damping Control (CDC) suspension has become increasingly widely used in automobiles because it can continuously adjust the damping force by changing the current input to the solenoid valve, thereby adapting to varying road conditions and driving demands [1,2].

Existing research on CDC suspension mainly concentrates on two aspects. The first is control strategy design, including skyhook control, acceleration-driven damping (ADD) control, model predictive control, and fuzzy logic control. Wu et al. [3] proposed a road-preview-based model predictive control for a CDC-equipped vibration isolation platform, and verified its effectiveness through full-vehicle tests. Chen et al. [4] applied skyhook damping control to a commercial vehicle cab suspension with CDC dampers, and demonstrated that it effectively suppresses vertical and pitch vibrations. Lin et al. [5] improved the conventional ADD strategy by introducing continuously variable damping, which preserves the acceleration optimization effect while avoiding deterioration of suspension working space.

The second research direction focuses on the modeling and characterization of CDC dampers themselves. Li et al. [6] established a nonlinear model of CDC dampers considering system time delay, and compared single-valve and dual-valve configurations under the improved skyhook

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control. Klockiewicz and Laski [7] investigated how friction, hysteresis, and actuation delay in adjustable damper models affect suspension dynamic responses.

However, most of these studies rely on simulation or quarter-car test rigs, and few have systematically quantified the vibration transmission characteristics of CDC suspension at the full-vehicle level. Wang and Zhao [8] compared the transfer functions of air spring suspension and traditional suspension using a four-poster test bench, and found that air springs provide significantly better vibration isolation in the mid-frequency range. Nevertheless, such comparative studies have not yet been extended to CDC suspension. Moreover, the damping force of CDC dampers is inherently nonlinear with respect to piston velocity, and this nonlinearity may lead to amplitude-dependent transmission behavior at the vehicle level.

This article focuses on the same vehicle model. Sensors are installed in the load transfer path of the vehicle. The four-channel road simulation test bench can provide a uniform frequency sweep signal to the entire vehicle to excite the entire vehicle. The same input load excitation ensures a single variable input for the entire vehicle test. Thus, the vibration signals at each point on the transmission path are obtained, the corresponding transfer function is calculated, and the transmission characteristics of CDC suspension under different damping modes and excitation amplitudes are analyzed [9]..

2. Theoretical Analysis

2.1. System Frequency Response Function Identification

The four-channel road simulation test bench is not an absolutely linear system. There is a certain amplitude and phase difference between the command signal and the actual displacement of the actuator. Therefore, it is necessary to use the frequency sweep excitation signal as the target and the drive signal of the actuator as the response signal, the system error is eliminated through the iteration principle, so that the driving signal of the actuator is consistent with the target excitation signal.

The basis of data iteration is RPC control technology, which is mainly used to reproduce the vibration and motion forms of samples in the actual mechanical environment to the laboratory environment. RPC technology is mainly used to convert the expected response signal into the driving signal of the equipment. It can compensate for the performance attenuation of the hydraulic system, solve the coupling problem between each channel, and ensure that the amplitude and phase of the signal remain accurate.

The system frequency response function (FRF) is a mathematical model that tests the relationship between the input signal and the output signal of the system. The purpose of solving FRF is to test the stable approximate relationship between the system input (Input) and output (Output) signals at each desired frequency. For this study, the command signal of the actuator is defined as the input (random excitation signal, Drive) in the test system, and then the actual displacement signal of the actuator is measured as the response signal (Response) and the signal is Fourier Leaf transform solves the mathematical relationship between the input frequency domain signal and the response frequency domain signal, and finally obtains the system frequency response function.

$$H(f) = Y(f) / X(f) \tag{1}$$

$$X(f) = \int x(t)\cdot e^{(-j2\pi ft)}dt,\ Y(f) = \int y(t)\cdot e^{(-j2\pi ft)}dt \tag{2}$$

2.2. Transfer Function Definition and Analysis Method

The transfer function is an important parameter for the evaluation of suspension vibration reduction effect and a technical reference method for vehicle anti-resonance design. The dimensionless ratio of the transfer function response amplitude to the excitation amplitude is

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similar to the system frequency response function mentioned in the previous section of the system. Can be a ratio of load, displacement, velocity or acceleration. As long as the stiffness meets the requirements, the smaller the transmissibility, the better the transmission effect and the better the vibration absorption effect. The larger the transmissibility, the easier it is to produce resonance and the worse the vibration reduction effect. The frequency corresponding to the peak value of the transfer function is the natural frequency of the elastic element.

