

Research on Load Damage Reproduction Error of CDC Shock Absorber Equipped Vehicle in Spindle Coupled Road Simulation Test with Real Vehicle Dynamic Current Playback

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Abstract

Spindle coupled road simulation is an essential bench technique for chassis durability verification. For vehicles equipped with CDC shock absorber, most existing bench tests adopt constant amplitude fixed current excitation, which cannot reproduce the time varying solenoid valve current measured on real roads, resulting in non-negligible load and fatigue-damage reproduction deviation. To quantify such errors, this paper implements real vehicle dynamic CDC shock absorber current synchronous playback based on self-developed current playback hardware on an MTS 329 LT spindle coupled test bench. Two test schemes, constant current iteration and real vehicle dynamic current playback iteration, are compared. Time domain load response, inverse transfer function frequency domain characteristics, rain-flow counting fatigue damage of shock absorber towers and suspension control arms are analyzed. Test results demonstrate that constant current schemes produce obvious damage bias: the damage relative error can reach 27.4% for strut tower vertical acceleration and 31.8% for lower control arm strain damage. The system transfer function presents frequency segmented features under dynamic current conditions: significant time varying disturbance occurs within 0-10 Hz, while characteristics above 10 Hz remain basically stable. This work reveals the error mechanism between the two test schemes and provides test scheme reference for durability bench verification of electronically controlled suspension vehicles.

Keywords

CDC Shock Absorber; Spindle Coupled Road Simulation; Dynamic Current Playback; Iteration.

1. Introduction

With electrification and intelligent upgrading of automotive suspensions, CDC shock absorber are widely applied in mid to high passenger car for real time adjustable damping, improving both ride comfort and handling performance [1]. Spindle coupled road simulation test reproduces wheel six degree of freedom loads in laboratory conditions via RPC (Remote Parameter Control) iteration and is widely adopted for chassis and body durability assessment. For passive damper vehicles, system transfer function is approximately time invariant, and conventional RPC iteration can obtain satisfied load damage correlation [2]. However, CDC shock absorber adjust damping force instantaneously by solenoid valve current output from vehicle ECU according to road excitation and vehicle motion status. When conducting spindle coupled simulation tests for CDC shock absorber equipped vehicles, two critical challenges arise: multi system signal synchronization and time variant system dynamics induced by continuously changing CDC shock absorber current.

Existing published studies mostly adopt several discrete constant current grades to investigate CDC vehicle bench performance, revealing U shaped strut tower damage distribution and frequency segmented transfer function characteristics under fixed current excitations.

Nevertheless, real vehicle CDC solenoid current fluctuates continuously with road conditions rather than maintaining static constant values. Quantitative research on load damage reproduction error caused by adopting constant current instead of real vehicle dynamic current playback is insufficient [3].

In this paper, real road measured CDC dynamic current time history signal is imported into self-developed playback equipment and synchronously output during spindle coupled iteration tests. Comparative tests between constant current scheme and dynamic current playback scheme are performed. Time domain load, frequency domain transfer function, rain-flow fatigue damage of key chassis components are calculated and compared. The reproduction error formation mechanism is discussed, and suggestions for CDC vehicle spindle coupled durability test are proposed.

2. Spindle Coupled Road Simulation and CDC Shock Absorber Test Difficulties

Spindle coupled road simulation applies multi channel excitation on wheel spindles through hydraulic actuators, reproducing six component spindle forces and moments collected from proving ground roads. RPC iteration solves drive signals by de-convolution of system transfer function to minimize deviation between bench response and real vehicle target response.

For CDC equipped vehicles, three extra difficulties exist compared with passive vehicles:

1. Dual signal synchronous requirement: Not only spindle drive signals but also CDC solenoid valve current time history must be reproduced; time asynchrony between road excitation and damping adjustment introduces response distortion.
2. Time variant transfer function property: Different solenoid current yields different damping characteristics, further altering whole vehicle suspension system dynamic behaviour. The conventional RPC workflow assumes linear time invariant system, which no longer strictly holds for CDC vehicles.
3. Damage equivalence risk: Constant current bench conditions deviate from real road continuous current variation, leading to inconsistent load sequence and fatigue damage accumulation even if spindle target forces converge [4].

