

Research on the Method of Whole Vehicle Load Spectrum Compilation Based on Road Surface Irregularity

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Abstract

With the rapid development of the automobile industry, vehicle durability has become one of the important indicators for measuring automobile performance. As a key factor affecting vehicle durability, road surface grade has a significant impact on the load borne by the vehicle during actual driving. This study aims to explore a method for compiling a vehicle durability load spectrum based on road surface grade, in order to provide a theoretical basis and technical support for automobile durability design and testing. First, this paper reviews the classification standards of road surface grades and the characterization methods of road surface roughness, and analyzes the influence of different road surface grades on vehicle load. Secondly, through field measurement and statistical analysis, a load model under different road surface grades is established, and a time domain load signal that conforms to the actual road surface characteristics is generated using the filtered white noise method. Furthermore, combined with vehicle dynamics and load transfer mechanism, the response characteristics of the vehicle under different road surface grades are studied, and the vehicle durability load spectrum is compiled. The method of this study is characterized by comprehensively considering the statistical characteristics of road surface roughness and the dynamic response of the vehicle, ensuring the practicality and accuracy of the load spectrum. The effectiveness of the compiled load spectrum is verified by simulation analysis of the load spectrum under typical road surface grades. The research results show that the load spectrum can provide load input close to actual road conditions for vehicle durability tests, which is of great significance for improving the level of automobile durability design.

Keywords

Pavement Grade; Vehicle Durability; Load Spectrum; Filtered White Noise Method; Simulation Analysis.

1. Introduction

As an indispensable means of transportation in modern life, the durability of automobiles is one of the key indicators to measure automobile performance, which is directly related to the service life and safety of automobiles. The vehicle durability test is an important means to evaluate the durability performance of automobiles, and the load spectrum, as an important tool to simulate actual road conditions, plays a vital role in improving the accuracy and efficiency of the test. However, the traditional load spectrum compilation method often ignores the impact of road surface grade on vehicle durability, which limits the accuracy and reliability of the load spectrum in practical applications.

Pavement grade is classified according to the flatness, structural strength and functional performance of the road surface. Different grades of roads have significantly different effects on the loads generated by vehicle driving. For example, high-grade roads usually have better

flatness and lower roughness coefficients, while low-grade roads may have more potholes and cracks, causing the vehicle to be subjected to greater impact and vibration during driving. Therefore, the method of compiling the vehicle durability load spectrum based on pavement grade is of great significance for simulating real road conditions and improving the accuracy of automobile durability evaluation.

At present, there is a certain foundation for the research on road roughness at home and abroad, but there is relatively little research on how to effectively combine road surface grade with vehicle durability load spectrum. This paper aims to fill this gap and proposes a method for compiling vehicle durability load spectrum based on road surface grade. This method analyzes the road roughness characteristics under different road surface grades, uses the filtered white noise method to generate a time domain load signal that conforms to the actual road surface characteristics, and combines vehicle dynamics and load transfer mechanism to compile a durability load spectrum that can reflect the response characteristics of the vehicle under different road surface grades [1,2].

This study first reviews the classification standards of road surface grades and the characterization methods of road surface roughness, and then establishes load models for different road surface grades through field measurements and statistical analysis. On this basis, this paper further studies the response characteristics of the vehicle under different road surface grades and compiles the vehicle durability load spectrum. The effectiveness of the compiled load spectrum is verified by simulation analysis of the load spectrum under typical road surface grades.

The innovation of this study is that a method for compiling the vehicle durability load spectrum that comprehensively considers the statistical characteristics of road roughness and the dynamic response of the vehicle is proposed, which provides a new technical means for automobile durability design and testing. The research results can not only improve the accuracy and efficiency of automobile durability testing, but also provide an important theoretical basis for automobile durability design.

2. Basic Theory

2.1. Spatial Power Spectral Density

Power Spectral Density (PSD) is a statistic that describes the spatial distribution characteristics of road surface roughness. It is usually used to characterize the energy distribution of road surface roughness in the spatial frequency domain. Spatial frequency refers to the number of times the road surface roughness changes within a unit length, while spatial power spectral density represents the energy content of road surface roughness per unit spatial frequency.

