Original Research Article

Study on Compiling Method of Bench Fatigue Test Specification for Pickup Trucks Leaf-spring Bushing

Hui Huang, Wentao Ge, Zufeng Qiu*

Jiangling Motors Corporation Limited Company, Nanchang 330200, China

Abstract: In order to compile the bench fatigue test specification for pickup trucks leaf-spring bushing, the multi-body dynamics body model of the pickup trucks was built, the hub acceleration and suspension displacement which has been acquired from proving ground are taken as target signal, by applying virtual iteration technique, the dynamic load spectrum of bushing has been extracted. In order to keep the connection between the bench test and the road of proving ground, according to equivalent damage theory, the bench fatigue test specification has been compiled by using multi-block fatigue load method, and the time consuming of bench test has been shortened, and acceleration factor of 5.03 was achieved by comparing the test time of bench test and proving ground, the bushing has ultimately passed the durability validation of bench test.

***Keywords*：** Leaf-spring bushing; Virtual iteration; Dynamic load spectrum; Multi-block fatigue load; Bench fatigue test

1. Introduction

The utilization of non-independent suspension with leaf-spring is widespread in pickup trucks and light trucks. The rubber bushing, situated between the leaf-spring and the frame, not only serves as a connecting element but also functions to attenuate the force and vibration transmitted to the frame by the axle. As an integral component of non-independent suspension, it exerts a significant influence on the maneuverability and comfort of the vehicle[1]. Rubber bushings are prone to fatigue failure under alternating loads. Therefore, conducting fatigue durability verification of rubber bushings is imperative in preventing failures during actual customer usage.

The bench fatigue test based on road load spectrum not only ensures the correlation between bench testing and real-world road conditions, but also offers the advantages of a simple testing device and a shorter testing period, making it widely utilized in the industry. Variable load sequence endurance bench testing converts the part's road load spectrum into a variable load sequence (referred to as ‘load block’), which can accurately reflect the part's fatigue performance under various amplitude sizes of loads, thus closely resembling actual operating conditions[2]. Therefore, this paper adopts the ‘load block’ method to develop bushing fatigue specification. The leaf-spring bushing, being a rubber component, poses challenges in directly obtaining its load through conventional testing methods. Virtual iteration utilizes a signal from an easily measured position as a target signal and compensates for inaccuracies in parameter input through iterative processes. This approach ensures that model simulation results closely match with target signals collected by load spectrum, ultimately yielding accurate loads for key components.

2. Load Spectrum Acquisiton

The road load spectrum was acquired at an automotive proving ground, encompassing reinforced rough and off-road surfaces. The reinforced rough road included over 10 variations, such as washboard road, belgian blocks road, and longwave road. Acquisition channels primarily comprised the six-component force at the wheel center, displacement of front and rear suspension, and acceleration of front and rear hub. Figure 1 illustrates the measurement of the six-component force at the wheel center; Figure 2 shows direct measurement of rear suspension displacement via cable sensor; Figure 3 displays hub acceleration measurements.

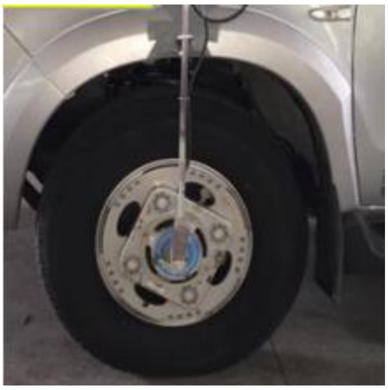


Figure 1. Six-component force of wheel.

Figure 2. Rear suspension displacement.

Figure 3. Rear hub acceleration.

3. Modeling of Vehilce Multi-Body Dynamics

According to the actual interconnection relationship between the components of the sample vehicle, a multi-body dynamics model of the vehicle is established, comprising front suspension, rear suspension, steering, frame, body and powertrain subsystems. The front suspension features a double-wishbone arm structure while the rear suspension is a non-independent leaf spring suspension. The front suspension system consists of upper control arm, lower control arm, knuckle, anti-roll bar, bumpstop, coil spring and shock absorber. Similarly, the rear suspension system comprises rigid axle with leaf springs and dampers connected through rubber bushings. Both systems are connected to the frame through bushings with stiffness data derived from actual test data. Flexible processing of the frame is carried out due to its bending and torsional deformation under road roughness excitation using modal synthesis method[3] and finite element software to calculate modal neutral file for establishing rigid-flexible coupling vehicle multi-body dynamics model as shown in Figure 4.