The self-developed CDC current playback device supports random current playback within 0-2 A, output latency less than 20 ms, satisfying real time synchronous requirement together with MTS RPC control system.

3. Test Scheme Design

3.1. Test Bench and Test Sample

Test bench: MTS 329 LT spindle coupled road simulation bench with RPC control system; self-developed CDC dynamic current playback unit.

Test vehicle: mass produced SUV, both front rear dampers are CDC solenoid valve type.

Sensor configuration: PCB uniaxial accelerometers mounted on four strut towers for vertical acceleration acquisition; Strain gauges installed on front lower control arm dangerous section; high precision series current sensor for CDC solenoid valve current logging. Sampling frequency set as 2048 Hz.

3.2. Test Working Conditions

Target road load spectrum: Belgian proving ground durability road spectrum, acquired via wheel force transducer on real vehicle. Two test schemes:

Scheme A (Constant current reference scheme): Select 0.3 A constant current (medium damping condition, corresponding to minimum damage point in existing literature). Keep CDC current fixed at 0.3 A during RPC iteration and data recording.

Scheme B (Dynamic current playback scheme): Import real road measured CDC solenoid valve dynamic current time history signal; current playback equipment synchronously outputs fluctuating current together with bench actuator drive signals.

Table 1. Key test condition parameters

Item	Parameter setting
Bench system	MTS 329 spindle-coupled, RPC iteration
Sampling frequency	2048 Hz
Scheme A current	Constant 0.3 A
Scheme B current	Real vehicle measured dynamic current (range 0-1.2 A)
Target spectrum	Belgian road durability spectrum
Damage evaluation algorithm	Rain-flow counting + Miner cumulative damage

After RPC iteration convergence for both schemes, keep actuator drive signals unchanged, record acceleration, strain and current data synchronously for subsequent load damage calculation. Rain-flow cycle counting and Miner linear cumulative damage rule are adopted for fatigue damage computation [5]. The key control parameters of this experiment are summarized in **Table 1**.

4. Test Result Analysis

This section sequentially analyses time domain vibration response, frequency domain system transfer characteristics, total cumulative fatigue damage and time-varying instantaneous damage rate. The internal logical chain is as follows: the real-road continuously fluctuating CDC current changes suspension damping ratio instantaneously (Figure 4), which first modifies the time domain peak value and shock pulse feature of strut tower acceleration (Figure 1). This time domain difference further manifests itself as amplitude deviation in low frequency band of inverse transfer function in frequency domain (Figure 2). These time frequency response differences finally accumulate into large deviations of total fatigue damage of key chassis parts (Figure 3). The four groups of results are mutually validated: time domain response is the direct manifestation of damping variation; transfer function difference explains the physical origin of response deviation from the perspective of system dynamics; cumulative damage quantifies the final engineering consequence; instantaneous damage rate curve correlates dynamic current fluctuation with damage generation process in time sequence.

4.1. Time Domain Response Comparison

Under completely identical actuator drive signals, the peak amplitude of vertical acceleration at strut tower under dynamic current playback is consistently higher than constant 0.3 A condition across the whole 0-20 s observation window, as shown in Figure 1. Not only the peak to peak amplitude increases, but also several sharp transient shock pulses can be observed in Scheme B waveform, which are obviously suppressed in Scheme A constant current test.

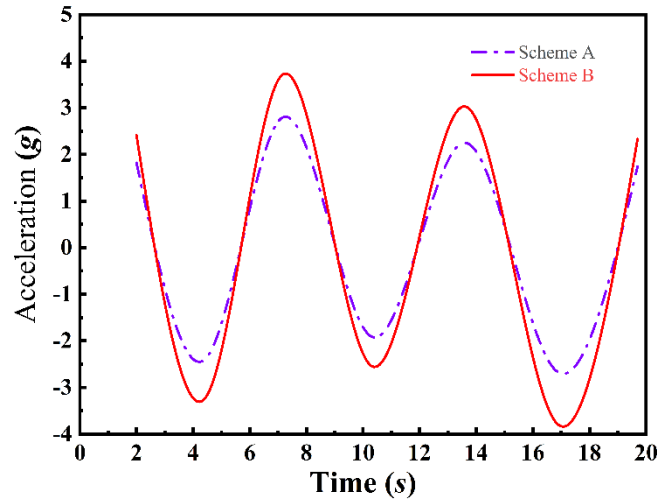


Figure 1. Comparison of left front strut tower vertical acceleration time history