In vehicle engineering, spatial power spectral density is an important parameter because it directly affects the excitation force to which the vehicle is subjected when driving. The roughness of the road surface can be regarded as a random process, and its statistical characteristics can be described by the spatial power spectral density. A typical spatial power spectral density function usually has the following form:

$$G_q(n) = G_q(n_0) \left(\frac{n}{n_0}\right)^{-w} \quad (1)$$

Among them, $G_q(n_0)$ is the pavement power spectrum density value at the reference spatial frequency n_0 , also known as the pavement roughness coefficient; n is the spatial frequency, which is the reciprocal of the wavelength; w is the frequency index, which determines the rate at which the pavement power spectrum density changes with the spatial frequency.

The filtered white noise method regards the single-wheel road excitation $q(t)$ as the response of a first-order linear system excited by unit white noise $w(t)$. Considering the road cutoff frequency, the frequency response function of the system is:

$$H_{q \sim w}(w) = \frac{2\pi n_0 \sqrt{G_q(n_0)u}}{jw + 2\pi n_0 u} \tag{2}$$

Where: w is the original frequency; u is the speed of the car; n_0 is the spatial cutoff frequency of the road surface

Equation (2) is converted into a differential equation expression, and $q(t)$ the time domain model of single-wheel road excitation is:

$$\dot{q}(t) = -2\pi n_0 u \cdot q(t) + 2\pi n_0 \sqrt{G_q(n_0)u} \cdot w(t) \tag{3}$$

2.2. Coherence Function Mathematical Model

In vehicle dynamics, the coherence function is used to analyze the correlation between the left and right wheel tracks and road excitations, which is crucial for understanding and predicting the dynamic response of vehicles on uneven roads. This paper adopts the mathematical model of the coherence function given by Lu Fan and Bogsjo, which takes into account the road excitation frequency and the vehicle wheelbase [3,4,5]. This model is quite close to the measured curve, and its structure is simple and easy to calculate.

$$coh_{LR}(w) = e^{-\frac{\rho L_{lr}}{\pi v} w} \tag{4}$$

Where: ρ is the fitting coefficient, L_{lr} is the left and right wheelbase of the vehicle.

2.3. Time Domain Relationship between Front and Rear Axle Road Excitation

Assuming that the front and rear wheel tracks of the car are the same and the car is traveling in a straight line at a constant speed, the road excitation of the rear wheel lags behind the front wheel excitation for a period of time in the same wheel track:

$$\tau = L_{fr}/u \tag{5}$$

The front and rear wheel road excitation is related to:

$$q_r(t) = q_f(t - \tau) \tag{6}$$

Where: L_{fr} is the wheelbase of the front and rear wheels, and $q_f(t - \tau)$ and $q_r(t)$ are the road excitations of the front and rear wheels respectively.

2.4. Theoretical Basis of Four-column Stand

The four-channel wheel-coupled road simulation test equipment is an important equipment for automobile durability testing. It can simulate various vibrations and loads that a car is subjected to when driving on actual roads indoors, so as to evaluate the durability of the whole vehicle and its components. The four-channel wheel-coupled road simulation test equipment is usually composed of hydraulic actuators, hydraulic pump sources, servo control systems, data acquisition systems, computers and software systems. These components work together to achieve accurate excitation of the four tires of the car. The equipment simulates the vertical vibration of the car when driving on the road through hydraulic actuators. Each actuator is connected to a tire of the car. By controlling the displacement or force of the actuator, the tire load under different road conditions can be simulated. The equipment uses an electro-hydraulic servo control system for precise control, which usually includes position closed-loop proportional control and identification iterative control methods. The servo control system can drive the actuator according to a preset reference signal (such as a road load spectrum), while the identification iterative control method optimizes the control signal through system identification to improve the accuracy of the test.

