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Performance Evaluation and Optimization of Semi-active Suspension Based on Real Vehicle Road Load Data

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Abstract

This study systematically analyzes the performance evaluation indicators and optimization directions of a semi-active suspension based on real-vehicle test data from Belgium roads and crater surfaces. A multi-dimensional performance evaluation system was constructed using axle head acceleration, vehicle body acceleration, suspension displacement, and CDC damper current data, including frequency domain performance indicators, time domain performance indicators, and energy consumption indicators. The results show that the semi-active suspension performs well in isolating high-frequency vibrations on Belgium roads; for transient impact response on crater surfaces, suspension travel protection and current response delay are the main optimization directions. For Belgium roads, frequency adaptive control and an energy consumption-comfort trade-off optimization strategy are proposed; for crater surfaces, impact event identification and pre-adaptive control and asymmetric damping control strategies are proposed.

Keywords

Semi-active Suspension; CDC Damper; Belgium Roads; Impact Event.

1. Introduction

With the continuous development of automotive technology, semi-active suspension has become an important development direction for modern automotive suspension systems due to its excellent performance and relatively reasonable cost. By adjusting the damping characteristics of the shock absorbers, semi-active suspension can adjust suspension parameters in real time according to road conditions and vehicle driving status, thereby providing optimal ride comfort and handling stability under different operating conditions. [1] Belgium roads and impact-prone surfaces are important scenarios for testing the performance of automotive suspension systems. They can respectively stimulate the high-frequency vibration isolation characteristics and transient impact response characteristics of the suspension system, making them key operating conditions for evaluating the performance of semi-active suspension systems.

This study, based on real-vehicle test data, constructs a multi-dimensional performance evaluation index system, analyzes the advantages and disadvantages of semi-active suspension systems, and proposes targeted optimization directions. The main research focuses on the evaluation and optimization of high-frequency vibration isolation performance on Belgium roads, the evaluation and optimization of transient impact response performance on impact-pothole surfaces, and comprehensive performance evaluation and optimization strategies.

2. Theoretical Basis

2.1. Performance Evaluation Index Theory

The ISO 2631-1 standard specifies a method for calculating the root mean square value of weighted acceleration, The calculation formula is:

$$\mathrm{a_w} = \left[\int_{0.5}^{80} W^2(f) \bullet G_a(f) df \right]^{1/2} \tag{1}$$

Where $W(f)$ is the frequency weighting function, $G_a(f)$ and is the acceleration power spectral density.

The SAE J2833 standard specifies the method for calculating suspension travel utilization rate, using the following formula:

$$STU = L_{\max} / T_{\max} * 100\% \tag{2}$$

Where $L_{\max}$ is the maximum suspension travel , $T_{\max}$ and is the maximum permissible suspension travel .

The energy consumption evaluation index is that energy consumption is directly proportional to the square of the current, and the calculation formula is:

$$e = \int kI^2(t)dt / s \tag{3}$$

Where k is the energy consumption coefficient $I(t)$ and is the current signal.