In the constant 0.3 A scheme, suspension maintains a fixed medium damping ratio all the time. Although this damping level is regarded as the optimal damping point under static graded current test, it cannot reproduce the frequent switching between high damping (near 0 A) and low damping (near 1.2 A) states that occur during real vehicle driving. When CDC switches to low damping state under real road conditions, the shock absorber's ability to suppress body transient vibration weakens, leading to larger acceleration peak; when CDC switches to high damping state, road impact loads transmit more directly to the strut tower and produce sharp pulse responses. Both above mentioned typical transient behaviours disappear under fixed 0.3 A excitation. The deviation observed in this time domain waveform is not isolated. It reflects the macroscopic output difference caused by time variant damping of CDC suspension.

4.2. Inverse Transfer Function Frequency Domain Characteristic

The inverse transfer function quantifies the input output dynamic relationship between bench actuator drive and vehicle body response, and it is the core basis of RPC iteration algorithm.

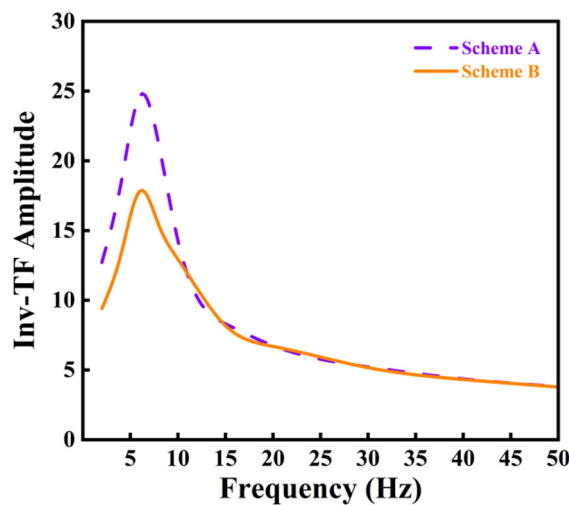


Figure 2. Left front channel inverse transfer function amplitude curve

As shown in Figure 2, obvious amplitude divergence between Scheme A and Scheme B appears within 0-10 Hz low medium frequency band, which corresponds to body bounce and pitch

vibration mode. The inverse transfer function amplitude under constant 0.3 A is distinctly higher than the averaged amplitude obtained under dynamic current playback. Above 10 Hz, the two curves almost overlap without significant deviation. This conclusion is consistent with the frequency segment characteristic concluded in previous constant current research: CDC solenoid valve has limited response bandwidth, and its damping adjustment hardly affects high frequency dynamic performance of suspension system.

4.3. Cumulative Fatigue Damage Distribution Histogram

The control arm exhibits larger relative error than strut tower. This phenomenon can be interpreted as follows: the lower control arm bears multi axial loads transmitted from wheel spindle, and it is more sensitive to those transient impact pulses which are missing in constant current test as shown in Figure 3.

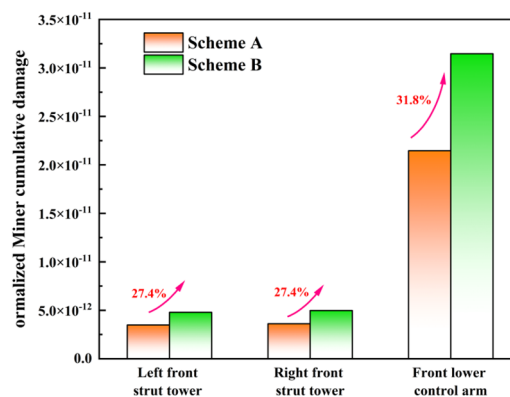


Figure 3. Normalized cumulative damage histogram for three key components

Constant 0.3 A test underestimates fatigue damage for both strut tower and control arm. Relative error reaches 27.4% for tower acceleration damage and 31.8% for control arm strain damage. Even if we select the “optimal medium damping constant current” from static tests, substantial damage reproduction error still exists, because CDC shock absorber continuously switches between high damping/low damping states in actual road driving. Static constant current cannot replicate the mixed load sequence generated by real time damping adjustment.

