Mechanical Systems and Signal Processing 118 (2019) 305–316

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Analysis of the stick-slip vibration of a new brake pad with double-layer structure in automobile brake system

Daogao Wei [a,*], Junwei Song [a], Yanghai Nan [b], Weiwei Zhu [a]

[a] School of Automotive and Transportation Engineering, Hefei University of Technology, Hefei 23009, Anhui, China
[b] School of Engineering and Built Environment, Glasgow Caledonian University, Glasgow, UK

ARTICLE INFO

Article history:
Received 1 December 2017
Received in revised form 13 July 2018
Accepted 26 August 2018

Keywords:
Stability
Hopf-bifurcation
Chaos
Stick-slip
Tangential vibration

ABSTRACT

This study establishes a dynamic model of a new brake system with two-layer structure to explore the mechanism of vibration and noise reduction of a brake pad with new structure. The model is used to analyze the effects of parameters of the double-layer pad on the stability and stick-slip vibration characteristics of the brake system. The stability of the brake system is optimized by brake parameters with respect to the stability diagram of brake pressure under a relatively wide range. System vibration modes can be changed from period-doubling bifurcation to chaos based on the variation of brake pressure and the parameters of double-layer pad via numerical analysis. The chaotic vibration region is optimized in this study using the correlation coefficient, which consists of friction-layer pad mass m_{b2} and connection stiffness k_2. Results show that the range of chaotic vibration region can be reduced when the friction-layer pad mass and connection stiffness are large.

1. Introduction

The stick-slip vibration (creep groan) induced by vehicle braking under low speed is one of the challenges in the automotive industry. Scholars have experimentally and theoretically studied this phenomenon. Experimental studies [1–4] mainly focus on testing various friction materials; these methods are costly and inefficient and the results are merely experimental. By contrast, theoretical studies reveal the mechanism of stick-slip vibration by analyzing the dynamic models of brake system. This approach is efficient and the results are universal. The single degree of freedom (SDOF) of slider–sliding belt model was widely used as a brake system model because of its simple structure. Recent related studies found that (1) the stick-slip vibration is a Hopf bifurcation [5,6] induced by the negative correlation between friction and velocity [7–9]; studies also found the existence of (2) a boundary value of relative velocity, that is, stick-slip motion will occur only when relative velocity is lower than the boundary value of relative velocity [10–12].

Scholars proposed complicated models with multiple degrees of freedom (MDOF) because the slider–sliding belt model neglects the interaction between the disk and pad. Shin [13,14] simplified the physical model into a two-DOF system model coupled with a friction pair of disk and pad; this study found the periodic and chaotic vibration of the system. Paliwal [15] considered the interfacial coupling stiffness between the disk and pad based on Shin's model, and studied the impact of coupling stiffness on the stability and stick-slip vibrations of the brake system. Yang [16] established a three-DOF model by considering the flexible connection between the caliper and the pad, and discussed the characteristics of period-doubling

* Corresponding author.
E-mail address: weidaogao@hfut.edu.cn (D. Wei).

https://doi.org/10.1016/j.ymssp.2018.08.055
0888-3270/

bifurcation and chaos for various disk speeds. These models are self-excited vibration model with dimensionless parameters. Brecht [17] proposed a model that considered the effect of power train based on real physical parameters; this model could simulate the event for brake release on takeoff.

Each dynamic model is denoted by a tangential vibration perspective. Crowther [18,19] created a four-DOF torsional model by integrating the driveline, which is composed of the power plant, disk, and tire, with brake torsional subsystems coupled with friction pair; this study identified three types of stick-slip motions with different brake pressures. Zhang [20] simplified this four-DOF torsional model into a two-DOF model and analyzed the periodic stick-slip motion of the system under different driving speeds. Wu [21] built a subtle seven-DOF model by considering the torsional and tangential motion of the pad. He studied the effect of the release rate of brake pedal on stick-slip vibration. Hetzler [22] proposed a new brake system model that considered the tangential and torsional motion of the pad and disk. This study presented the behavior of periodic stick-slip motion. To reduce brake groan, two primary aspects were considered, namely, friction material and brake structure. Li [23] developed a torsional model of a wedge brake with SDOF using harmonic excitation from the driveline; this study investigated the effect of actuation force and wedge angle on system vibration. Lin [24] analyzed brake lining with three layer structures and found that this structure could significantly reduce vibration and braking noise. Shen [25] provided three-layer pad with two materials; the first and the third pad are plastic and the second is made of felt material. This approach can reduce noise and improve the impact resistance of pad to ensure the stability of the brake system. Gao [26] proposed a process of obtaining pad through metal-based sintering; this process improves the friction coefficient of adhesion and wear resistance. These studies show that the single-layer pad widely used in automobiles has been changed to a multi-layer pad, which is composed of different materials. This transformation was achieved by changing the structure to obtain pad with varied stiffness and damping. To a certain extent, this process can improve the stability of the braking system and reduce braking vibration and noise. However, these studies mainly verified the ability of multi-layer pad to improve braking vibration by means of experiments. The dynamic mechanism of the brake system remains unclear.