System identification is the process of obtaining the frequency response function (FRF) of the road simulation test equipment. By inputting a white noise signal and collecting the system's response, the system's FRF can be estimated. This is crucial for subsequent waveform reproduction control.

Waveform reproduction control technology (such as remote parameter control RPC) is used to ensure that the vibration response of each measuring point of the vehicle during the test is as consistent as possible with the response during actual road driving. This usually involves using FRF to calculate the required drive signals and continuously optimizing these signals through an iterative process. The load spectrum is the input signal for road simulation tests, which is based on real vehicle tests or road data analysis. The compilation of the load spectrum needs to take into account the actual load of the vehicle during use and be designed in combination with the cumulative fatigue damage theory to achieve fast and accurate durability evaluation. [6,7]

In order to shorten the test cycle and reduce costs, the four-channel wheel-coupled road simulation test equipment can realize rapid simulation tests. This usually involves accelerated processing of the measured road load spectrum while ensuring that the load characteristics that are critical to durability evaluation are not lost.

3. Test Verification

3.1. Time Domain Signal Modeling based on Road Surface Grade

Modeling based on road surface grade requires determining vehicle track width, wheelbase, driving speed, road surface grade, and road surface fitting parameters. The parameter list is as follows:

Table 1. Vehicle time-domain road simulation parameters

Simulation parameters	Numeric	unit
Vehicle wheelbase	1660	mm
Vehicle wheelbase	2915	mm
Vehicle speed	40,60,80	Km/h
Road surface grade	C	
Road surface fitting parameters	3.4	

Use MATLAB/Simulink software to generate signals. The program framework is as follows:

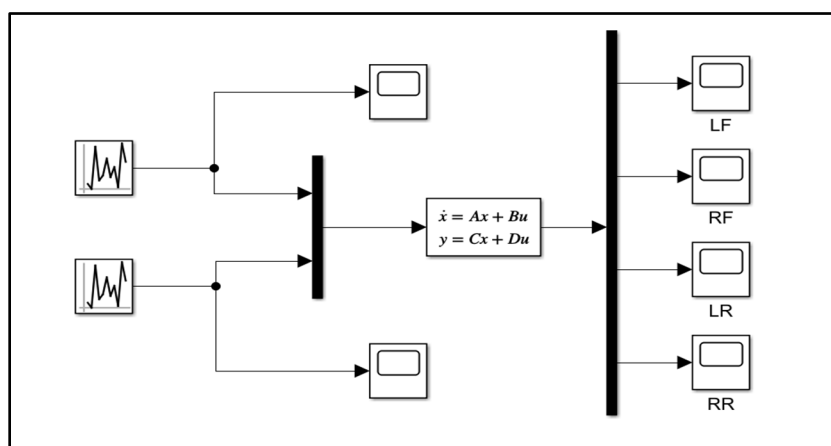


Figure 1. Simulink program block diagram

3.2. Four-column Bench Test

The verification work of this study was carried out using a four-column test bench. First, the acceleration sensor needs to be installed at the axle head position of the vehicle, and the road surface roughness time domain signal is generated based on the road surface grade. Through iteration, the actual displacement signal of the four-column test bench actuator is made consistent with the road surface roughness time domain signal. Different drive signals are

played, and the response signals of the vehicle axle head under the corresponding drive are collected, and compared and analyzed in the time domain, frequency domain, statistics and relative damage. The dotted line, dotted line and straight line represent the axle head response of the vehicle under C-grade road surface at driving speeds of 40km/h, 60km/h and 80km/h, respectively.

