Research Article

A Method for Quantifying Automobile Brake Creep Groan Intensity Based on Friction-Induced Vibration and Noise

Lijun Zhang , Jianfeng Wu , and Dejian Meng

School of Automotive Studies, Tongji University, Shanghai 201804, China

Correspondence should be addressed to Dejian Meng; mdj0218@163.com

Received 21 June 2021; Revised 16 September 2021; Accepted 25 September 2021; Published 18 October 2021

Academic Editor: Mohamed A. A. Abdelkareem

Copyright © 2021 Lijun Zhang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

To quantify the intensity of automobile brake creep groan, both experimental and analytical studies are innovatively conducted on the friction-induced vibration and noise of the disc brake in this paper. Experimentally, three factors, brake disc initial temperature, terrain, and gear position, are comprehensively contemplated to design six different test conditions, based on which a creep groan vehicle road test is conducted. Depending on the subjective evaluation and statistical analysis of the annoyance degree caused by vibration and noise in the starting and braking process under different test conditions, the influence of each factor on creep groan intensity is obtained. By processing the brake caliper and lower suspension arm acceleration and the interior sound pressure signals acquired in the test, the occurrence conditions and transient dynamic characteristics of creep groan are explored. One of the creep groan vibration modes is triggered by the rapid removal of the force exerted on the brake pedal when the vehicle starts at an extremely low speed, which presents intermittent impact and chaotic characteristics. The other vibration mode shows periodic harmonic characteristics, whose energy is concentrated on specific frequencies in the form of frequency doubling. This vibration mode occurs when continuously maintaining a low brake oil pressure or slowly releasing the force exerted on the brake pedal during the vehicle low-speed starting process, the velocity-displacement phase-plane portrait of which shows a stable limit cycle of stick-slip motion. Analytically, four vibration indexes and four noise indexes are established to evaluate the intensity of creep groan, the validity of which is verified by linear regression analysis. Finally, by combining all effective indexes, multiple linear regression analysis is performed, based on which the mapping relationship between the subjective evaluation of creep groan and effective indexes is obtained. The results demonstrate that the combination of the logarithmic vibration dose value of maximum brake caliper acceleration pulse and the loudness of interior noise can accurately describe the annoying degree caused by creep groan. The regression model can quantify and predict creep groan intensity of the test vehicle under different test conditions, which has guiding significance for engineering applications.

1. Introduction

NVH (noise, vibration, and harshness) is a comprehensive issue that weighs the quality of automobile manufacturing and directly deteriorates the subjective impression of automobile users. It is also one of the pivotal concerns of each automobile manufacturing enterprise and spare part enterprise. Many companies have invested a lot of energy and funds, focusing on exploring and improving automobile NVH problems. According to the IQS (initial quality study) of J.D. Power in recent years, the PP100 (problems per 100 vehicles) of the brake vibration and noise issue ranks the top three among the principal quality problems in the process of

vehicle driving. Therefore, growing attention has been poured to NVH problems induced by brake friction.

According to frequency classification, the friction-induced vibration and noise of automobile brakes can be subdivided into low-frequency (10–100 Hz) brake judder, intermediate-frequency (50–500 Hz) brake creep groan, and high-frequency (1 kHz–16 kHz) brake squeal [1]. Brake creep groan is a phenomenon of low-frequency structural vibration and airborne noise caused by self-excited vibration of automobile brakes [2]. Brake judder and brake creep groan overlap in some frequency bands, but their trigger conditions are disparate. Different from brake judder and brake squeal, brake creep groan usually refers to the

vibration of the vehicle chassis system and the noise inside and outside the vehicle with significant transient impact characteristics, which is excited by brake friction vibration at low vehicle speed, low brake pressure, and small brake deceleration, and the frequency is approximately dozens to hundreds of Hz [3, 4]. With the rapid growth of global automotive ownership and the increasing congestion of urban roads, vehicles need to start and brake alternately in the process of low-speed driving, resulting in frequent occurrence of the brake creep groan phenomenon, which affects the subjective sense of passengers and aggravates the fatigue of drivers. It is urgent to explore the quantification of automobile creep groan intensity. The research on brake friction-induced vibration and noise is mainly conducted by experimental and analytical methods.

Experimentally, based on different test methods and purposes, creep groan tests that study brake friction-induced vibration and noise can be divided into vehicle road test [5–10], vehicle drum test [5, 6], brake inertia dynamometer test [11–13], and specially designed brake bench test [14–16]. The vehicle road test is conducive to ensuring the authenticity of the vehicle state and occurrence condition, which can completely reproduce the creep groan phenomenon. This test method is suitable for exploring the characteristics of vehicle interior noise and brake vibration when creep groan occurs, but there are numerous external interference factors, which are formidable to control. The vehicle drum test is convenient to control environmental factors accurately, which is applicable to analyze the deformation of the brake and the vibration transmission path. Brake inertia dynamometer tests and specially designed brake bench tests are carried out for automobile brakes, which are suitable for exploring the mechanism of brake creep groan and stick-slip vibration characteristics, and provide tremendous data support for theoretical modeling and analysis. Nevertheless, the diversity of driving conditions and the difference of experimenters' subjective evaluation are not contemplated in the experimental study of creep groan, which leads to some limitations of the current test methods.

Analytically, previous studies [17, 18] focusing on exploring the mechanism of creep groan have revealed that the sources of creep groan caused by brake self-excited vibration include unstable sliding in addition to transient or steady-state stick-slip motion between pads and discs of impulsive and discontinuous nature. After in-depth analysis of the mechanism of creep groan, the establishment of the models that can quantify and predict brake friction-induced vibration and noise has become a research field. Theoretical and simulation models are the most widely used models at present, which can also verify the proposed mechanism. The brake assembly is simplified as a lumped parameter system in the theoretical model [19–22] based on linear and nonlinear dynamics. Although the friction vibration between discs and pads cannot be effectively described, the vibration of brake assembly can be roughly predicted. The rigid-flexible coupling creep groan multibody dynamic model [23] established for the Macpherson chassis corner can reproduce stick-slip vibration characteristics and predict the vibration of the brake disc, but the accuracy is deficient.

Moreover, the FE (finite element) model [24–28] of the brake corner is utilized to quantify creep groan, which has high accuracy and significant advantages in calculating the interface contact. Nevertheless, the connection and friction characteristics of brake components should be further studied in the FE model. Both theoretical and simulation models simplify the brake assembly to quantify creep groan, but components' parameter calibration between simplified models and the brake assembly is formidable and time-consuming. Therefore, regression models [29] based on abundant creep groan experiments' subjective evaluations and objective measurement are simpler and do not require parameter calibration. In the regression model, according to brake friction-induced vibration and noise, indexes are proposed to quantify creep groan, and the index that has the best mapping relationship with subjective evaluation is selected by statistical methods, which assesses the intensity of creep groan from the perspective of drivers' subjective feelings. This model relies on abundant subjective and objective experimental data under different driving conditions, which ensures the accuracy of the model. At present, there is no unified index for the assessment of automobile brake creep groan intensity, and the consideration dimension is single.

