Advances in Engineering Software 98 (2016) 112–122

Contents lists available at ScienceDirect

Advances in Engineering Software

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

Optimization design of a disc brake system with hybrid uncertainties

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ARTICLE INFO

Article history:
Received 27 January 2016
Revised 17 March 2016
Accepted 17 April 2016
Available online 26 April 2016

Keywords:
Optimization design
Brake squeal
Hybrid uncertainties
Probabilistic variable
Interval variable

ABSTRACT

Squeal reduction of disc brake systems have been extensively investigated for both academic and industrial purposes. However, most of the existing optimization designs of squeal reduction are based on deterministic approaches which have not considered the uncertainties of material properties, loading conditions, geometric dimensions, etc. In this paper, a hybrid probabilistic and interval model is introduced to deal with the uncertainties existing in a disc brake system for squeal reduction. The uncertain parameters of the brake system with enough information are treated as probabilistic variables, while the parameters with limited information are treated as interval variables. To improve computational efficiency, the response surface methodology (RSM) is introduced to replace the time-consuming finite element (FE) simulations. By the hybrid uncertain model, an optimization design based on reliability and confidence interval is proposed to explore the optimal design for squeal reduction. In the proposed optimization, both the design objective and the design constraint are interval probabilistic functions due to the effects of hybrid uncertainties. In this case, the maximum of the upper bound of confidence interval of design objective is selected as the objective function, while the minimal value of the probabilistic constraint is selected as the constraint function. The combinational algorithm of Genetic Algorithm and Monte-Carlo method is employed to perform the optimization. The results of a numerical example demonstrate the effectiveness of the proposed optimization on reducing squeal propensity of the disc brake systems with hybrid uncertainties.

1. Introduction

The friction-induced vibrations existing in disc brake systems can induce a dynamic instability, and causes an inconvenient squealing noise. Disc brake squeal has become one of the most difficult concerns associated with vehicle disc brake systems, which have poor performances on system stability [1]. Brake squeal, especially with the frequency range from 1 to 16 kHz, frequently leads to customer complaints and results in enormous warranty costs. Therefore, extensive efforts have been undertaken by industrial corporations as well as by the scientific communities to predict and remove the squeal noise, and some interesting review papers have been presented on this subject [2–10]. So far, however, there is not yet a comprehensive understanding of the root cause of this phenomenon due to its immense complexity.

Optimization designs of disc brake systems for squeal reduction have been extensively studied in the field of automotive engineering. For example, Guan et al. [11] suggested sensitivity analysis methods to determine the dominant modal parameters of substructures of a disc brake system for squeal suppression, and the dominant modal parameters were selected as optimization target to explore modifications of disc and bracket to eliminate squeal modes. Spelsberg-Korspeter [12,13] performed a structural optimization of brake rotor, and the mathematical difficulties of such an optimization were discussed. Lakkam and Koetniyom [14] proposed an optimization study for squeal reduction, which aimed to minimize the strain energy of vibrating pads with constrained layer damping. The results of their research could guide to specify the position of the constrained layer damping patch under pressure conditions. Shintani and Azegami [15] presented a solution to a non-parametric shape optimization problem of a disc brake model to suppress squeal noise, the optimum shape of brake pad was found and the real part of the complex eigenvalue representing the cause of brake squeal was minimized. The above-mentioned studies on optimization designs of disc brake systems are all restricted to deterministic optimizations, in which all design variables and parameters involved are regarded as certain values. However, due to the effects of manufacturing/measuring errors, aggressive environment factors and unpredictable external excitations, uncertainties associated with loading, material properties, geometries,

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http://dx.doi.org/10.1016/j.advengsoft.2016.04.009

and environmental conditions are unavoidable. Without considering the uncertainties, the optimality yielded by deterministic optimization approaches will be destroyed and the constraint conditions will be violated [16–18]. In order to take into account various uncertainties, the reliability-based design optimization (RBDO) is introduced and has been intensively studied both in the methodology and in applications [19–21]. In RBDO, the performances and reliabilities of uncertain systems can be considered simultaneously. Compared with the deterministic optimization, RBDO aims to seek a reliable optimum by converting deterministic constraints into probabilistic constraints. Therefore, RBDO can be considered as a potential method to improve the dynamic performance of disc brake systems considering uncertainties of practical engineering.