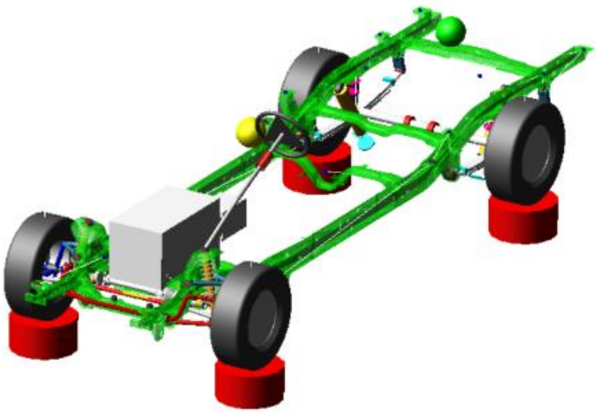


Figure 4. Rigid-flexible coupling vehicle multi-body dynamics model.

4. Virtual Iteration and Load Extracted

The virtual iteration process involves utilizing the signal from an easily measurable position (such as the spring displacement signal) as the target signal. This is achieved by calculating the transfer function and its inverse function of the vehicle model to derive the excitation signal in reverse, ensuring that the simulation result of the model closely approximates the target signal collected by the load spectrum. The flow chart illustrating these steps can be found in Figure 5[4]. The driving signal for the virtual iteration of the vehicle model is defined as the displacement at the tire's ground point, while the target signal encompasses both the suspension displacement and hub acceleration. The ultimate output from the last iteration results, specifically pertaining to dynamic load and deflection torsion angle of leaf spring bushing, can be observed in Figure 6 (using radial force and torsion angle of rear eye bushing on washboard road as an example).

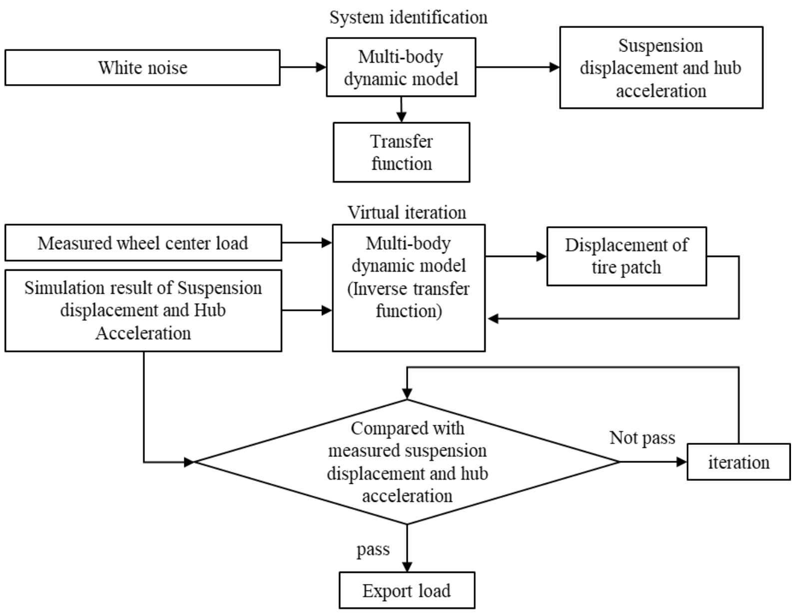


Figure 5. Flow chat of virtual iteration.

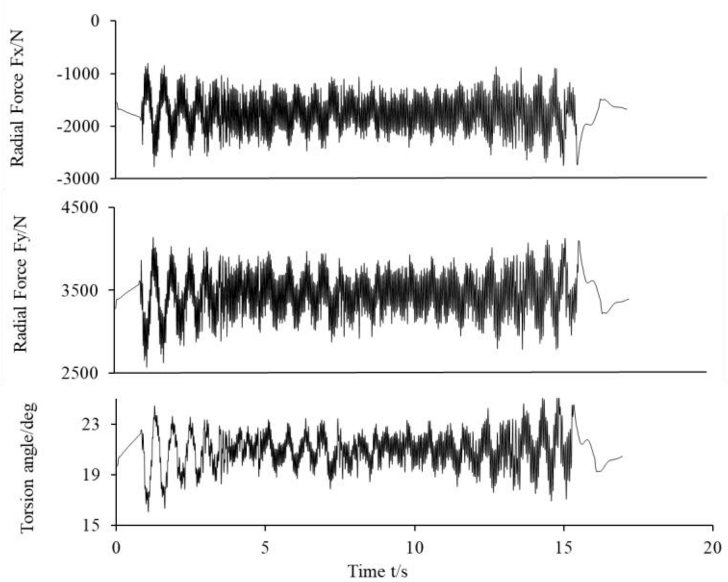


Figure 6. Rear eye bushing radial force and torsion angle.