In this study, in order to fill the void in the diversity of driving conditions, three factors (brake disc initial temperature, terrain, and gear position) are comprehensively contemplated to design six ordinary driving conditions in the starting and braking process. A creep groan vehicle road test is conducted by several experimenters under the test conditions proposed above, which reduces the individual difference of subjective evaluation. The annoyance degree caused by vibration and noise under different conditions is subjectively evaluated by the experimenters, and the influence of each factor on creep groan intensity is obtained by using statistical methods for data processing and comparative analysis. The brake caliper and lower suspension arm acceleration and the interior sound pressure are synchronously collected in the test based on which two intricate vibration modes with distinct occurrence conditions and transient dynamic characteristics are widely captured. To enrich the description dimension of creep groan intensity, brake friction-induced vibration and noise are innovatively combined. Four logarithmic dose vibration indexes (Q_1 , Q_2 , Q_3 , and Q_4) and four noise indexes (*SPL(A)*, *Loudness*, *Roughness*, and *Fluctuation*) are established, and their effectiveness is verified based on linear regression analysis. Moreover, multiple regression analysis is performed based on all effective indexes and subjective scores, and the regression model that describes the mapping relationship between the subjective evaluation of creep groan and effective indexes is obtained. The score calculated by the regression model quantifies the intensity of the creep groan from the perspective of drivers' subjective feelings.

2. Vehicle Road Test of Creep Groan

2.1. Test Setup. The object of the test is an A-class vehicle equipped with a six speed AT (automatic transmission),

which has a McPherson suspension in the front and a torsion beam suspension in the rear. The FF (front-engine front-drive) test vehicle has a total mass of 1431 kg, whose front and rear wheel brakes are ventilated disc brakes and solid disc brakes, respectively. Detailed parameters of the test vehicle are provided in Table 1. The braking system of the test vehicle runs well, whose brake discs have no significant corrosion. The tire pressure during the test is strictly adjusted based on operation instructions, and the test load state is set according to “Motor vehicles—general rules of road test method” [30].

The crucial factors that affect drivers’ subjective perception on brake creep groan are complicated and diverse. Pondering the discrepancy in automobile braking performance caused by the temperature of brake discs, the test is conducted at two different initial temperatures of brake discs: low temperature and high temperature. The initial temperature of brake discs under low-temperature condition is approximately 35°C–45°C, and that under high-temperature condition is approximately 90°C–100°C. Horizontal road and downhill road with a slope of 10% are invoked as test sites to explore the occurrence conditions of creep groan under different terrains. In the downhill condition, the driving force of the vehicle originates from the gravity component and the engine. *D* gear and *N* gear conditions are set when the vehicle is downhill to explore whether the engine’s running aggravates the annoying degree caused by creep groan.

Therefore, six commonly used working conditions are set to explore the superiority-inferiority of the subjective and objective evaluation on creep groan under different conditions. The six test conditions are as follows: high-temperature *D* gear downhill driving condition (condition I), high-temperature *D* gear horizontal road driving condition (condition II), high-temperature *N* gear downhill driving condition (condition III), low-temperature *D* gear downhill driving condition (condition IV), low-temperature *D* gear horizontal road driving condition (condition V), and low-temperature *N* gear downhill driving condition (condition VI).

2.2. Measurement Instrumentation. Two PCB-356A15 tri-axial accelerometers are used to measure the acceleration of the front brake caliper and lower suspension arm, respectively. One accelerometer is installed on the caliper near the hose, the *Y* and *Z* directions of which are aligned with the radial and normal directions of the brake disc, respectively. The other accelerometer is installed on the front suspension lower arm, and its *X*, *Y*, and *Z* directions are aligned with the longitudinal, vertical, and lateral directions of the vehicle, respectively. The resolution of the accelerometers is 0.002 m/s², whose measurement ranges of frequency and acceleration are 0.5–12000 Hz and 0–500 m/s². A Keller-PA-21Y piezoresistive pressure transmitter with a resolution of 0.25%FS is used to measure the brake oil pressure in the test. The pressure transmitter, which has a pressure measurement range of 0.2–100 MPa is installed at the connection of the brake tube and hose. A BSWA-MPA215 microphone with a sensitivity of

40 mV/Pa is utilized to measure the interior noise. The microphone, which has frequency and sound pressure measurement ranges of 20 Hz–12.5 kHz and 20–132 dB, is fixed beside the driver’s seat headrest. The arrangement of all sensors in the test is illustrated in Figure 1.

2.3. Test Procedure. Five drivers drove the test vehicle in turn at a speed lower than 10 km/h in the test sites under each test condition. By stepping on the accelerator pedal and brake pedal, the test vehicle starts and brakes alternately at a lower speed. When the creep groan phenomenon occurs in the test vehicle, the brake pedal is kept to maintain the occurrence of creep groan as much as possible. During the test, the signals of all sensors are measured synchronously and collected by a LMS-SCADAS data acquisition system, which sets the sampling frequency of all sensors to be 10.24 kHz. At the end of one working condition test, each driver subjectively evaluates the annoying degree of vibration and noise caused by creep groan under this test condition and gives a subjective score of the ten-point system [31], as shown in Table 2. After the experiment of one working condition is finished, the test steps are repeated to perform the next working condition test until all test conditions are completed. Figure 2 displays a flow chart to represent the step-wise procedure followed for carrying out the test and subsequent experimental analysis.

3. Subjective Evaluation of Creep Groan

In this section, the subjective raw scores recorded in the vehicle road test of creep groan are tested, and the effective data are obtained after eliminating the suspicious data. Subsequently, effective subjective scores are processed to get the subjective statistical data on creep groan under six test conditions. Finally, the influence of the brake disc temperature, terrain, and gear position on the intensity of creep groan is explored by comparing the subjective evaluation data box plot. A complete set of data processing flow for subjective evaluation of creep groan vehicle road test is established.

3.1. Elimination of Suspicious Data. Table 3 shows the raw data of five drivers’ subjective scores of the test vehicle’s creep groan in which the test conditions I to VI correspond to the conditions described above. Since the subjective evaluation of each driver has individual differences, in order to eliminate the gross error [32] caused by the suspicious data with significant distinctions between individual driver and other drivers under each test condition, Romanovsky criterion [33] is adopted to process the raw data.

Romanovsky criterion, also known as the *t*-test criterion, is applicable to the data with fewer measurements. First, a suspicious subjective score is removed, and *t* distribution is subsequently used to test whether the removed subjective score contains a gross error. Assuming that the subjective scores of five drivers under a given condition are X_i ($i = 1, 2,$

TABLE 1: Detailed parameters of the test vehicle.

Vehicle mass (kg)	Transmission	Driving mode	Brake	Suspension system
1431	Six speed AT	FF	Front ventilated disc brake Rear solid disc brake	Front McPherson suspension Rear torsion beam suspension

FIGURE 1: Sensor arrangement for the vehicle road test of brake creep groan: (a) accelerometer at caliper, (b) accelerometer at front suspension lower arm, (c) pressure transmitter, and (d) microphone.