Even though great success has been achieved in the stability analysis and optimization design of disc brake systems for squeal reduction, there are only a few papers that investigate brake squeal problem with uncertainties at present. Of those papers, Grange et al. [22] have used the random decrement technique and the Ibrahim time domain method to identify the modal parameters of an equivalent linear brake system for squeal analysis. Sarrouy et al. [23] have carried out an uncertain simulation of brake squeal based on polynomial chaos expansions and a simplified disc brake, in which the friction coefficient and the contact stiffness of the brake are modeled as random parameters. Tison et al. [24] have proposed a complete strategy to improve the prediction of squeal simulations by introducing random uncertainty and robustness concepts. Lü and Yu [25] have presented an uncertain optimization method for brake squeal reduction of vehicle disc brake systems with interval parameters. In this research, the uncertain system parameters are all treated as interval variables due to limited data of system parameters. The interval method seems somewhat conservative. Based on the work of [25], both random variables and interval variables are used to deal with the hybrid uncertainties of brake system and the stability of such a brake system has been investigated by the same authors recently [26]. Nevertheless, the stability optimization design and the numerical optimization method of such a hybrid uncertain brake system have not been explored in [26]. Another recent work on uncertain squeal problem can be found in [27]. In this research, Nobari et al. [27] presented a random process and a Kriging surrogate model to overcome the high computational workloads of uncertain analysis of brake systems, and three benefits gained from the surrogate model were discussed, namely coming up with some design recommendations to reduce brake noise, quantifying uncertainty and variability existing in a brake system and conducting a reliability analysis in terms of noise. This research mainly focused on the construction and application of the surrogate model with uncertainties, but the uncertainty analysis and optimization method for squeal reduction was not explored, just as in [26].

Probabilistic methods are the traditional approaches to cope with the uncertainties arising in practical engineering problems, just as we can see in the above researches [22–27]. In the probabilistic methods, the uncertain parameters are treated as probabilistic variables whose probability distributions are defined unambiguously [28]. To construct the precise probability distributions of probabilistic variables, a large number of statistical information or experimental data is required. Unfortunately, in the design stage of disc brake systems, the information to construct the precise probability distributions of some probabilistic variables (e.g. the friction coefficient) is not always sufficient due to the immeasurability or assumptions. For this case, the hybrid probabilistic and interval model has been proposed for overcoming the deficiencies of probabilistic methods. In the hybrid probabilistic and interval model, the uncertain parameters with sufficient data to construct probabilistic distributions are treated as probabilistic variables, while the uncertain parameters without sufficient data to construct the distributions are treated as interval variables. The hybrid probabilistic and interval model was firstly proposed by Elishakoff et al. [29,30], and subsequently applied to the response analysis of hybrid uncertain systems [31,32]. As previously mentioned, the disc brake systems are treated as either deterministic systems or almost probabilistic uncertain systems in the existing researches. From the overall perspective, researches on the hybrid probabilistic and interval model are still in its preliminary stage and some important issues are still unsolved. For example, the application of the hybrid probabilistic and interval model in the optimization of brake squeal is not yet explored.

The purpose of this paper is to take into account the hybrid uncertainties existing in a disc brake system, and develop an optimization approach for improving system stability and reducing squeal propensity. By using hybrid probabilistic and interval model, the uncertainties of the thickness of the back plate, the Elastic modulus of component materials and the brake pressure are represented by probabilistic variables, whose distribution parameters are well-defined; whereas the uncertainties of the friction coefficient, the densities of component materials and the assumptive Elastic modulus of the friction material are modeled by interval variables, whose lower and upper bounds are well-defined. Based on the hybrid uncertain model, the optimization design based on reliability and confidence interval for a disc brake system is proposed. To improve the computational efficiency of the proposed optimization, RSM is employed to establish the surrogate model of the real part of the domain unstable eigenvalue, which is adopted as the design objective. The mass of the design component is taken as the design constraint. Due to the effects of hybrid uncertainties, both the design objective and design constraint are interval probabilistic functions. In this case, the maximum of the upper bound of confidence interval of design objective is selected as the objective function, while the minimal value of the probabilistic constraint is selected as the constraint function. The combinational algorithm of Genetic Algorithm and Monte-Carlo method is employed to perform the optimization. The effectiveness of the proposed approach is demonstrated by a numerical example.

2. Complex eigenvalue analysis of disc brake systems

2.1. A simplified disc brake system

Disc brake systems are one of the most important safety and performance components in automobiles. There are several major components in a car disc brake system: brake disc, brake pad assemblies, carrier bracket, calliper and a hydraulic actuation system. The brake disc is rigidly mounted on the axle hub and rotates with the wheel. The pair of brake pad assemblies generally consist of friction material and back plates. When the hydraulic pressure is applied, the piston of actuation system is pushed forward to press one brake pad against the brake disc and simultaneously the other brake pad is pressed by the calliper against the disc. Then, a frictional torque is generated to slow the disc rotation. For the purpose of simulating the vibration characteristics of a disc brake system reasonably with the acceptable computational burden, a simplified model of disc brake system is taken for investigation. The simplified disc brake consists of a disc and a pair of brake pads, as shown in Fig. 1. The similar models have been previously considered and successfully used by some studies, such as [23,33–35].

2.2. Complex eigenvalue analysis

The CEA can be carried out by two stages. In the first stage, the steady state of the brake system is found and the actual CEA is performed in the second stage.