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Research on Damage Characteristics and Iteration Strategy Optimization of CDC Shock Absorber Vehicles in Spindle Coupled Road Simulation Test

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Abstract

To solve the problems of iteration efficiency and damage assessment of vehicles equipped with CDC shock absorbers in spindle coupled road simulation test,the tests were carried out under 5 gradient current excitations (0A, 0.15A, 0.3A, 0.6A, 1.2A) based on independently developed current playback equipment.By analyzing the vertical acceleration damage rule of shock absorber towers and transfer function characteristics, it was found that the acceleration damage shows an obvious U-shaped distribution—with the maximum damage at 0A and 1.2A, and the minimum at 0.6A. The transfer function exhibits frequency-segmented characteristics: in the 0~10Hz range, the vertical peak of the inverse transfer function is the highest at 0.3A, while there is no significant difference among different currents above 10Hz. The research results provide an optimization idea for the spindle coupled road simulation test iteration of CDC shock absorber vehicles, and have strong engineering value for improving the test accuracy and efficiency of electronic control suspensions.

Keywords

CDC Shock Absorber; Transfer Function; Iteration Optimization.

1. Introduction

With the electrification and intelligent upgrading of automotive suspension systems, CDC shock absorbers are widely used in mid-to-high-end models due to their real-time adjustable damping characteristics, significantly improving vehicle comfort and handling stability. As a core bench technology for automotive durability and performance evaluation, the spindle coupled road simulation testing can accurately reproduce real road loads. However, it faces many challenges in testing CDC shock absorber[1] vehicles, such as electronic control system synchronization and dynamic changes in damping characteristics. Traditional bench test schemes do not fully consider the current-damping coupling characteristics of CDC shock absorbers. Based on independently developed current playback equipment, this paper systematically studies the acceleration damage rule and transfer function variation characteristics of CDC shock absorber vehicles under different current excitations, and proposes targeted iteration optimization strategies to provide technical support for the spindle coupled road simulation test[2] of CDC shock absorber vehicles.

2. Introduction to Spindle Coupled Road Simulation Technology

Spindle coupled road simulation test [3] is an advanced indoor bench test technology in the automotive engineering field. Its core lies in accurately reproducing the six-degree-of-freedom motion of each wheel of the vehicle through 24 independent control channels. The system is mainly composed of a load transfer system, a power drive system (hydraulic or electric), a digital control system, and a data acquisition and analysis system. The test principle is as follows: first, collect load data such as wheel six-component force, acceleration and component strain on real roads; generate bench drive signals after data processing and iteration; then apply excitations to the vehicle wheels through actuators to simulate various road conditions. This technology has the advantages of high test efficiency, strong controllability, and good repeatability, while significantly shortening the R&D cycle. Its main applications include durability verification of vehicle chassis and body structures, performance evaluation of suspension systems, and reliability testing of components, and it has become an essential bench test link in the new car R&D process of mainstream automobile manufacturers at home and abroad.

3. Differences Between Vehicles Equipped with CDC Shock Absorbers and Ordinary Shock Absorbers

The core differences between vehicles equipped with CDC shock absorbers [4] and ordinary shock absorbers are reflected in three aspects: shock absorber structure, control method, and performance. In terms of structure, CDC shock absorbers add electronic control components such as solenoid valves and displacement sensors, and can adjust the valve opening through current. In terms of control method, CDC shock absorbers output current in real time by the ECU according to signals such as vehicle speed and road conditions to dynamically adjust the damping force. Ordinary shock absorbers adopt passive control, and their damping characteristics are not adjustable. In terms of performance, CDC shock absorbers can adapt to different road conditions—providing small damping on smooth roads to ensure comfort, and large damping on complex roads to improve stability. Ordinary shock absorbers can only balance comfort and handling under fixed damping, and cannot achieve full-condition optimization. In addition, the suspension system of CDC shock absorber vehicles has faster dynamic response and stronger adaptability to road excitations, which makes the control logic of its bench test more complex.

4. Difficulties in Spindle Coupled Road Simulation Test Iteration of CDC Shock Absorber Vehicles

Compared with ordinary shock absorber vehicles, the spindle coupled road simulation test iteration of CDC shock absorber vehicles faces three core difficulties. First, the difficulty of dual-system synchronous control is high. Ordinary vehicles only need to achieve load control, while CDC vehicles need to meet the synchronization of load and current. Otherwise, it will lead to delays in damping adjustment and road excitations affecting test authenticity. Second, the solution of transfer function is complex. The transfer function characteristics of ordinary vehicles are fixed, while the transfer function of CDC vehicles shows significant nonlinearity with current change—different currents correspond to different transfer characteristics, requiring solution under multiple current excitations. Third, the requirement for the authenticity of working condition simulation is higher. In addition, the response delay of CDC shock absorbers in the high-frequency range will lead to sudden changes in transfer function characteristics, further increasing the difficulty of iteration convergence and easily causing problems such as insufficient low-frequency drive and excessive high-frequency impact.