4.4. Dynamic Current Time History and Corresponding Instantaneous Damage Rate Curve

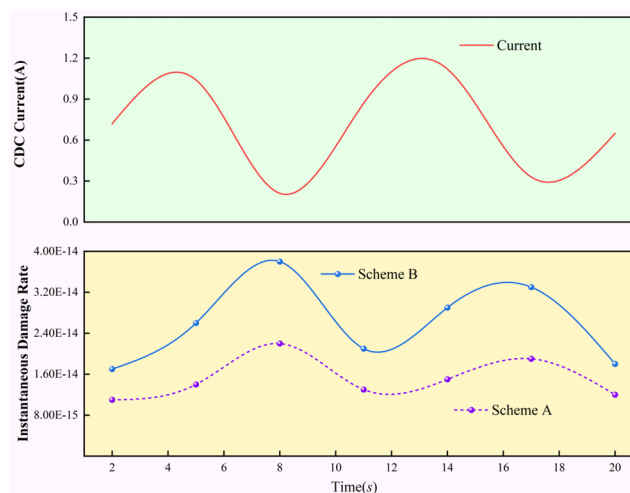


Figure 4. Real vehicle measured CDC dynamic current time history and upper subplot: real vehicle measured CDC dynamic current time history

As shown in Figure 4, in real vehicle condition, CDC current frequently switches between near maximum damping (low current) and near minimum damping (high current). At time instants with extreme current (close to 0 A or close to 1.2 A), Scheme B shows significantly higher instantaneous damage rate, while Scheme A keeps fixed 0.3 A and cannot capture those high damage transient moments. This is the root cause of cumulative damage underestimation in traditional constant-current bench tests.

5. Discussion

From test results, even adopting the optimal medium damping constant current (0.3 A) obtained from static graded current tests, obvious load damage reproduction error still exists for CDC vehicle spindle coupled road simulation. The error mechanism can be summarized in two aspects:

1. Frequency domain time variant disturbance: Real vehicle dynamic current continuously changes suspension damping ratio, leading to time variant whole vehicle transfer function within 0-10 Hz dominant vibration band. Static constant current transfer function cannot represent averaged and time varying dynamic characteristics under real road working conditions.
2. Load sequence difference for fatigue accumulation: Real road CDC continuously jumps between high damping/low damping states, generating mixed high impact transient load events corresponding to 0 A and 1.2 A static conditions. Constant current bench eliminates these alternating damping load sequences, thus underestimating total cumulative fatigue damage.

For engineering practice: if CDC vehicles adopt spindle coupled durability bench test, real vehicle measured dynamic current time history synchronous playback is strongly recommended. When dynamic current playback hardware is unavailable, we should be aware that constant current schemes bring inherent damage deviation, and safety margin adjustment for test load spectrum should be considered.

Limitation of present work: This paper focuses on damage reproduction error under existing converged drive signal condition. Further research can target improving RPC iteration workflow adapted to dynamic current time variant CDC system. The temperature drift effect of CDC damper during long duration durability cycle is not included in current test, which will be studied in follow up work.

6. Conclusion

Based on self-developed CDC dynamic current playback equipment, comparative spindle coupled road simulation tests are carried out between constant 0.3 A scheme and real vehicle dynamic current playback scheme. Main conclusions are summarized:

1. Compared with real vehicle dynamic current playback condition, traditional constant 0.3 A medium damping test scheme significantly underestimates fatigue damage: relative error reaches 27.4% for strut tower acceleration damage and 31.8 % for front lower control arm strain damage.
2. Under dynamic current playback condition, system inverse transfer function presents frequency segment property: obvious time varying disturbance within 0-10 Hz low medium frequency band; transfer function characteristics are almost unchanged above 10 Hz.
3. The reproduction error originates from two factors: time variant frequency response disturbance induced by continuously varying CDC damping and loss of alternating damping transient load sequences in static current bench condition.

4. To improve load damage correlation for CDC vehicle spindle coupled durability bench, synchronous playback of real road measured CDC dynamic current time history should be adopted as preferred test scheme.

References

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