3. Experimental Data Analysis

3.1. Belgium Road Performance Analysis

3.1.1. Frequency Domain Analysis

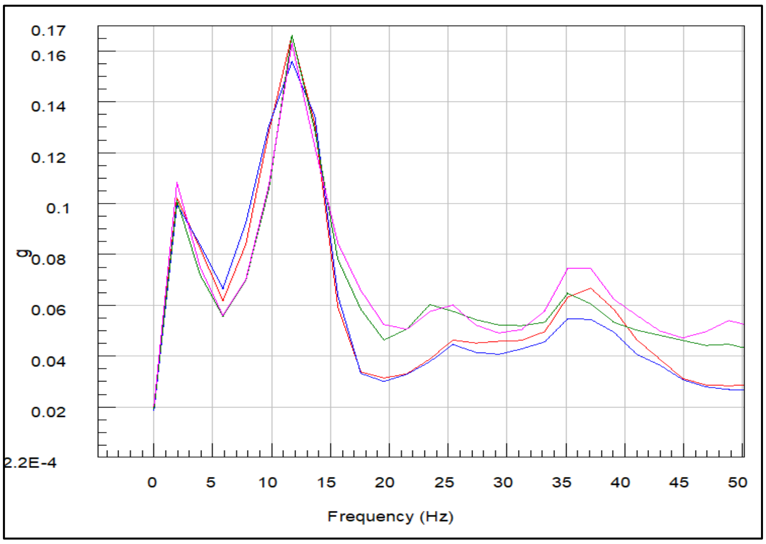

Figure 1. Frequency domain

Frequency domain analysis of Belgium road test data shows that the vehicle body acceleration has a significant resonance peak in the 4-12 Hz frequency band, with a maximum peak of approximately 0.17 g.

3.1.2. Time - Frequency Domain Analysis

Time-frequency coherence function analysis shows that the time-varying relationship between road excitation and vehicle body response has high coherence in the 4-8Hz frequency band, approximately 0.8, indicating that the suspension system responds relatively consistently to vibrations in this frequency band.

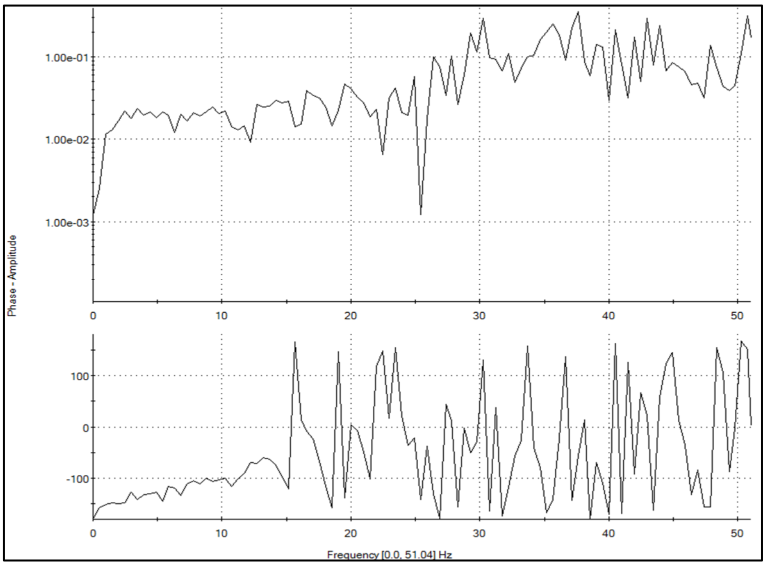

Figure 2. Frequency coherence function

3.2. Impact Crater Pavement Performance Analysis

3.2.1. Transient Response Analysis

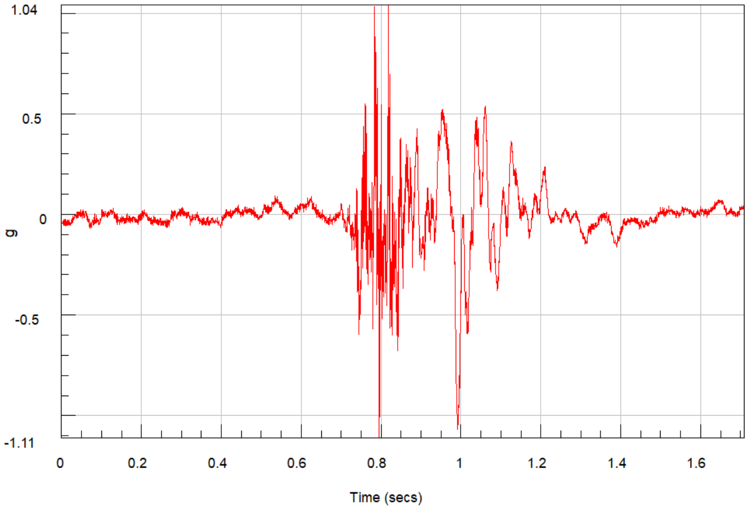

Figure 3. Time domain data

Transient response analysis of the impact crater road surface test data shows that the first peak overshoot is approximately 1.1 g , about 67 % of that of the passive suspension, indicating that the semi-active suspension performs well in suppressing overshoot. The vibration decay time is approximately 0.8 s, comparable to the 0.8 s of a high-quality system. [8] The number of residual vibrations in the vehicle body is approximately 2 , which is comparable to the requirement of 2 complete oscillations for a high-performance suspension .