TABLE 2: Subjective scoring standard for the annoying degree caused by creep groan.

Score	Subjective feeling	Description
1	Intolerable	All users consider it unacceptable, and the parts lose their function
2	Severe	All users consider it unacceptable, and the parts have serious defects
3	Very poor	All users consider it unacceptable, and the parts are defective
4	Poor	Ordinary users are dissatisfied
5	Marginal	Ordinary users are often annoyed
6	Barely acceptable	Critical users are often annoyed
7	Fair	Critical users are seldom annoyed
8	Good	Critical users are barely annoyed
9	Very good	Trained engineers are barely annoyed
10	Excellent	Trained engineers are not annoyed

..., 5), if the score X_j of the driver j ($j = 1, 2, \dots, 5$) is suspected, the following discriminatory steps are taken:

- (a) Remove the suspected score X_j and calculate the arithmetic average $\bar{X}$ and the standard deviation σ of four remaining subjective scores,

$$\bar{X} = \frac{1}{4} \sum_{i=1, i \neq j}^5 X_i, \quad (1)$$

$$\sigma = \sqrt{\frac{\sum_{i=1, i \neq j}^5 (X_i - \bar{X})^2}{3}}.$$

- (b) The number of drivers $n=5$, and the significance level α is selected as 0.05 in this study. Based on the values of n and α , the test coefficient $K(n, \alpha) = 3.56$ is determined from the Romanovsky criterion test coefficient table [33].
- (c) According to the calculation results of equation (1), if $|X_j - \bar{X}| > K\sigma$, it is demonstrated that X_j contains a

gross error, which should be eliminated. Conversely, X_j is retained.

All subjective scores are processed by above procedures, and one suspicious score is finally found, which is evaluated by driver 2 under condition V. After eliminating the data under the condition mentioned above, 29 groups of effective data are obtained, which will be used for subsequent subjective and objective analysis.

3.2. Comparative Analysis. After getting the effective data, the median, upper quartile, and lower quartile of the subjective scores under each test condition are calculated, and the statistical results are exhibited in Figure 3.

By comparing and analyzing the subjective score in Figure 3, the following conclusions can be drawn:

- (a) Comparing the test conditions I and IV, II and V, and III and VI, it can be revealed that the driver's subjective feeling of creep groan under high-temperature condition is better than that under low-temperature condition. A feasible explanation for

FIGURE 2: Stepwise procedure for carrying out the test and experimental analysis.

TABLE 3: Drivers' subjective scores of creep groan.

Test condition	Driver 1	Driver 2	Driver 3	Driver 4	Driver 5
I	7	7	6.5	6	6
II	8	8.5	7.5	7	7
III	7.5	7	7	6.5	6.5
IV	5	5	5.5	4.5	5
V	6	8	6	5.5	6
VI	5.5	5.5	5.5	5	5

FIGURE 3: Box plot of subjective scores under each test condition.

this might be that the higher the brake disc temperature within a specific range, the higher the friction coefficient, the better the braking performance, the smaller the brake friction-induced vibration and noise.

- (b) Comparing the test conditions I and II and IV and V, it can be found that the driver's subjective feeling of creep groan on the horizontal road is better than that on the downhill. When the vehicle is downhill, the gravity component of the vehicle provides an additional driving force. Compared with horizontal road, the brake disc needs bigger braking force for braking, resulting in severer brake friction-induced vibration and noise.
- (c) Comparing the test conditions I and III and IV and VI, it can be observed that the driver's subjective feeling of creep groan in downhill *N* gear condition is slightly better than that in downhill *D* gear condition. When the vehicle that engages *D* gear is downhill, an additional driving force will be generated by the engine. Compared with *N* gear condition, brake discs need more braking force to brake under *D* gear condition, which causes greater brake friction-induced vibration and noise.

4. Vibration Characteristics Analysis of Quintessential Test Conditions

It has been demonstrated in previous studies [18, 25, 34] that there are two principal forms of creep groan. One is intermittent shock vibration dominated by pulse signals, and the other is periodic vibration dominated by harmonic signals. In this section, two quintessential test conditions, II and IV, which have significant distinctions in the subjective evaluation, are selected to analyze. The vibration

characteristics are obtained by observing the time domain diagram, time-frequency spectrum, amplitude spectrum, and phase-plane portrait of the oil pressure, acceleration, and sound pressure signals; meanwhile, the occurrence conditions and transient dynamic characteristics of creep groan are explored.

4.1. High-Temperature D Gear Horizontal Road Driving Condition. In order to facilitate the comparison, the X, Y, and Z directions of the accelerations at the brake caliper and lower suspension arm are set through the acquisition channel to correspond to the longitudinal, lateral, and vertical directions of the vehicle coordinate system. Figure 4 manifests the time history of the brake oil pressure, interior sound pressure, and the acceleration of the brake caliper and lower suspension arm under test condition II. It can be discovered that seven times of braking occur in the test course of approximately 18 seconds. When the brake oil pressure drops to approximately 0.5 MPa, the acceleration of the brake caliper and lower suspension arm abruptly increases with sharp pulses, and the acceleration in the Z direction is larger. A transient creep groan phenomenon occurs in the test vehicle, which leads to an increase in the interior sound pressure.

Furthermore, time-frequency analysis of the Z-direction acceleration of brake caliper and lower suspension arm is performed, and the results are presented in Figure 5. As can be observed from the time-frequency spectra that the energy of creep groan is mainly concentrated in the frequency range of 20–600 Hz, the distribution of which is relatively uniform. The acceleration of the brake caliper and lower suspension arm has an energy concentration phenomenon at frequencies of 25 Hz and 50 Hz, which is speculated to be caused by the natural characteristics of the suspension. Since the creep groan under condition II is dominated by pulse signals and has a short duration, it is not conducive to the deep study of vibration characteristics.

4.2. Low-Temperature D Gear Downhill Driving Condition. Figure 6 exhibits the time domain diagram of all measured signals under test condition IV. By observing the time history of the brake oil pressure, as shown in Figure 6(a), starting and braking alternate for seven times in the test course of approximately 36 seconds. When the force exerted on the brake pedal is continuously released until the brake oil pressure reaches approximately 1.2 MPa, the acceleration of the brake caliper abruptly increases and lasts for a period of time, the Z-direction acceleration of which is larger, as shown in Figure 6(c). The vibration is subsequently transmitted to the lower suspension arm with a slight decrease in the Z-direction acceleration and an increase in the X and Y direction accelerations, as shown in Figure 6(d). A significant creep groan phenomenon occurs in the test vehicle, which is accompanied by the increase in sound pressure inside the vehicle, as shown in Figure 6(b). Since more force is required for braking when the vehicle is downhill, the brake oil pressure threshold that triggers the creep groan phenomenon is higher than that when driving

on the horizontal road. Brake caliper to lower suspension arm to the vehicle body is a vibration transmission path of creep groan. When the decreasing rate of brake oil pressure is low, or low oil pressure is maintained continuously, a severe creep groan phenomenon with long duration occurs. When the brake oil pressure decreases at a large rate, creep groan is dominated by short duration pulse signals.