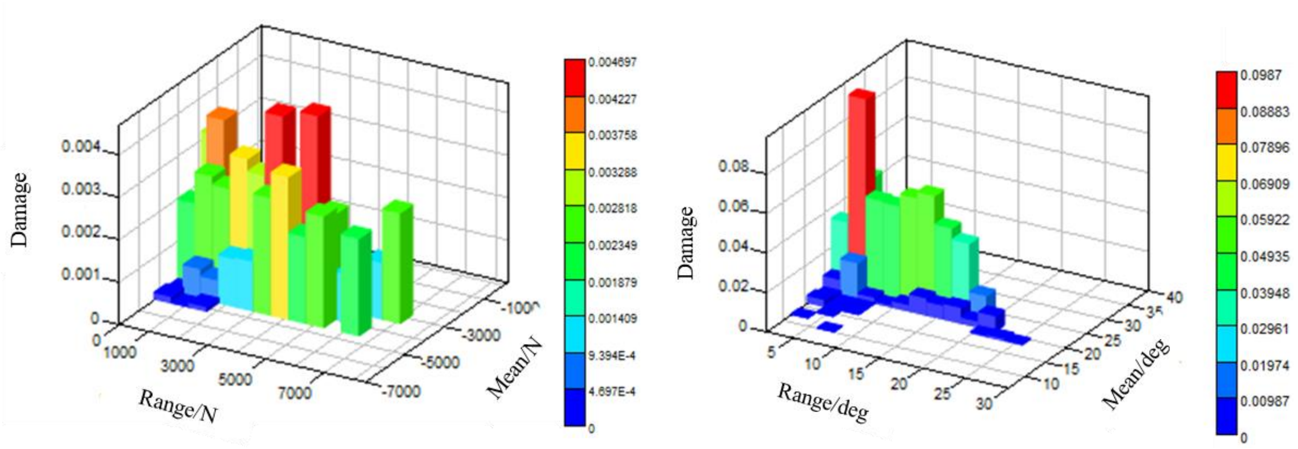
5. Compiling of Bench Fatigue Test Specification

The bench fatigue test involves the application of load exclusively in the radial and torsional directions, with the force signal being applied radially and the angle signal being applied torsionally. The rain-flow counting method is a two-parameter statistical technique commonly employed in fatigue research to characterize the load on components[5]. There are numerous low-amplitude and small-load signals in the radial force of the bushing, totaling 5,440,000 cycles. Given that continuous loading during a 3Hz bench test requires 503 hours, it is imperative to develop accelerated bench test specifications. In order to establish bench fatigue test specifications for bushings, it is imperative to ascertain the damage value derived from the rain-flow histogram of amplitude mean value as depicted in Figure.7. The procedural steps are as follows:

(a) Perform FEA analysis on the rubber components to derive the force-strain curve between the loading point and strain concentration area, and fit it with a third-degree polynomial;

(b) Compute the damage value under a single cycle of each mean amplitude using the strain-life curve of the rubber material;

(c) Multiply the damage value under a single cycle by its corresponding number of cycles to obtain total damage under each mean amplitude, as illustrated in Figure 7.



(a)Damage range-mean value histogram of radial force.

(b) Damage range-mean value histogram of torsion angle.

Figure 7. Damage range-mean value histogram.

The bushing bench fatigue test specification employs the load block method, this study adopts a three-stage load spectrum for development. Initially, based on the bushing load magnitude, radial force is categorized into 3 sections: 0~2700N, 2700~5100N and >5100N; while torsion angle is divided into 3 sections: 0~9deg, 9 ~19deg and >19deg. The damage value of each section is then accumulated. Subsequently, within each interval, the average amplitude load with maximum damage in a single cycle is selected as the typical load for testing purposes. The cycle number of this typical load is calculated using formula (1), resulting in the formulation of bench fatigue test specifications for bushings as depicted in Table 1 and Table 2.

$$EC = \frac{\left(\sum Dam_{block}\right)}{Dam_{tar} \;/\; Counts_{tar}} \qquad (1)$$

In formula (1), the number of cycles required to predict a typical load is denoted as EC; Dam_{block} represents the defined interval damage value, while Dam_{tar} signifies the damage value of the selected typical load. $Counts_{tar}$

refers to the number of cycles selected for a typical load.

