



Brake squeal reduction of vehicle disc brake system with interval parameters by uncertain optimization



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ARTICLE INFO

Article history:

Received 11 December 2013

Received in revised form

18 July 2014

Accepted 24 August 2014

Handling Editor: H. Ouyang

Available online 16 September 2014

ABSTRACT

An uncertain optimization method for brake squeal reduction of vehicle disc brake system with interval parameters is presented in this paper. In the proposed method, the parameters of frictional coefficient, material properties and the thicknesses of wearing components are treated as uncertain parameters, which are described as interval variables. Attention is focused on the stability analysis of a brake system in squeal, and the stability of brake system is investigated via the complex eigenvalue analysis (CEA) method. The dominant unstable mode is extracted by performing CEA based on a linear finite element (FE) model, and the negative damping ratio corresponding to the dominant unstable mode is selected as the indicator of instability. The response surface method (RSM) is applied to approximate the implicit relationship between the unstable mode and the system parameters. A reliability-based optimization model for improving the stability of the vehicle disc brake system with interval parameters is constructed based on RSM, interval analysis and reliability analysis. The Genetic Algorithm is used to get the optimal values of design parameters from the optimization model. The stability analysis and optimization of a disc brake system are carried out, and the results show that brake squeal propensity can be reduced by using stiffer back plates. The proposed approach can be used to improve the stability of the vehicle disc brake system with uncertain parameters effectively.

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1. Introduction

Due to the consistent customer complaints and high warranty costs, brake squeal noise has become one of the important concerns associated with the automotive brake systems [1–3]. If the brake system comes into an unstable state in the working process, the strong vibration and a harsh noise may be caused. The brake squeal noise, especially in the frequency range between 1 and 16 kHz, is most annoying to passengers' hearing [4,5].

Several classic theories have been formulated to explain the mechanism of the disc brake squeal phenomenon. However, there is neither a comprehensive understanding of the problem nor a generalized theory of the brake squeal mechanism yet [5,6]. For the last several decades, researches on brake vibration and noise have been conducted by using the theoretical, experimental, and numerical approaches [3,7]. The theoretical approaches provide a good insight into the mechanism of squeal, but the complicated brake system has to be considerably simplified and the accurate analysis results cannot be

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provided. The experimental approaches can effectively investigate the effects of different parameters and operating conditions on the squeal of a brake system, however, the experiments are mostly expensive and time-consuming. Instead of a simple schematic model, the numerical methods can simulate different structures, material compositions and operating conditions of a disc brake or of different brakes or of even different vehicles, when used rightly. CEA method is a widely used approach for brake squeal investigation. Since a good correlation between the CEA numerical analysis results and the available experimental data is already verified experimentally, the CEA approach has already become an effective approach to the brake squeal investigation [8,9].