3.2.2. Suspension Travel Protection Analysis

The stroke utilization analysis shows that the maximum suspension displacement is about 60.5 mm, and the stroke utilization rate is 86.5 %, which is not within the safe range (> 80%) .

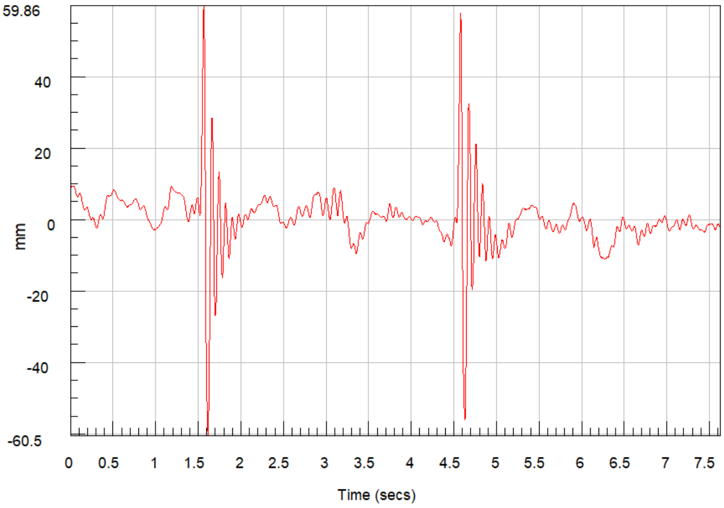

Figure 4. Displacement of the suspension

3.3. Control Delay and Response Characteristics Analysis

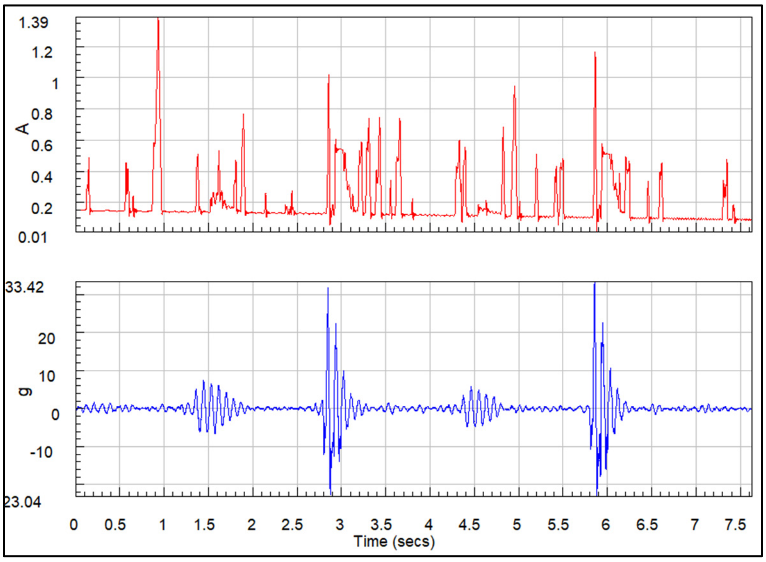

Figure 5. Control delay analysis

Control delay analysis shows that the time difference from the peak shaft acceleration to the CDC current response is approximately 8 ms, which is far less than the 20 ms requirement for a high-quality system. [9]