Table 1. Radial direction test specification.

Load Block	Range/N	Mean/N	Repeat Count	Frequency /Hz
Block 1	1500	-4300	890000	3
Block 2	3900	-4300	172000	3
Block 3	6300	-4300	13700	3

Table 2. Torsion direction test specification.

Load Block	Range/deg	Mean/deg	Repeat Count	Frequency /Hz
Block 1	7	25	666000	3
Block 2	17	25	330000	3
Block 3	25	25	11400	3

According to the specified bushing bench fatigue test criteria (Table 2 and Table 3), fatigue tests were conducted on three bushing samples using the MTS biaxial test bench, as depicted in Figure 8. The fatigue failure assessment parameters for rubber bushings primarily encompass performance degradation and static stiffness loss rate (which should be below 20%) [6]. Post-testing analysis revealed no discernible cracks, rubber stripping, or wear failure modes in the three samples, as illustrated in Figure 9. Radial static stiffness assessments were carried out on the three samples before and after the fatigue test, with results detailed in Table 3. The observed change in radial stiffness of the bushings was found to be less than 20%, thus confirming their resilience through bench fatigue testing. The duration of the bench test was set at 100 hours; if the original signal loading took 503 hours, then an acceleration coefficient of 5.03 indicates a significant acceleration effect.

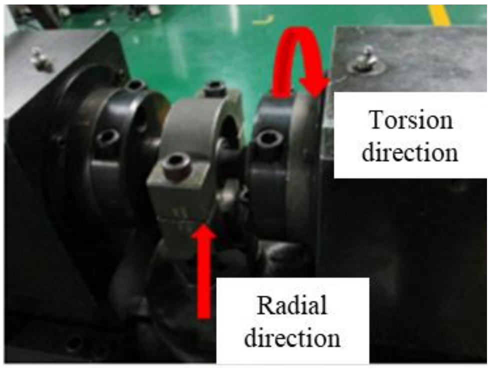


Figure 8. Bushing test-rig.

Figure 9. Bushing after bench fatigue test.

Table 3. Radial stiffness measurement after fatigue test.

Number	Radial stiffness before fatigue	Radial stiffness after fatigue	Rate delay
1	2660	2547	4.25%
2	2851	2658	6.77%
3	2726	2619	3.93%

6. Conclusion

In order to ensure the correlation between the fatigue test of the rubber bushing bench and the road conditions at the proving ground, a specific solution is proposed:

(1) Employing virtual iteration technology based on measured road load spectrum, the vehicle multi-body dynamics model was utilized as the carrier to extract dynamic load and yaw torsion angle of the bushing from

signals such as hub acceleration and suspension displacement. This provided a reliable boundary for conducting the bench fatigue test.

(2) Formulating the bench fatigue test specification of the bushing based on damage equivalent principle using load block method resulted in an acceleration factor of 5.03 times, demonstrating significant acceleration effect. The rubber bushing successfully passed validation of the bench fatigue test, offering a feasible engineering solution for durability verification of chassis rubber parts with high engineering application value.

References

[1] LingYang LI, YunQing ZHANG, ShiWei WU, et al. Optimization of Suspension Elastomeric Bushing Compliance under Constraints of Handling, Ride and Durability [J]. SAE, 2010-01-0721.

[2] YANG XiaoJun, LI Jun, LIN Yang, et al. Accelerated durability test of rear axle based on failure mode [J]. Modern Manufacturing Engineering, 2014(12):37-41.

[3] FENG HaiXing, LIU HaiLi, ZHANG SongBo, et al. Application of Component Mode Synthesis on Dynamic Analysis of Automotive Body Structure [J]. Automotive Engineering, 2012, 34(9):811-815.

[4] Manfred Becker, Thomas Langthaler, Markus Olbrich, etc. The Hybrid Road Approach for Durability Loads Prediction. SAE, 2005-01-0628.

[5] WeiDong ZHANG, MingChao GUO, Sridhar Srikantan. Rainflow Counting Based Block Cycle Development for Fatigue Analysis using Nonlinear Stress Approach [J]. SAE, 2013-01-1206.

[6] SUN XiaoBang, KONG LingYang, SHI Jing, et al. Experimental Study on Fatigue Failure of Shock Absorber Rubber Bushing [J]. Machinery Design & Manufacture, 2015 (12):62-64.