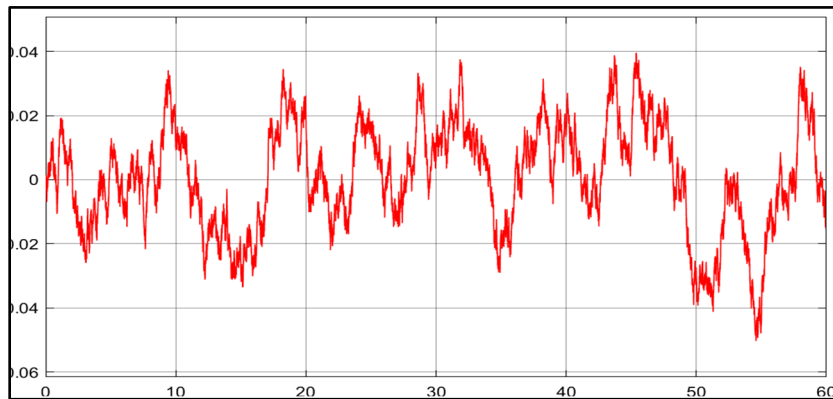


Figure 2. Example of generating a single channel signal

On the same road grade, the vehicle will be driven at different speeds of 40km/h, 60km/h and 80km/h, and the axle head data of the whole vehicle will be collected on the test bench. From the acceleration time domain comparison results in Figure 3, it can be seen that the axle head acceleration values obtained under the three working conditions are significantly different, which is consistent with the empirical data collected in the test field.

It can be seen from the frequency domain diagram in Figure 4 that when the vehicle speed increases, the amplitude of the axle head acceleration increases significantly, but the frequency corresponding to the peak value of the response signal does not change. It can be seen that the peak frequency of acceleration is only related to the road surface grade and has nothing to do with the vehicle speed.

It can be seen from the comparison chart of penetration counts in Figure 5 that when the speed increases, the signal counts of different amplitudes of the shaft head response signal will all increase, which is consistent with the situation in the actual vehicle test field.

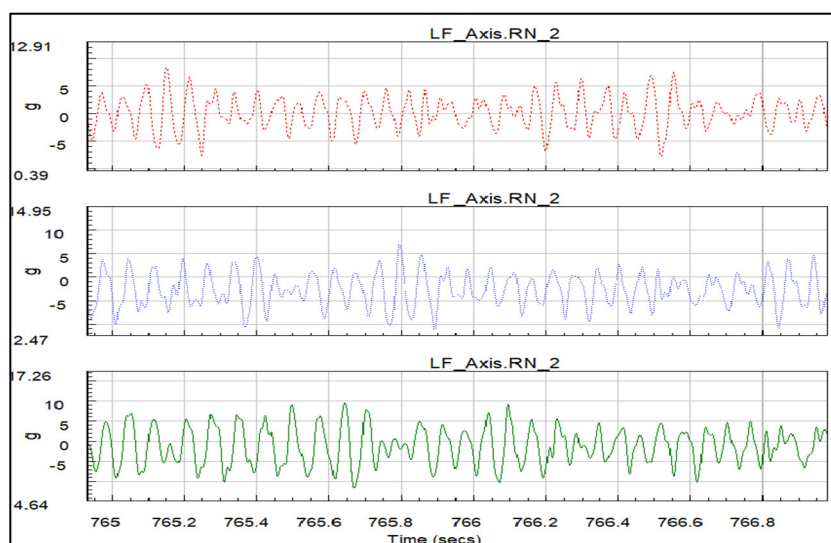


Figure 3. Axle head response signals at different speeds on C-grade road

Table 2. Time domain data comparison

	Maximum	Minimum	RMS value
40km/h	12.9	-10.4	2.9
60km/h	15.4	-12.0	3.4
80km/h	18.3	-13.6	4.6