The influence of transfer function and natural frequency is of great significance. The transfer function is similar to the frequency response function of the road simulation system. The transfer function takes the axle head acceleration as the system input and the body shock absorber tower package position as the system output. The relationship between the input and the output is calculated to obtain the suspension transfer function [8,9,].

$$H(f) = A_body(f) / A_axle(f) \tag{3}$$

$$\gamma^2(f) = |G_xy(f)|^2 / [G_xx(f) \cdot G_yy(f)] \tag{4}$$

2.3. Sweep Excitation

The Sine swept road excitation can be used to analyze the vibration frequency response characteristics of vehicle suspension systems. According to the frequency change rules, the sine sweep test is divided into a linear sine frequency sweep test and a logarithmic sine frequency sweep test. This article uses a linear sine frequency sweep test, which is mainly used in sinusoidal slow scan tests for accurate identification of product modal parameters.

This paper uses a constant velocity sweep signal as the excitation signal for experiments. The constant speed sweep input speed curve is similar to the spectrum composition of the actual road. The response spectrum obtained is similar to that of the random road surface response spectrum. The vibration response is closest to the actual vehicle test.

$$f(t) = f_0 + (f_1 - f_0) \cdot t / T \tag{5}$$

$$x(t) = A \cdot \sin[2\pi \cdot f(t) \cdot t] \tag{6}$$

2.4. CDC Damper Nonlinearity.

The damping force of a CDC damper is a nonlinear function of piston velocity. At low velocities, the damping force increases rapidly with velocity; at high velocities, the growth rate slows down, exhibiting a "softening" characteristic. When the CDC system changes the current input, the entire damping-velocity curve shifts up or down. Under small excitation amplitudes, the suspension operates near the low-velocity region where the damping ratio is higher; under large amplitudes, it enters the high-velocity region where the equivalent damping ratio is relatively lower. This inherent nonlinearity of the damper may manifest as amplitude-dependent transfer functions at the vehicle level [6,7].

$$F_d = c(v) \cdot v \tag{7}$$

3. Test Verification

3.1. Bench Construction

The vehicle ride characteristics test was carried out on a four-channel road simulation test bench. The test vehicle is a mid-size passenger car equipped with CDC dampers on all four corners. According to the conventional test requirements, the entire vehicle was counterweighted. The main driver and passenger driver were each counterweighted 75 kg. Before the test, acceleration sensors were installed on the wheel axles. The position of the axle head and shock absorber tower package, and the sensor location are shown in theFigure below. The test direction is vertical, and the upward signal is positive.

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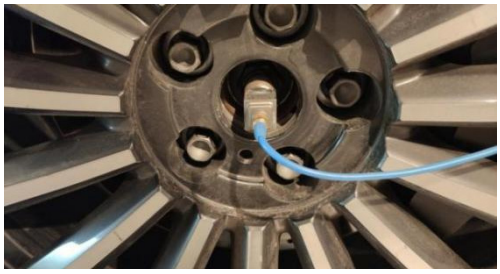


Figure 1. Position of accelerometer on axle head



Figure 2. Position of accelerometer on top mount

3.2. Test Input

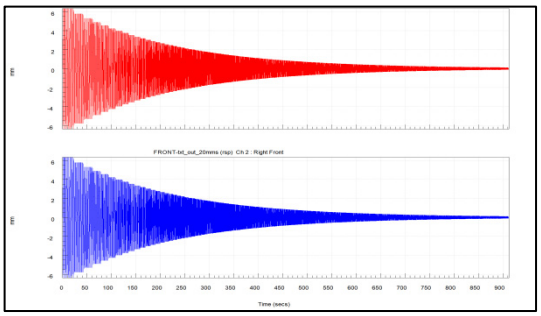


Figure 3. Drive signal

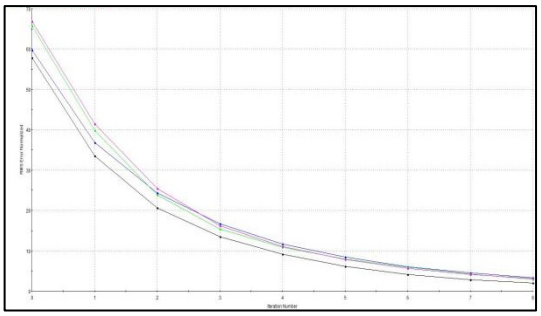


Figure 4. Driving signal iteration root mean square error results

Three sets of test conditions were designed to investigate the effects of damping mode and excitation amplitude. The CDC system was set to three modes via diagnostic tool: comfort mode (minimum damping), normal mode (medium damping), and sport mode (maximum damping). Three constant-velocity sweep amplitude levels were selected: low amplitude, medium amplitude, and high amplitude. The sweep frequency covers 0.5~30 Hz, which includes both the body bounce resonance and the wheel-hop resonance.

