Mechanical Systems and Signal Processing 93 (2017) 281–298

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

A unified approach for squeal instability analysis of disc brakes with two types of random-fuzzy uncertainties

Hui Lü [a,*], Wen-Bin Shangguan [a], Dejie Yu [b]

[a] School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou, Guangdong 510641, China
[b] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha, Hunan 410082, China

ARTICLE INFO

Article history:
Received 12 May 2016
Received in revised form 6 December 2016
Accepted 10 February 2017
Available online 20 February 2017

Keywords:
Squeal instability
Random uncertainty
Fuzzy uncertainty
Unified approach

ABSTRACT

Automotive brake systems are always subjected to various types of uncertainties and two types of random-fuzzy uncertainties may exist in the brakes. In this paper, a unified approach is proposed for squeal instability analysis of disc brakes with two types of random-fuzzy uncertainties. In the proposed approach, two uncertainty analysis models with mixed variables are introduced to model the random-fuzzy uncertainties. The first one is the random and fuzzy model, in which random variables and fuzzy variables exist simultaneously and independently. The second one is the fuzzy random model, in which uncertain parameters are all treated as random variables while their distribution parameters are expressed as fuzzy numbers. Firstly, the fuzziness is discretized by using α-cut technique and the two uncertainty analysis models are simplified into random-interval models. Afterwards, by temporarily neglecting interval uncertainties, the random-interval models are degraded into random models, in which the expectations, variances, reliability indexes and reliability probabilities of system stability functions are calculated. And then, by reconsidering the interval uncertainties, the bounds of the expectations, variances, reliability indexes and reliability probabilities are computed based on Taylor series expansion. Finally, by recomposing the analysis results at each α-cut level, the fuzzy reliability indexes and probabilities can be obtained, by which the brake squeal instability can be evaluated. The proposed approach gives a general framework to deal with both types of random-fuzzy uncertainties that may exist in the brakes and its effectiveness is demonstrated by numerical examples. It will be a valuable supplement to the systematic study of brake squeal considering uncertainty.

1. Introduction

During the braking of automotive, friction-induced vibrations and instabilities can be excited by friction and it is likely to produce undesirable squealing noise. The squealing noise usually ranges from 1 to 16 kHz and its sound pressure level is greater than 70 dB [1]. Brake squeal is a source of considerable discomfort and can lead to dissatisfaction of the passengers both inside and outside the automobile. Although this issue has been extensively studied for many years, it still remains an unsolved problem and it has become one of the major concerns and a great challenge for automotive manufacturers and researchers.

* Corresponding author.
E-mail address: lvhui588@126.com (H. Lü).

http://dx.doi.org/10.1016/j.ymssp.2017.02.012

Brake squeal has been studied since 1930s and the review of this complex phenomenon has been comprehensively reported in the literature [1–6]. In those review papers, several squeal mechanisms have been summarized such as stick-slip, sprag-slip, hammering and mode-coupling. Recently, the mechanisms of moving loads [7] and time delay [8] have also been presented for squeal phenomenon.

In addition to the mechanism researches, considerable numerical and experimental studies are available for squeal analysis and optimization in the literature. For example, sensitivity analysis methods for squeal problem were presented by Guan et al. [9], Butlin et al. [10] and Nechak et al. [11]; parameter studies for brake stability analysis were carried out by Liu et al. [12] and Júnior et al. [13]; the damping effects on squeal noise was investigated by Fritz et al. [14,15]; structural optimizations for squeal suppression were proposed by Guan et al. [16] and Soh et al. [17]; the nonlinear or chaotic phenomenon formulations of squeal noise were conducted by Sinou et al. [18], Massi et al. [19] and Oberst et al. [20]; and new efficient reduction methods for stability analysis of brake systems are proposed by Monteil et al. [21]. It can be seen that considerable effort has been dedicated to analyze and resolve squeal problem and great success and significant results have been achieved. However, all the above-mentioned studies are based on deterministic methods which cannot take input uncertainty into account.