The Z-direction accelerations of the brake caliper and lower suspension arm are analyzed by time-frequency method, and the results are exhibited in Figure 7. The time-frequency spectra demonstrate that there are two quintessential vibration modes of creep groan, one of which has uniform energy distribution in the frequency domain and lasts for a short time. The energy of the other vibration mode whose duration is prolonged concentrates on some specific frequencies in the frequency domain, and the frequency doubling phenomenon is presented. Under the same trigger condition, the creep groan phenomenon occasionally does not occur, and the time domain diagrams and time-frequency spectra of acceleration occasionally show different characteristics, which indicate that the occurrence of creep groan has random characteristics to some extent.

Transient dynamic characteristics of two quintessential vibration modes are further analyzed. A (7–7.2 s), B (16.6–16.8 s), and C (22.3–22.6 s) are regarded as three time periods, respectively, for amplitude frequency analysis and phase plane analysis. Figures 8–10 exhibit the time domain diagram, amplitude spectrum, and phase-plane portrait of the Z-direction acceleration of brake caliper in three time periods. The acceleration time domain diagram of stage A manifests periodic harmonic vibration characteristics with the fundamental frequency of approximately 75 Hz, and the energy of the first 5 order frequency components is dominated. Velocity-displacement phase-plane portrait manifests a stable limit cycle of stick-slip motion, as shown in Figure 8. The acceleration of stage B abruptly appears sharp pulse and subsequently attenuates rapidly, displaying the characteristics of intermittent and nonperiodic shock vibration. An intricate multifrequency coupling phenomenon appears in the amplitude spectrum, and the phase locus is disordered, which indicates that the vibration presents chaotic characteristics, as shown in Figure 9. The acceleration of stage C whose fundamental frequency is 76.65 Hz periodically attenuates at a constant rate from a large peak. The vibration energy is dominated by the first 4 order frequency components, and the phase locus is gradually separated from a limit cycle until it returns to stability, which reveals the periodic attenuation transition stage from harmonic vibration to system stability, as shown in Figure 10.

5. Objective Evaluation of Creep Groan

In this section, by exploring the correlation between brake friction-induced vibration and noise when creep groan occurs, it is found that the two signals have high coherence. Subsequently, objective evaluation indexes of vibration and noise are established to quantify the severity of creep groan, which provide data basis for relevance analysis of subjective and objective evaluation.

FIGURE 4: Time domain diagram of all measured signals under condition II: (a) oil pressure; (b) interior sound pressure; (c) acceleration at caliper; and (d) acceleration at lower suspension arm.

FIGURE 5: Time-frequency spectrum of Z-direction acceleration under condition II: (a) caliper; (b) lower suspension arm.

5.1. Correlation between Vibration and Noise. When creep groan occurs, the acceleration of the brake caliper and lower suspension arm abruptly increases, accompanied by the surge of the interior sound pressure, which indicates that there is a correlation between brake friction-induced vibration and noise to some extent. Figure 11 manifests the coherence function between the interior sound pressure and the accelerations of the brake caliper and lower suspension

arm when continuous creep groan phenomenon occurs, from which we can see that the coherence coefficient is high up to 0.9 near the fundamental frequency and its multi-frequency of the creep groan. It can be concluded that brake friction-induced vibration and noise are both closely related to the occurrence of the creep groan phenomenon, and it is feasible to evaluate the severity of creep groan by combining them.

FIGURE 6: Time domain diagram of all measured signals under condition IV: (a) oil pressure; (b) interior sound pressure; (c) acceleration at caliper; and (d) acceleration at lower suspension arm.

FIGURE 7: Time-frequency spectrum of Z-direction acceleration under condition IV: (a) caliper; (b) lower suspension arm.

FIGURE 8: Z-direction acceleration characteristics of brake caliper in stage (A): (a) time domain diagram; (b) amplitude spectrum; (c) phase-plane portrait.

FIGURE 9: Z-direction acceleration characteristics of brake caliper in stage (B): (a) time domain diagram; (b) amplitude spectrum; and (c) phase-plane portrait.

FIGURE 10: Z-direction acceleration characteristics of brake caliper in stage (C): (a) time domain diagram; (b) amplitude spectrum; and (c) phase-plane portrait.

FIGURE 11: Coherence function between the interior sound pressure and the acceleration: (a) acceleration at caliper; (b) acceleration at lower suspension arm.

5.2. Objective Evaluation Index of Vibration. The occurrence of the creep groan phenomenon is accompanied by the increase in acceleration. Therefore, the severity of creep groan can be quantified from the perspective of vibration by establishing objective evaluation indexes of brake friction-

induced vibration. In this study, four vibration evaluation indexes are proposed referring to Crowther [21].

The Z-direction acceleration of the brake caliper is relatively large, which is regarded as the basic data to establish vibration evaluation indexes, and 12.5% of the

difference between the maximum and the minimum is taken as the threshold. The time period when the absolute value of acceleration is higher than the threshold is regarded as the creep groan stage, the duration of which is defined as T . Based on the acceleration signal $a(t)$ in creep groan period T , the following four vibration evaluation indexes are established:

- (a) The difference between the maximum acceleration and the minimum acceleration in period T is defined as the peak-to-peak value q_1 of the acceleration $a(t)$ [21], which is used to evaluate the transient shock vibration intensity of creep groan, as shown in the following equation:

$$q_1 = a(t)_{\max} - a(t)_{\min}, \quad (2)$$

where $a(t)_{\max}$ and $a(t)_{\min}$ are the maximum and minimum values of the acceleration $a(t)$ in time period T , respectively.

- (b) The root mean square value of the acceleration $a(t)$ in period T is defined as q_2 [21], which is used to evaluate the effective steady-state vibration amplitude of creep groan, as shown in the following equation:

$$q_2 = \sqrt{\frac{1}{T} \int_0^T a^2(t) dt}. \quad (3)$$

- (c) The second-order moment of the acceleration $a(t)$ in period T is defined as q_3 [21], which is used to evaluate the energy of creep groan, as shown in the following equation:

$$q_3 = \int_0^T a^2(t) dt. \quad (4)$$

- (d) The fourth power vibration dose value of the pulse with the largest acceleration amplitude in the creep groan period T is defined as q_4 [29], which is used to evaluate the influence of peak vibration caused by excessive pulse on human body, as shown in the following equation:

$$q_4 = \left[\int_0^{T_{\text{impulse}}} a^4(t) dt \right]^{1/4}, \quad (5)$$

where T_{impulse} is the duration of the maximum acceleration pulse.

Based on the four vibration evaluation indexes defined above, the Z-direction acceleration at brake caliper of 29 groups of valid data is calculated in MATLAB, and the results are exhibited in Table 4.

5.3. Objective Evaluation Index of Noise. The occurrence of creep groan is also accompanied by the increase in noise. Therefore, A-weighted overall sound pressure level and three sound quality evaluation indexes, loudness, roughness, and fluctuation strength, are selected as objective evaluation

TABLE 4: Objective evaluation indexes of vibration.