Taking the frequency sweep excitation signal (that is, the generated frequency sweep drive target signal) as the target, iterate the most responsive actuator signal of the four-channel road

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simulation test equipment. The iteration error RMS is less than 1%, which is a relatively ideal result.

3.3. Test Results and Analysis

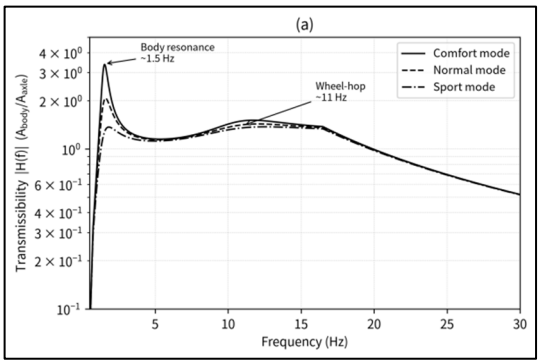


Figure 5. Transfer functions from axle head to top mount under three CDC damping modes

The solid, dashed and dotted lines in the Figure represent the transfer functions from the axle head to the topmount of comfort mode, normal mode and sport mode respectively. It can be clearly seen that under the same frequency sweep excitation, the transfer functions of the three damping modes are quite different. Overall, increasing the damping level mainly suppresses the resonance peak near the body natural frequency (around 1~2 Hz). In comfort mode, the peak transmissibility is the highest, indicating weaker damping and stronger resonance. In sport mode, the peak is effectively suppressed, showing the strongest vibration attenuation at the body resonance frequency.

In the mid-frequency range around 10~12 Hz (wheel-hop resonance), the difference among the three modes is relatively smaller. The damping adjustment has a limited effect on the wheel-hop peak, which is mainly determined by the tire stiffness and unsprung mass. In the high-frequency band, there is not much difference among the three due to the smaller amplitude.

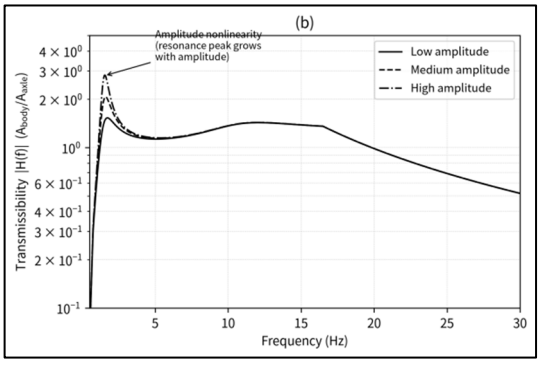


Figure 6. Transfer functions under three excitation amplitude levels (Normal mode)

Furthermore, the transfer function exhibits clear amplitude-dependent nonlinearity. At the body resonance frequency, the peak transmissibility increases as the excitation amplitude increases. Under low-amplitude excitation, the equivalent damping ratio is higher, resulting in a lower resonance peak. Under high-amplitude excitation, the suspension enters the high-velocity region of the damper where the equivalent damping ratio decreases, leading to a higher resonance peak. This amplitude-dependent behavior is consistent with the nonlinear external characteristic of the CDC damper.

The CDC tuning gain is the largest at low excitation amplitudes, especially around the body resonance frequency. At high excitation amplitudes, the CDC tuning gain decreases. The damper

is already in the saturated high-velocity region, and further increasing the current has a diminishing effect. This finding suggests that CDC calibration has the most significant impact on low-amplitude, low-frequency road inputs.

4. Conclusion

Based on a four-channel road simulation test bench, this article compares the transfer functions from the axle head to the topmount of CDC suspension under three damping modes and three excitation amplitude levels through frequency sweep tests. The main conclusions are as follows:

(1) Increasing the CDC damping level effectively suppresses the body resonance peak in the low-frequency range (around 1~2 Hz), but has a relatively limited effect on the wheel-hop resonance (around 10~15 Hz). This indicates that CDC tuning primarily targets ride comfort rather than road holding.

(2) The transfer function of CDC suspension exhibits clear amplitude-dependent nonlinearity. As the excitation amplitude increases, the equivalent damping ratio decreases, leading to a higher resonance peak. This is consistent with the nonlinear external characteristic of the hydraulic damper.

(3) The effective tuning bandwidth of CDC is concentrated in the low-frequency, low-amplitude region. The damping adjustment provides the largest relative benefit when the suspension operates near the low-velocity, high-sensitivity region of the damper characteristic.

The conclusion of this study can provide a good research basis for subsequent research on the resonance of CDC suspension on the car body and interior and exterior trim parts, as well as for CDC calibration optimization.

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