In engineering practice, brake systems are highly complex structures, whose parameters often exhibit a quite high degree of uncertainty inevitably. Nowadays, in order to present robust designs and improve the predictions of numerical simulations, it is a common trend to introduce non-deterministic studies into squeal simulations in automotive industry. To describe the uncertainty existing in brakes, the random method is most widely proposed. Sarrouy et al. [22,23] improved the efficiency and accuracy of the linear and non-linear brake squeal analyses based on polynomial chaos expansions. Tison et al. [24] and Nechak et al. [11] presented a complete strategy or sensitivity analysis to improve the prediction of squeal simulations by introducing robustness. Nobari et al. [25] presented an efficient approach of uncertainty propagation for brake instability analysis via kriging method. Recently, Renault et al. [26] have improved the correlation between experimental and numerical prediction of unstable frequencies for an automotive brake by considering the detected uncertainty. And in the recent work of Zhang et al. [27], a stochastic approach has been developed to demonstrate the potential of an uncertainty analysis in improving the prediction of nonlinear brake squeal propensity using a linear method. These non-deterministic studies have achieved significant successes in squeal instability analysis and they have greatly promoted the development of the analysis methods of uncertain squeal problem.

Nevertheless, in these non-deterministic studies, the uncertain parameters of brakes are all treated as random variables whose probability distributions are defined unambiguously. In fact, to construct the precise probability distributions, a great number of statistical or experimental data is required. Unfortunately, under some uncertainty cases, the data of some uncertain parameters of brakes is limited, or it is difficult to measure their exact probability distributions. Consequently, the non-probabilistic approach, such as fuzzy method, has been considered as a useful alternative to random method. Therefore, in addition to random method, the fuzzy method has also been widely applied in squeal instability analysis. For example, Giannini [28] presented a fuzzy model to predict the zones of possible squeal frequencies, in which all the characteristic parameters of a simplified experimental brake are modeled with fuzzy numbers; Gauger et al. [29] applied fuzzy finite element simulations to conduct squeal analysis of an industrial brake and the contact parameters and the friction coefficient are all described as fuzzy numbers. And very recently, Massa et al. [30] presented a comprehensive strategy to calculate the fuzzy frequencies and fuzzy growth rates of a friction-induced vibration system by integrating fuzzy logic, fuzzy sets and interval theories. These non-deterministic studies have also achieved great successes in squeal instability analysis. However, only the interval bounds of analysis results at specific fuzzy levels can be obtained when fuzzy method is employed, and the probability distributions of analysis results are all missing.

Apparently, the random method and the fuzzy method are applied to handle the squeal problem separately rather than simultaneously in all existing studies of brake squeal. In engineering practice, randomness and fuzziness may exist in the brakes simultaneously under some special cases. To cope with these special cases and to keep the advantages of random method and fuzzy method simultaneously, two uncertainty analysis models with mixed variables can be introduced. The first one is the random and fuzzy model. In this model, the random variables are applied to describe the uncertain parameters whose probability distributions can be determined with sufficient data, while the fuzzy variables are employed to describe the uncertain parameters with limited or fuzzy information. The second one is the fuzzy random model, in which the uncertain parameters are all treated as random variables, but their distribution parameters (e.g., means or standard deviations) can only be expressed as fuzzy numbers but not deterministic values due to limited or fuzzy information. Both types of random-fuzzy uncertainty cases are very likely to appear in automotive brakes. Brake squeal analysis with both types of uncertainties is coming to attract researchers' attentions. Recently, based on interval analysis [31], the squeal analysis and optimization of disc brakes with both random and interval uncertainty have been investigated by Lü and Yu [32,33]. Nevertheless, from the overall perspective, squeal analysis with two different types of uncertainties is still at the preliminary stage and some important issues still remain to be solved. For example, squeal analysis involving both random and fuzzy uncertainties is not yet explored, especially a unified approach for squeal analysis involving two types of random-fuzzy uncertainties has not been explored.

Therefore, this paper aims to explore and put forward a unified approach for squeal instability analysis of disc brakes with two types of random-fuzzy uncertainties. It is desired to properly process the randomness and fuzziness simultaneously existing in an uncertain brake, and put forward an accurate and effective way for the uncertainty analysis of squeal instability. This paper is organized as follows. First, the deterministic analysis of squeal instability is introduced in Section 2. Then,