5. Analysis of Vertical Acceleration Damage of Tower Packs Under Different Constant Amplitude Current Excitations

5.1. Test Scheme Design

5.1.1. Test Equipment and Samples

The test adopts an MT S329LT spindle coupled road simulation bench, equipped with an RPC control system and independently developed CDC current playback equipment. This equipment

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can achieve accurate playback of 0~2A random current without starting the vehicle, with a current control accuracy of less than 20ms, meeting the requirements of bench tests for the stability and accuracy of current signals. The test is carried out based on an SUV model of a certain brand, and both front and rear shock absorbers of the vehicle are CDC type.

5.1.2. Sensor Layout and Data Acquisition

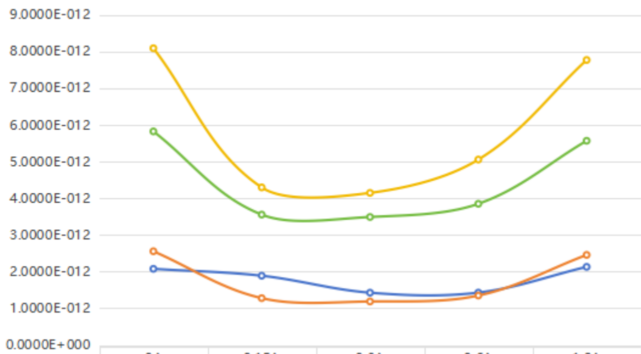
PCB unidirectional acceleration sensors are pasted on the surfaces of front and rear shock absorber towers to collect vertical acceleration signals. The sensor sampling frequency is set to 2048Hz, with a range of ±50g, ensuring the collection of high-frequency impact and low-frequency vibration signals. Current signals are collected through high-precision current sensors connected in series in the CDC solenoid valve circuit. During the test, other sensor data such as actuator six-component force are collected synchronously.

5.1.3. Test Working Condition Setting

The Belgian road load spectrum collected from a certain test site is selected as the bench target signal. The target signal is restored through iteration to obtain the final 24 drive signals. Keeping the drive signals unchanged, 5 constant amplitude gradients are set for current excitation: 0A, 0.15A, 0.3A, 0.6A, 1.2A. The damage calculation results of tower pack acceleration under different current excitations are compared.

5.2. Test Result Analysis

The vertical acceleration damage results of front and rear tower packs under different current excitations are shown in Figure 1.



	0A	0.15A	0.3A	0.6A	1.2A
LF	2.0757E-012	1.8880E-012	1.4261E-012	1.4283E-012	2.1297E-012
RF	2.5545E-012	1.2778E-012	1.1872E-012	1.3485E-012	2.4549E-012
LR	8.0846E-012	4.2939E-012	4.1445E-012	5.0524E-012	7.7648E-012
RR	5.8192E-012	3.5531E-012	3.4880E-012	3.8473E-012	5.5641E-012

Figure 1. Damage Results of Tower Package Acceleration Under Different Current Excitations of Shock Absorbers

As can be seen from the figure, both front and rear tower packs show a significant U-shaped distribution of acceleration damage: the damage value is the largest at 0A and 1.2A, the smallest at 0.3A, and the damage values at intermediate currents are between the two, showing a continuous and smooth change trend without obvious sudden changes.

5.2.1. Analysis of Damage Mechanism Under Each Current Working Condition

a) Damage Mechanism at 0A Current (Maximum Damping)

At 0A current, the solenoid valve of the CDC shock absorber is in a de-energized state, the valve opening is almost completely closed, and the damping force reaches the maximum. At this time, the damping ratio of the suspension system is too large, leading to an increase in the natural frequency of the system and triggering high-frequency resonance of the system, which significantly increases the peak acceleration of the tower pack. At the same time, under the high damping state, the buffering effect of the shock absorber on road impact is significantly weakened, and the impact load is almost directly transmitted to the body tower pack, resulting in a substantial increase in the proportion of high-frequency impact components in the acceleration signal. The continuous vibration caused by high-frequency resonance and the direct transmission of impact load are superimposed, making the fatigue damage of the tower pack structure accumulate rapidly, and finally forming a damage peak.

b) Damage Mechanism at 1.2A Current (Minimum Damping)

At 1.2A current, the valve opening of the CDC shock absorber is nearly fully open, and the damping force drops to the minimum. At this time, the shock absorption effect of the system on low-frequency excitations is greatly reduced, and the vertical vibration displacement of the body increases significantly, leading to frequent impact of the shock absorber on the stroke limit block and generating high-amplitude impact loads. Different from the 0A working condition, the damage under the 1.2A working condition is mainly caused by low-frequency vibration amplification and stroke impact, and the damage distribution is more concentrated in the medium and low-frequency stress cycles.