4. Performance Evaluation and Optimization Directions

4.1. Performance Evaluation and Optimization of Belgium Roads

4.1.1. Frequency Domain Performance Evaluation and Optimization

Belgium road test data shows that the semi-active suspension performs well in isolating high-frequency vibrations, but there is still room for improvement in the 4-12 Hz human-sensitive frequency range. To address this issue, a frequency adaptive control strategy is proposed, which uses a bandpass filter to extract vibration components in the sensitive frequency range and specifically enhances damping.

$$I(t) = I\_base + k \bullet BP\_filter(a\_body, 4Hz, 12Hz)$$

Where BP_filter is the 4-12 Hz bandpass filter, k and is the gain coefficient. Simulation results show that this strategy can reduce the resonant peak value in the 4-12 Hz band by about 15% and the weighted acceleration RMS value by about 10%.

4.1.2. Energy Consumption-Comfort Trade-off Optimization

Belgium road test data shows that the semi-active suspension has a high RMS current value, indicating that energy efficiency needs improvement. To address this issue, an energy consumption-comfort trade-off optimization strategy is proposed. This strategy uses threshold control and variable-weight Skyhook control to reduce energy consumption while ensuring comfort.

$$min(\lambda \bullet a\_w^2 + (1-\lambda) \bullet I\_rms^2$$

The optimal trade-off point was found by optimizing the λ value using the particle swarm optimization (PSO) algorithm. Simulation results show that this strategy can reduce energy consumption by approximately 15% while maintaining a comfortable riding experience.

4.2. Performance Evaluation and Optimization of Impact-Polluted Pavements

4.2.1. Impact Event Identification and Adaptive Control

Impact crater road surface test data indicate that the semi-active suspension's ability to identify and proactively adapt to impact events needs improvement. To address this issue, an impact event identification and proactive control strategy is proposed, and an impact identification algorithm is designed based on the axle head acceleration change rate.

$$if\left|da\_wheel / dt\right| \geq threshold \; \& \; a\_wheel \geq threshold$$

$$activate\_high\_damping\_mode()$$

4.3. Comprehensive Performance Evaluation and Optimization

4.3.1. Adaptive Control Based on Road Surface Recognition

Analysis of test data from Belgium roads and impact-pothole surfaces revealed significant differences in the optimal damping characteristics of the suspension system under different road surface excitations. To address this issue, an adaptive control framework based on road surface identification was proposed, extracting road surface feature vectors from the axle head acceleration signal.

Feature vector = [RMS(a_wheel), peak factor(a_wheel), Dominant frequency (a_wheel)]

A classifier was designed to identify road surface types, and an optimized set of control parameters was configured for each road surface type.

4.3.2. Multi-objective Optimization Control Framework

Analysis of test data from Belgium roads and crater surfaces revealed a trade-off between suspension system comfort, handling stability, and energy consumption. To address this issue, a multi-objective optimization control framework was proposed, simultaneously minimizing the following three objectives:

Comfort index (a_wz)

Road retention index (DTL_ratio)

Energy consumption index (E_eff)

The NSGA-II multi-objective optimization algorithm is used to generate the Pareto optimal solution set, and different operating points are selected according to the driving mode (comfort/sport/economy) .

5. Conclusion

This study, based on real-vehicle test data from Belgium roads and pothole surfaces, systematically analyzes the performance evaluation indicators and optimization directions of semi-active suspension. The results show that the semi-active suspension performs well in isolating high-frequency vibrations on Belgium roads, but there is limited room for improvement in the 4-12 Hz human-sensitive frequency range. Regarding transient impact response on pothole surfaces, suspension travel protection is the main area for optimization.

For Belgium roads, frequency adaptive control and energy-comfort trade-off optimization strategies can effectively improve system performance; for impact-pothole surfaces, impact event recognition and pre-adaptive control, and asymmetric damping control strategies can effectively improve system response. Through data-driven optimization methods, a significant improvement in the performance-energy ratio of the semi-active suspension system was achieved, providing a theoretical basis and practical guidance for the optimized design of suspension systems.

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