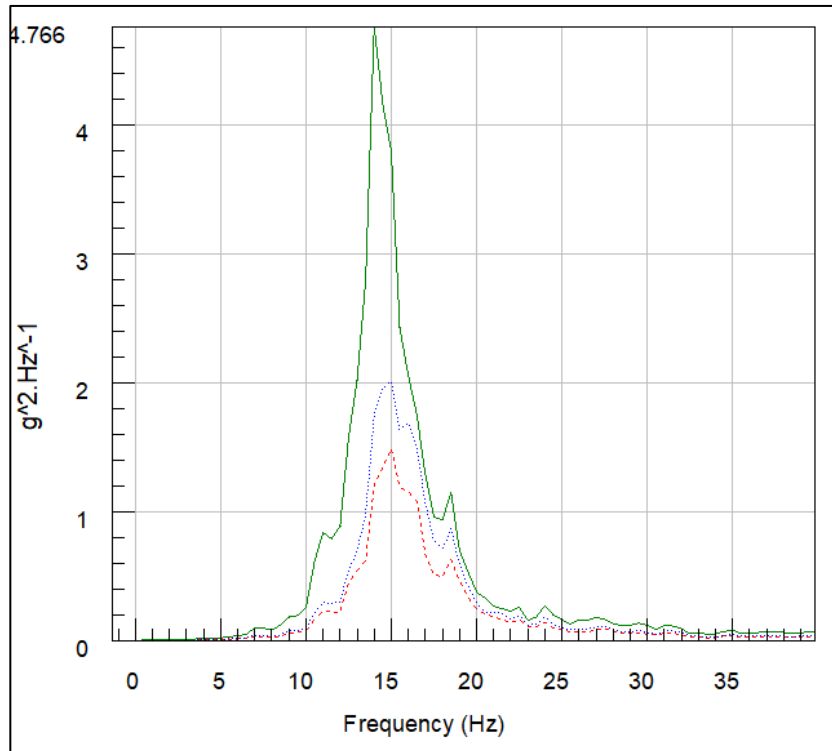


Figure 4. Comparison of frequency domain results at different speeds

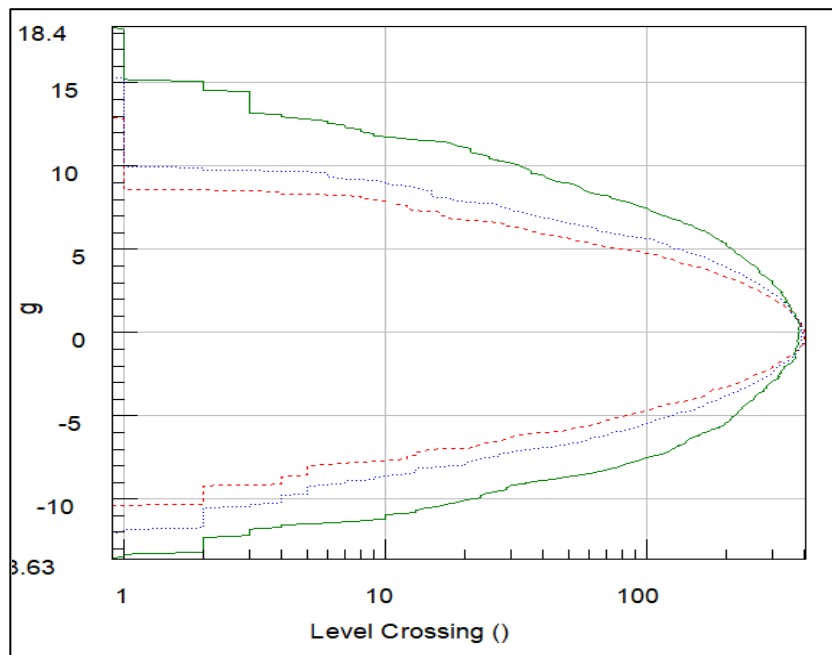


Figure 5. Comparison of cross-level counting results at different speeds

4. Conclusion

This paper takes the road grade as the input condition, conducts MATLAB modeling, generates the time domain signal of road roughness, and uses the time domain signal as the input of the four-column test bench to collect the vehicle axle head acceleration signal. The data is analyzed from different angles, and the conclusions are as follows:

- 1) Graded pavement can generate pavement excitation signals by combining whole vehicle and vehicle status parameters;
- 2) The time domain excitation signal generated by the graded road surface can be used as the input of the four-channel road simulation bench;
- 3) Judging from the analysis results of the vehicle axle head response data, the time domain signal generated by the road surface grade as an excitation is logically consistent with the actual measured data of the test site.

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