c) Damage Mechanism at 0.3A Current (Medium Damping)

At 0.3A current, the damping ratio of the CDC shock absorber is close to the optimal damping ratio of a single-degree-of-freedom vibration system. Under this damping state, the system achieves the best balance between resonance suppression and energy dissipation: for low-frequency excitations (0~10Hz), it can effectively suppress body displacement and avoid shock absorber stroke impact; for high-frequency excitations (10~50Hz), it can quickly dissipate vibration energy and reduce resonance amplification effect, thereby achieving the optimal shock absorption effect in the full frequency range.

6. Transfer Function Changes Under Different Current Excitations and Iteration Strategy Optimization

6.1. Test and Analysis Method of Transfer Function

The transfer function is used for the calculation of bench drive signals and is the core data of spindle coupled road simulation test iteration. Based on the same white noise drive, this paper solves the transfer function under 5 constant amplitude current excitations respectively, focusing on the inverse transfer function curves such as the vertical channel.

6.2. Analysis of Transfer Function Variation Characteristics

6.2.1. Distribution Characteristics of Full-Frequency Transfer Function

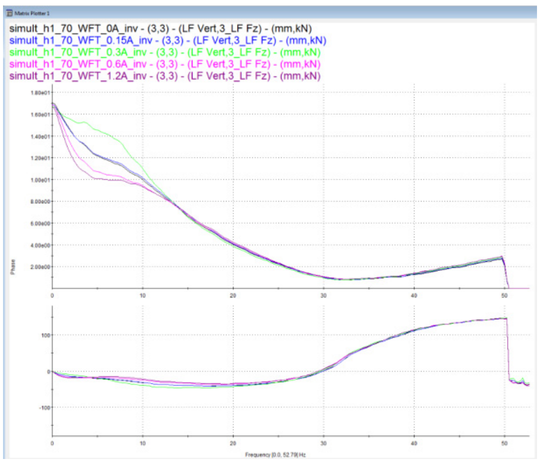


Figure 2. Inverse Transfer Function Curve of the Vertical Direction of the Left Front Tower Package Under Different Current Excitations

The vertical inverse transfer function curve of the left front tower pack under different current excitations is shown in Figure 2. As can be seen from the figure, the transfer function exhibits significant frequency-segmented characteristics, which are clearly divided into the low-medium frequency band (0~10Hz) and the high-frequency band (10~50Hz) with 10Hz as the dividing point. The characteristics of the two bands are significantly different, and this law is reflected in the transfer functions of both front and rear tower packs.

6.2.2. Transfer Function Characteristics in the 0~10Hz Band

The 0~10Hz band is the dominant frequency band of vertical body vibration. The damping adjustment of the CDC shock absorber responds fully in this band, and the transfer functions under different currents are significantly different. The vertical peak of the inverse transfer function is the highest at 0.3A current. From the perspective of iterative application, the higher the peak of the inverse transfer function, the larger the generated drive signal, which can accelerate the iteration convergence process.

6.2.3. Transfer Function Characteristics in the 10~50Hz Band

The 10~50Hz band belongs to the high-frequency vibration range. In this band, the inverse transfer function curves under various currents basically overlap, with no obvious regular changes, and the transfer function characteristics under different currents tend to be consistent.

6.3. Principles for Selecting Transfer Functions

For different vehicle models, it is recommended to select multiple excitation currents to solve the transfer function. The frequency-segmented characteristics of the transfer function are universal. To quickly complete the iteration process and reduce damage to the vehicle, the transfer function with a higher amplitude of the inverse transfer function can be selected in the low-frequency region for subsequent iteration work.

7. Conclusion

Through spindle coupled road simulation test, this paper systematically studies the vertical acceleration damage rule and transfer function characteristics of CDC shock absorber vehicles under different constant amplitude current excitations, and draws the following main conclusions:

1) The vertical acceleration damage of the tower pack shows a significant U-shaped distribution. The damage is the largest at 0A (maximum damping) and 1.2A (minimum damping), and the smallest at 0.3A (medium damping). The high damping at 0A leads to enhanced system high-frequency resonance and impact transmission; the low damping at 1.2A leads to intensified low-frequency resonance and stroke impact; the optimal damping ratio at 0.3A achieves the balance between resonance suppression and energy dissipation, which is the core reason for the minimum damage.

2) The transfer function exhibits frequency-segmented characteristics. In the 0~10Hz range, the peak of the inverse transfer function is the highest at 0.3A current, and there is no difference in characteristics among different currents above 10Hz. Reasonable selection of the transfer function can reduce the number of iterations.

Acknowledgments

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