Many numerical approaches have been presented to explore the squeal phenomenon with the CEA approach. In the 1980s, Liles [10] presented a method for determining the geometric stability characteristics of a disc brake assembly by the use of finite element method (FEM). In this research, a CEA method was performed to determine which modes were unstable and therefore likely to produce squeal. In the 1990s, Chargin et al. [11] developed a unique nonlinear method accounted for both superelement modes and surface friction data for the analysis of brake squeal, both transient responses and complex eigenvalues were provided for the analysis of brake systems. In the 21st century, a front disc brake system was used as an example for the investigation of the low frequency squeal by Kung et al. [12]. Many different modifications to the brake system were proposed. Ouyang et al. [13] developed a moving-load model for the disc-brake stability analysis, and solved the dynamic instability as a nonlinear eigenvalue problem. Compared with the non-moving-load model, a more realistic disc-brake model was constructed by their method; more unstable frequencies were predicted and correlated very well with the experimental squeal frequencies. As the complex eigenvalue analysis and the dynamic transient analysis were typically two different methodologies that could be used to predict squeal in a disc brake [11], Abubakar and Ouyang [14] explored a proper way of conducting both types of analyses and investigating the correlation between them for a large degree-of-freedom disc brake model. Guan et al. [15] explored the sensitivity analysis methods to determine the dominant modal parameters of substructures of a brake system for the brake squeal suppression analysis, the related formulas of sensitivities of the positive real part of the squeal mode to substructures' modal parameters were derived. Fritz et al. [8,16] computed the brake system eigenvalues by using a technique based on FEM, and the effects of damping on the coalescence patterns of system eigenvalues were investigated. Liu et al. [17] and Junior et al. [18] investigated the effects of system parameters on the disc brake squeal, and the insulation and damping materials were applied to suppress the brake squeal. Dai and Lim [19] applied an enhanced dynamic FE model with friction coupling to optimize the design of the disc brake pad structure for squeal noise reduction and the analysis showed that the eigenvalues possessing positive real parts tended to produce unstable modes with the propensity towards the generation of squeal noise. In order to improve the FE model accuracy, Nishizawa et al. [20] and Nonaka et al. [21] conducted researches aiming to incorporate the dynamic stiffness of the pads into FE modal analysis, and the change in the squeal frequency resulting from the change in the thicknesses of the pads was reproduced. In recent years, Nouby et al. [22] proposed a mathematical approach to investigating the influencing factors of the brake pad on the disc brake squeal by integrating finite element simulations with statistical regression techniques. Their predicted results showed that the brake squeal propensity could be reduced by increasing Young's modulus of back plate and modifying the shape of friction material by adding chamfers and slots. Lakkam and Koetniyom [23] proposed an optimization method for brake squeal by using FEM, assumed-coupling mode method and experiment operations. According to this research, the position/geometry of the constrained layer damping patch could be optimized by minimizing the strain energy of vibrating pads with constrained layer. Sarrouy et al. [24] proposed numerical approaches to dealing with the brake stability problem with uncertainties. The work of Sarrouy et al. was based on polynomial chaos expansions and took place in the context of uncertain systems. Through their methods, the stochastic eigenvalue problems of a disc brake system could be processed efficiently and accurately compared with Monte Carlo simulations.

Although so many researches on brake squeal have been conducted through CEA numerical approaches, however, only a few investigate the brake squeal problem with uncertainties. In engineering practices, many different factors appear to affect brake squeal, such as geometrical dimensions, material properties and loading conditions. Variabilities always exist in these factors in reality [6,24]. When taking those variabilities into account, parameter uncertainties have to be introduced into the analysis model of brake systems for obtaining more reliable results. To deal with the uncertain problem with limited information, the interval model, in which the fluctuations of uncertain parameters are assumed to fall into a hyper-rectangle, has been developed. It just needs to obtain the upper and lower bounds of an uncertain parameter, if the uncertain parameter is treated as an interval variable. The lower and upper bounds of interval variables can be easily obtained in engineering practice. Therefore, the analysis methods based on the interval analysis have been well developed and widely applied [25]. In addition, carrying out reliability analysis while considering the uncertainties can ensure the system with uncertain parameters is always in a reliable state [26]. In order to improve the performance of the system with uncertainties, the optimization under uncertainty should be carried out during the design process. For the uncertain problems with limited information, several theories for the optimization with non-probabilistic parameters have been proposed for the designs of engineering structures in recent years [27–30]. Thus it is necessary to conduct uncertain optimization for reducing the brake squeal of a real brake system.

In this paper, attention is focused on the stability analysis and the optimization of the vehicle disc brake system with uncertainties. The stability of a disc brake system is investigated via the CEA method. Based on the FE model, the dominant unstable mode is extracted. And the damping ratio corresponding to the dominant unstable mode is chosen as the indicator of instability. Uncertain parameters are employed to deal with the uncertainties existing in the geometrical, material and loading properties of brake system components. For simplicity, only the frictional coefficient, the elastic properties of

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