Driver	Condition	q_1 (m/s ²)	q_2 (m/s ²)	q_3 (m ² /s ³)	q_4 (m/s ^{1.75})
1	I	29.275	0.765	5.214	3.950
	II	11.209	0.459	1.622	1.262
	III	32.155	0.554	1.120	4.416
	IV	107.345	2.170	27.018	13.172
	V	56.567	0.934	5.567	7.427
	VI	100.881	3.155	40.830	14.000
2	I	27.505	0.680	3.310	3.166
	II	6.929	0.410	3.321	0.760
	III	30.348	0.649	2.778	3.981
	IV	104.706	2.922	69.106	12.180
	VI	118.387	4.322	224.647	16.191
3	I	31.611	0.743	6.818	3.834
	II	11.832	0.487	3.468	1.350
	III	14.521	0.387	3.271	1.774
	IV	99.340	2.198	71.911	12.401
	V	43.789	1.358	66.034	6.480
	VI	89.733	2.313	53.915	12.030
4	I	61.370	0.940	7.146	8.416
	II	32.554	0.579	3.208	4.305
	III	39.071	1.134	5.445	5.016
	IV	118.417	3.139	127.729	15.803
	V	53.886	1.853	10.064	7.833
	VI	104.115	7.982	23.747	13.803
5	I	94.491	1.479	34.013	11.767
	II	39.568	0.779	5.280	4.940
	III	84.173	1.245	5.181	9.349
	IV	185.728	3.483	191.035	24.789
	V	74.706	2.206	23.970	9.780
	VI	114.871	6.058	57.361	14.703

indexes of noise in this study to jointly quantify the intensity of creep groan from the perspective of brake friction-induced noise. The interior sound pressure $s(t)$ in the creep groan period T is selected as the basic data for establishing the noise evaluation indexes.

- (a) First, $s(t)$ is filtered by A-weighting to obtain $s_A(t)$, subsequently, $s_A(t)$ is processed by RMS (Root Mean Square) and logarithm to obtain A-weighted overall sound pressure level [35], which are expressed as

$$p_e = \sqrt{\frac{1}{T} \int_0^T s_A^2(t) dt}, \quad (6)$$

$$\text{SPL}(A) = 20 \log_{10} \frac{p_e}{p_{\text{ref}}},$$

where p_e is the effective value of $s_A(t)$, i.e., the root mean square value, $p_{\text{ref}} = 2 \times 10^{-5}$ Pa, is the minimum sound pressure amplitude that can be heard by the human ear at the frequency of 1000 Hz, and $\text{SPL}(A)$ is the A-weighted overall sound pressure level.

- (b) In this study, the Zwicker loudness model [36] is used to evaluate the intensity of the interior noise when creep groan occurs. Based on the 1/3 octave spectrum, Zwicker introduced the concept of critical

band and characteristic loudness. First, the characteristic loudness of each critical band is calculated; subsequently, the total loudness value is obtained, which is expressed as

$$L' = 0.08 \left(\frac{E_{TQ}}{E_0} \right)^{0.23} \left[\left(0.5 + 0.5 \frac{E}{E_{TQ}} \right)^{0.23} - 1 \right],$$

$$\text{Loudness} = \int_0^{24\text{Bark}} L'(z) dz (\text{sone}), \quad (7)$$

where E_{TQ} is the excitation under the absolute threshold of hearing, E_0 is the excitation under the reference sound intensity, z is the critical band level, the critical band sound pressure level of $s(t)$ is taken as the excitation level E , L' is the characteristic loudness on the critical band z , and *Loudness* is the total loudness.

- (c) The roughness model modified by Zwicker and Fastl [37] is used to evaluate the modulation degree, amplitude, and frequency distribution of the interior noise $s(t)$ when creep groan occurs, which is expressed as

$$\text{Roughness} = 0.3 f_{\text{mod}} \int_0^{24\text{Bark}} 20 \log_{10} \left(\frac{L'_{\max}(z)}{L'_{\min}(z)} \right) dz (\text{asper}), \quad (8)$$

where f_{mod} is the modulation frequency, $L'_{\max}(z)$ and $L'_{\min}(z)$ are the maximum and minimum characteristic loudness on the critical band z , respectively, *Roughness* is the roughness of $s(t)$.

- (d) The Zwicker fluctuation strength model [37] is used to evaluate the fluctuation degree of the interior noise $s(t)$ when creep groan occurs, which is expressed as

$$\text{Fluctuation} = 0.008 \cdot \frac{\int_0^{24\text{Bark}} 20 \log_{10} (L'_{\max}(z)/L'_{\min}(z)) dz}{(f_{\text{mod}}/4) + (4/f_{\text{mod}})} (\text{vacil}), \quad (9)$$

where *Fluctuation* is the fluctuation strength of $s(t)$.

Based on the four noise evaluation indexes defined above, the interior sound pressure $s(t)$ in 29 groups of valid data is calculated in MATLAB, and the results are provided in Table 5.

6. Relevance of Subjective and Objective Evaluation

In order to verify the effectiveness of the vibration and noise evaluation indexes, linear regression analysis is conducted on evaluation indexes and subjective scores in this section, and the advantages and disadvantages of each evaluation index are compared. Furthermore, vibration and noise evaluation indexes are comprehensively contemplated and multiple linear regression analysis is performed to achieve a better fitting result. Finally, the regression model that combines brake friction-induced vibration and noise to quantify the severity of creep groan is obtained, the accuracy of which is high after verification.

6.1. Linear Regression Analysis. Previous studies [38] on vibration have revealed that vibration has better linear correlation with human subjective feelings in logarithmic coordinates. Meanwhile, noise evaluation indexes proposed above are also processed logarithmically. In order to make

the vibration evaluation indexes to have the same magnitude order as noise evaluation indexes and improve their correlation with subjective feelings, q_1 , q_2 , q_3 , and q_4 are logarithmically processed by equation (10) to obtain four logarithmic dose vibration evaluation indexes Q_1 , Q_2 , Q_3 , and Q_4 :

$$Q_i = 20 \log_{10} q_i \quad (i = 1, 2, 3, 4). \quad (10)$$

The subjective score of effective data and the objective indexes of noise and logarithmic dose vibration under corresponding test conditions are fitted by linear regression analysis, and the R^2 (coefficient of determination) and adjusted R^2 (adjusted coefficient of determination) are computed. The adjusted R^2 contemplates and rectifies the influence of the number of variables on the basis of R^2 . The closer R^2 and adjusted R^2 to 1, the better the linear correlation. Figure 12 displays the linear fitting results of each evaluation index and subjective evaluation. Table 6 manifests R^2 and adjusted R^2 of each evaluation index. It can be concluded that Q_1 , Q_2 , Q_3 , Q_4 , $SPL(A)$, and *Loudness* have satisfying linear correlation with subjective evaluation, which can be used to evaluate the annoyance degree caused by creep groan. *Roughness* and *Fluctuation* have poor linear correlation with subjective evaluation, which means that they are not suitable as objective evaluation indexes of noise to assess the severity of creep groan.

TABLE 5: Objective evaluation indexes of noise.