This study simplified the three-layer pad into a two-layer pad. The double-layer pad is divided into friction-layer and base-layer pad. The friction-layer pad contacts with the disk to produce brake force, whereas the base-layer pad acts as the buffer and support. In order to explore the vibration and noise reduction mechanism of brake system with multi-layer pad, a new dynamic model and differential equation of three-DOF are established. Analyzing the stability and the characteristics of bifurcation and chaos of the brake system and optimizing the pad parameters further increased the stability of the brake system and reduced the occurrence of chaotic vibration.

In this paper, we propose a brake system model of double-layer pad, which is based on the literature of the citations. Based on this model, the dynamic differential equation of brake system with three degrees of freedom is established. First of all, the stability of the brake system is analyzed qualitatively. Secondly, the influence of mass (m_{b2}) and stiffness (k_2) on the vibration characteristics of brake system is analyzed by numerical method. Second, the influence of pad mass discussion (m_{b2}) and connection stiffness (k_2) on the vibration characteristics of the brake system is analyzed numerically. Finally, the chaotic vibration characteristics of the brake system are optimized to determine the influence of m_{b2}, k_2 and brake pressure on the chaotic vibration region of the system.

2 Dynamic model of brake system with double-layer pad

Considering the existing multi-layer brake block products only have preliminary vibration test and manufacturing process analysis, we demonstrate that this product has better advantages of vibration reduction and noise reduction than single layer, which has not been analyzed by mechanical and mathematical models in the literature. We want to explore and explain its vibration mechanism by using dynamic and mathematical models, so as to provide theoretical reference for design, manufacture and test research, and also to provide a modeling method and solution technology for future optimal design of multi-layer brake blocks. The model has been greatly simplified in connection stiffness and damping, which needs further study.

We obtained the dynamic model of the brake system based on our former model [27–29] by connecting the base and friction-layer pad through a liner spring and damper; the former model is shown in Fig. 1. In this model, m_{b1} represents the mass of base-layer pad and the equivalent masses of the caliper, floor and so on, m_{b2} represents the mass of the friction-layer pad, and J_r denotes the inertia of the brake disk assembly. Parameters k_1, c_1 denote the stiffness and damping of the base-layer pad, whereas k_2, c_2 are the stiffness and damping between the base and friction-layer pad. The stiffness and damping of brake disk assembly are denoted by k_r, c_r; x_{b1} and x_{b2} denote the tangential displacement of the base and friction-layer pad respectively, and θ_r is the torsional angular displacement of the brake disk assembly; r_b indicates distance between the two pads and the center of the disk (hereafter referred to as friction radius), v_r is the relative velocity between the pad and disk; ω denotes the angular velocity input exerted on the disk; F_N is the brake pressure applied on the base-layer pad; and F_b is the friction force acting on the friction-layer pad; T_b represents the friction torque on the brake disk.

Following Newton's law, the mechanical model shown in Fig. 1 is represented by three differential equations of motion:

$$\begin{cases} m_{b1}\ddot{x}_{b1} + c_1\dot{x}_{b1} + k_1x_{b1} + c_2(\dot{x}_{b1} - \dot{x}_{b2}) + k_2(x_{b1} - x_{b2}) = 0 \\ m_{b2}\ddot{x}_{b2} + c_2(\dot{x}_{b2} - \dot{x}_{b1}) + k_2(x_{b2} - x_{b1}) = F_b \\ J_r\ddot{\theta}_r + c_r\dot{\theta}_r + k_r\theta_r = T_b \end{cases} \quad (1)$$