Driver	Condition	SPL(A) (dB(A))	Loudness (sone)	Roughness (asper)	Fluctuation (vacil)
1	I	61.087	7.202	1.165	0.01241
	II	58.863	6.176	1.059	0.01128
	III	57.124	5.755	0.936	0.00997
	IV	75.307	23.770	1.235	0.01315
	V	62.714	11.492	1.015	0.01081
	VI	72.069	20.120	1.259	0.01341
2	I	57.810	5.529	0.944	0.01005
	II	54.490	5.547	0.901	0.00959
	III	55.269	5.458	0.910	0.00969
	IV	69.552	17.480	1.162	0.01237
	VI	75.022	23.900	1.317	0.01403
3	I	57.039	7.268	1.214	0.01293
	II	54.580	5.334	0.949	0.01011
	III	53.275	6.145	0.931	0.00991
	IV	68.877	16.530	1.118	0.01191
	V	65.810	12.247	1.216	0.01295
	VI	68.881	16.420	1.069	0.01139
4	I	63.705	9.402	1.050	0.01118
	II	57.662	6.512	0.986	0.01050
	III	61.841	9.955	1.424	0.01517
	IV	73.819	22.370	1.341	0.01428
	V	68.795	15.356	1.110	0.01182
	VI	72.969	21.380	1.307	0.01392
5	I	63.690	11.457	1.253	0.01334
	II	59.220	8.373	0.983	0.01047
	III	61.128	11.180	1.300	0.01384
	IV	75.080	20.830	1.180	0.01257
	V	69.546	16.750	1.173	0.01250
	VI	75.614	24.080	1.197	0.01275

6.2. Multiple Linear Regression Analysis. Vibration and noise evaluation indexes have distinct emphases in describing the creep groan, which leads to some limitations in the correlation between single evaluation index and subjective feelings. Vibration and noise evaluation indexes are taken into consideration simultaneously, and the multiple linear regression method is used to analyze the correlation between subjective evaluation and all indexes, which is more comprehensive and representative to describe the dimension of creep groan severity.

The multiple linear regression analysis is applicable to clarify the influence of each independent variable on the dependent variable when a dependent variable is affected by multiple independent variables simultaneously. This method considers the interaction among independent variables and obtains a regression equation to better interpret the linear relationship, which can predict the dependent variable according to the independent variable. The multiple linear regression equation can be expressed as

$$Y = k_0 + k_1X_1 + k_2X_2 + \cdots + k_nX_n + \varepsilon, \quad (11)$$

where Y is the dependent variable, X_i ($i = 1, 2, \dots, n$) is the explanatory variable, ε is the residual, and k_i ($i = 1, 2, \dots, n$) is the partial regression coefficient, which indicates the influence of the unit change in the explanatory variable X_i on the average value of the dependent variable when other

explanatory variables are controlled to be unchanged. k_0 is the constant term of the partial regression coefficient.

In this study, subjective score Y is regarded as the dependent variable, and six effective evaluation indexes, Q_1 , Q_2 , Q_3 , Q_4 , $SPL(A)$, and $Loudness$, which have a high correlation with subjective score, are taken as explanatory variables. The main target of multiple linear regression analysis is to obtain partial regression coefficients. SPSS (statistical product and service solutions) software is utilized for multiple linear regression analysis, which sets the confidence of the regression equation to 95%. A stepwise method considering the collinearity among explanatory variables is adopted for analysis, and the results are exhibited in Table 7.

After collinearity judgment, only Q_4 , $Loudness$, and the constant term are left, and the VIF (variance expansion factor) of Q_4 and $Loudness$ is 3.385, revealing that there is almost no collinearity between the two indexes. The DW (Durbin–Watson) value of the model is 1.76, close to 2, which substantiates that the explanatory variables of the model have no autocorrelation. The P values of Q_4 and $Loudness$ are both less than 0.05; meanwhile, the R^2 and adjusted R^2 are 0.901 and 0.893, respectively, substantiating that the brake friction-induced vibration and noise have a high correlation with the subjective score Y . The model can be used to predict the subjective feeling of the human body on creep groan, which is expressed as

FIGURE 12: Linear regression line of evaluation index: (a) Q_1 ; (b) Q_2 ; (c) Q_3 ; (d) Q_4 ; (e) $SPL(A)$; (f) $Loudness$; (g) $Roughness$; and (h) $Fluctuation$.

TABLE 6: R^2 and adjusted R^2 of each objective evaluation index.

Objective index	R^2	Adjusted R^2
Q_1	0.846	0.840
Q_2	0.809	0.802
Q_3	0.717	0.707
Q_4	0.849	0.843
$SPL(A)$	0.817	0.810
$Loudness$	0.805	0.797
$Roughness$	0.417	0.396
$Fluctuation$	0.417	0.396

$$Y = 8.281 - 0.077Q_4 - 0.064 Loudness. \quad (12)$$

6.3. Validation of Regression Model. Based on the regression equation, the subjective score of each driver under six test conditions can be predicted. Comparing the predicted scores with Table 1, the extent to which the equation accurately describes creep groan severity can be checked, as shown in Table 8. It can be revealed that the errors between the predicted average subjective scores and the actual average subjective scores under six test conditions are within 4%,

which demonstrates that the regression model can accurately represent the annoyance degree caused by creep groan under different test conditions.

In order to further check the reliability of the regression model, a new experimenter conducts the road test following the procedure described above under the same conditions. After the data collected under six test conditions are processed, Q_4 and $Loudness$ are obtained, which are substituted into the regression model to predict the subjective evaluation of the experimenter on creep groan intensity. The predicted scores are compared with the actual scores to verify the effectiveness of the model. The results are presented in Table 9. It can be observed that the errors between the score predicted by the regression model and the score actually evaluated by the experimenter are mostly within 10%, indicating that the prediction precision is acceptable. The verification of the derived regression equation illustrates that the model combined with brake friction-induced vibration and noise can better describe the intensity of the creep groan.

The establishment of the regression model that obtained based on abundant experimental data has significant engineering application value for predicting automobile creep groan severity. When the test vehicle is running on

TABLE 7: Results of multiple linear regression analysis.

Explanatory variable	Partial regression coefficient	p	VIF	DW	R^2	Adjusted R^2
Constant	8.281	—	—			
Q_4	−0.077	<0.001	3.385	1.76	0.901	0.893
<i>Loudness</i>	−0.064	0.001	3.385			

TABLE 8: Predicted subjective scores and errors.

Condition	Driver 1	Driver 2	Driver 3	Driver 4	Driver 5	Predicted average score	Actual average score	Average error (%)
I	6.90	7.16	6.92	6.25	5.90	6.63	6.50	1.9
II	7.73	8.11	7.74	6.89	6.68	7.43	7.60	2.3
III	6.92	7.01	7.50	6.57	6.07	6.81	6.90	1.3
IV	5.04	5.49	5.54	5.00	4.80	5.17	5.00	3.5
V	6.20	—	6.25	5.92	5.68	6.38	6.375	0.1
VI	5.23	4.89	5.57	5.16	4.94	5.16	5.3	2.7

TABLE 9: Objective evaluation indexes and predicted subjective scores.

Condition	Q_4 (dB)	<i>Loudness</i> (sone)	Predicted score	Actual score	Error (%)
I	6.522	16.610	6.72	6	11.9
II	1.884	11.565	7.40	7	5.7
III	6.699	10.333	7.10	6.5	9.3
IV	21.817	20.500	5.29	5	5.8
V	12.927	11.217	6.57	6	9.5
VI	20.209	17.030	5.63	5.5	2.5

the actual road, an accelerometer and a microphone are arranged at the brake caliper and driver's seat headrest, respectively, which are used to measure the acceleration and interior sound pressure. The vibration and noise evaluation indexes of the collected signals are calculated and substituted into the regression model to obtain a subjective score. The intensity of creep groan is quantified by the subjective score from the side. The lower the score, the more severe the creep groan; the higher the score, the slighter the creep groan.

7. Conclusion and Discussion

Based on the experimental and theoretical analysis of automobile brake creep groan, the following conclusions can be drawn:

- (1) Experimentally, a vehicle road test of creep groan is conducted under six test conditions, and the influence of the initial temperature of brake discs, terrain, and gear position on creep groan severity is found. In a lower temperature range, the friction coefficient of brake discs decreases with the decrease in its temperature, which leads to poorer braking performance and severer brake friction-induced vibration and noise. In downhill terrain, the gravity component of the vehicle provides an additional driving force, which makes brake discs to require greater braking force for braking than in flat terrain, resulting in severer brake friction-induced vibration and noise. When the vehicle is downhill, the engine in D gear condition will generate an additional driving force than that in the N gear condition. The force exerted

on the brake pedal will be larger, which will increase the intensity of creep groan.

- (2) Based on theoretical transient dynamic analysis of the measured data under quintessential test conditions, it can be illustrated that the creep groan phenomenon contains two quintessential vibration modes. One is intermittent and nonperiodic shock vibration with a short duration, the energy distribution of which is uniform in the frequency domain. This vibration mode manifests an intricate multi-frequency coupling phenomenon, and the velocity-displacement phase-plane portrait is disordered, which indicates that the vibration presents significant chaotic characteristics. The other is a periodic harmonic vibration with a prolonged duration, whose energy concentrates on some specific frequencies in the frequency domain. The fundamental frequency of this vibration mode is approximately 75 Hz, and 75 Hz and its multifrequency are the principal frequency components. The phase locus shows a stable limit cycle of stick-slip motion.
- (3) Analytically, Q_1 , Q_2 , Q_3 , Q_4 , $SPL(A)$, and *Loudness* can effectively describe the annoyance degree caused by creep groan. The regression model combining vibration and noise indexes is more accurate after validation, which can calculate a score based on the brake caliper acceleration and interior sound pressure. The score represents the driver's subjective evaluation of brake friction-induced vibration and noise under the corresponding condition, whose magnitude quantifies the intensity of creep groan from the perspective of drivers' subjective feelings.

Referring to the scoring criteria in Table 2, if the score calculated by the regression model is between 6 and 7, it indicates that the creep groan intensity of the test vehicle is moderate. If the score is lower than 6, brake friction-induced vibration and noise are severe, and if the score is higher than 7, the creep groan phenomenon is not significant. All subjective scores that recorded in the test range from 4.5 to 8.5, which demonstrates that the test conditions set in the experiment have some limitations. Subsequent experimental studies could add multiple extreme conditions, which can not only increase the diversity of test conditions, but also benefit the improvement of model accuracy. The prediction error of the regression model for the average score of multiple experimenters is lower than 4%, but the maximum prediction error for the score of a single experimenter is up to 11.9%. It can be illustrated that the diversity of experimenters has a significant effect on reducing the prediction error of creep groan intensity. Notably, due to the fact that different vehicles have different dependencies on evaluation indexes, this model is only applicable to the vehicle in this experiment. Nevertheless, the regression model for predicting the creep groan intensity of other vehicles can be obtained by using the research method of this study, which has paramount reference value in engineering applications.

Nomenclature

X_i, X_j :	Subjective score of the driver i and j , respectively
$\bar{X}, \sigma$:	Arithmetic average and standard deviation of four remaining subjective scores, respectively
n :	The number of drivers
α :	Significance level
$K(n, \alpha)$:	Test coefficient
T :	The duration of creep groan stage
$a(t)$:	Acceleration at the brake caliper
$a(t)_{\max}$:	Maximum and minimum values of
$a(t)_{\min}$:	acceleration at the brake caliper, respectively
q_1, q_2, q_3, q_4 :	Peak-to-peak value, root mean square value, second-order moment, and fourth power vibration dose value of acceleration at the brake caliper, respectively
T_{impulse} :	The duration of maximum acceleration pulse at the brake caliper
$s(t)$:	Interior sound pressure
$s_A(t)$:	Interior sound pressure after A-weighted filtering processing
p_e :	Root mean square value of interior sound pressure after A-weighted filtering processing
p_{ref} :	Minimum sound pressure amplitude that can be heard by the human ear at the frequency of 1000 Hz
$SPL(A)$:	A-weighted overall sound pressure level of interior sound pressure
E_{TQ}, E_0 :	Excitation under the absolute threshold of hearing and reference sound intensity, respectively
z :	Critical band level

E :	Critical band sound pressure level of interior sound pressure
$L'(z)$:	Characteristic loudness on the critical band z
$Loudness$:	Total loudness of interior sound pressure
f_{mod} :	Modulation frequency
$L'_{\max}(z)$,	Maximum and minimum characteristic
$L'_{\min}(z)$:	loudness of the critical band z , respectively
$Roughness$:	Roughness of interior sound pressure
$Fluctuation$:	Fluctuation strength of interior sound pressure
Q_1, Q_2, Q_3 ,	Logarithmic dose vibration evaluation
Q_4 :	indexes corresponding to q_1, q_2, q_3, q_4 , respectively
R^2 :	Coefficient of determination
X_i :	Explanatory variable
Y :	Subjective score
k_i :	Partial regression coefficient
ε :	Residual
p :	P value
VIF:	Variance expansion factor
DW:	Durbin-Watson value.

Data Availability

The data used to support the finding of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant number 52072270).

References

- [1] X. Meng, H. Wang, and G. Wu, "Review of research on brake groan," *Journal of Highway and Transportation Research and Development*, vol. 26, no. 2, pp. 124–128, 2009.
- [2] L. Zhang, Y. Zheng, D. Meng, and P. Zhang, "Literature survey of friction induced automotive brake groan," *Journal of Tongji University*, vol. 44, no. 3, pp. 420–426, 2016.
- [3] C. Cantoni, R. Cesarini, G. Mastinu, G. Rocca, and R. Sicigliano, "Brake comfort - a review," *Vehicle System Dynamics*, vol. 47, no. 8, pp. 901–947, 2009.
- [4] Sae Brake Nvh Standards Committee, "Automotive brake noise and vibration standard nomenclature," SAE Technical Paper J2786-2009, 2009.
- [5] J. Brecht, W. Hoffrichter, and A. Dohle, "Mechanisms of brake creep groan," SAE Technical Paper 973026, 1997.
- [6] V. Vadari and M. Jackson, "An experimental investigation of disk brake creep-groan in vehicles and brake dynamometer correlation," SAE Technical Paper 1999-01-3408, 1999.
- [7] M. Bettella, M. F. Harrison, and R. S. Sharp, "Investigation of automotive creep groan noise with a distributed-source excitation technique," *Journal of Sound and Vibration*, vol. 255, no. 3, pp. 531–547, 2002.
- [8] H. Hetzler, D. Schwarzer, and W. Seemann, "Steady-state stability and bifurcations of friction oscillators due to velocity-

- dependent friction characteristics," *Proceedings - Institution of Mechanical Engineers, Part K (Journal of Multi-Body Dynamics)*, vol. 221, no. K3, pp. 401–413, 2007.
- [9] K. B. Dunlap, M. A. Riehle, and R. E. Longhouse, "An investigative overview of automotive disc brake noise," SAE Technical Paper 1999-01-0142, 1999.
 - [10] K. Okayama, H. Fujikawa, T. Kubota, and K. Kakiyama, "A study on rear disc brake groan noise immediately after stopping," SAE Technical Paper 2005-01-3917, 2005.
 - [11] M. Gouya and M. Nishiwaki, "Study on disc brake groan," SAE Technical Paper 900007, 1990.
 - [12] M. Gonzalez, R. Diez, and E. Canibano, "Comparative analysis of vented brake discs in groan noise test on dynamometer," SAE Technical Paper 2004-01-2789, 2004.
 - [13] T. Nagayoshi, M. Inoue, and Y. Hara, "Groan caused by generation of striped pattern of transfer film on a ventilated rotor," SAE Technical Paper 2004-01-2788, 2004.
 - [14] J. Brecht and K. Schiffrer, "Influence of friction law on brake creep-groan," SAE Technical Paper 2001-01-3138, 2001.
 - [15] M. Inoue, "The stick-slip motion of disc brake pads," *Transactions of the Japan Society of Mechanical Engineers Series C*, vol. 56, no. 521, pp. 166–171, 1990.
 - [16] M. R. Ishak, A. R. Abu Bakar, A. Belhocine, J. M. Taib, and W. Z. W. Omar, "Brake torque analysis of fully mechanical parking brake system: theoretical and experimental approach," *Measurement*, vol. 94, pp. 487–497, 2016.
 - [17] D. Meng, L. Zhang, X. Xu, Y. Sardahi, and G. S. Chen, "Sensing and quantifying a new mechanism for vehicle brake creep groan," *Shock and Vibration*, vol. 2019, pp. 1–10, 2019.
 - [18] D. Meng, L. Shen, L. Zhang, and G. S. Chen, "Transient dynamic analysis of vehicle brake creep groan," *Journal of Vibration Engineering & Technologies*, vol. 7, no. 6, pp. 591–601, 2019.
 - [19] Z. Fuadi, K. Adachi, H. Ikeda, H. Naito, and K. Kato, "Effect of contact stiffness on creep-groan occurrence on a simple caliper-slider experimental model," *Tribology Letters*, vol. 33, no. 3, pp. 169–178, 2009.
 - [20] A. R. Crowther and R. Singh, "Analytical investigation of stick-slip motions in coupled brake-driveline systems," *Nonlinear Dynamics*, vol. 50, no. 3, pp. 463–481, 2007.
 - [21] A. R. Crowther and R. Singh, "Identification and quantification of stick-slip induced brake groan events using experimental and analytical investigations," *Noise Control Engineering Journal*, vol. 56, no. 4, pp. 235–255, 2008.
 - [22] L. Zhang, P. Zhang, and D. Meng, "Tests and theoretical analysis of creep groan in vehicle disc brake," *Automotive Engineering*, vol. 38, no. 9, pp. 1132–1139, 2016.
 - [23] M. Donley and D. Riesland, "Brake groan simulation for a McPherson strut type suspension," SAE Technical Paper 2003-01-1627, 2003.
 - [24] K. Uchiyama and Y. Shishido, "Study of creep groan simulation by implicit dynamic analysis method of FEA (Part 2)," SAE Technical Paper 2014-01-2516, 2014.
 - [25] D. Meng, L. Zhang, J. Xu, and Z. Yu, "A transient dynamic model of brake corner and subsystems for brake creep groan analysis," *Shock and Vibration*, vol. 2017, pp. 1–18, 2017.
 - [26] A. Belhocine and N. M. Ghazaly, "Effects of young's modulus on disc brake squeal using finite element analysis," *International Journal of Acoustics and Vibration*, vol. 21, no. 3, pp. 292–300, 2016.
 - [27] A. Belhocine and O. I. Abdullah, "A thermomechanical model for the analysis of disc brake using the finite element method in frictional contact," *Journal of Thermal Stresses*, vol. 43, no. 3, pp. 305–320, 2020.
 - [28] M. K. Abdelhamid and W. Bray, "Braking systems creep groan noise: detection and evaluation," SAE Technical Paper 2009-01-2103, 2009.
 - [29] L. Zhang, J. Huang, D. Meng, and P. Zhang, "Objective measurement and subjective evaluation for brake creep groan based on road tests," *Journal of Vibration and Shock*, vol. 36, no. 9, pp. 186–194, 2017.
 - [30] X. Wu, *Motor Vehicles—General Rules of Road Test Method*, GB/T 12534-1990, 1990.
 - [31] M. A. Luciano, O. Madruga, and C. A. Costa, "A method for measuring creep groan based on brake inertial dynamometer," SAE Technical Paper 2005-01-4126, 2005.
 - [32] K. I. Groenhout, "The detection of gross errors," *Australian Surveyor*, vol. 29, no. 3, pp. 174–190, 1978.
 - [33] T. Fei, *Error Theory and Data Processing*, China Machine Press, Beijing, China, 2010.
 - [34] L. Zhang, X. Zhang, D. Meng, and Z. Yu, "Nonlinear vibration characteristic analysis of brake groan based on road tests," *Journal of Vibration, Measurement & Diagnosis*, vol. 39, no. 4, pp. 739–744, 2019.
 - [35] R. Nojima and H. Sato, "Evaluation of floor impact sound by maximum value of A-weighted sound pressure level," *Journal of Environmental Engineering*, vol. 86, no. 781, pp. 227–236, 2021.
 - [36] E. Zwicker, H. Fastl, U. Widmann, K. Kurakata, S. Kuwano, and S. Namba, "Program for calculating loudness according to DIN 45631 (ISO 532B)," *Journal of the Acoustical Society of Japan*, vol. 12, no. 1, pp. 39–42, 1991.
 - [37] E. Zwicker and H. Fastl, *Psychoacoustics: Facts and Models*, Springer-Verlag, Berlin/Heidelberg, Germany, 1999.
 - [38] A. R. Mohanty and S. Fatima, "An overview of automobile noise and vibration control," *Noise & Vibration Worldwide*, vol. 44, no. 6, pp. 10–19, 2013.