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Uncertainty quantification of squeal instability via surrogate modelling

Amir Nobari [a], Huajiang Ouyang [a,*], Paul Bannister [b]

[a] School of Engineering, University of Liverpool, The Quadrangle, Brownlow Street, Liverpool L69 3GH, United Kingdom
[b] Jaguar Land Rover, Abbey Road, Whitley, Coventry, CV3 4LF, United Kingdom

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ABSTRACT

One of the major issues that car manufacturers are facing is the noise and vibration of brake systems. Of the different sorts of noise and vibration, which a brake system may generate, squeal as an irritating high-frequency noise costs the manufacturers significantly. Despite considerable research that has been conducted on brake squeal, the root cause of squeal is still not fully understood. The most common assumption, however, is mode-coupling.

Complex eigenvalue analysis is the most widely used approach to the analysis of brake squeal problems. One of the major drawbacks of this technique, nevertheless, is that the effects of variability and uncertainty are not included in the results. Apparently, uncertainty and variability are two inseparable parts of any brake system. Uncertainty is mainly caused by friction, contact, wear and thermal effects while variability mostly stems from the manufacturing process, material properties and component geometries. Evaluating the effects of uncertainty and variability in the complex eigenvalue analysis improves the predictability of noise propensity and helps produce a more robust design.

The biggest hurdle in the uncertainty analysis of brake systems is the computational cost and time. Most uncertainty analysis techniques rely on the results of many deterministic analyses. A full finite element model of a brake system typically consists of millions of degrees-of-freedom and many load cases. Running time of such models is so long that automotive industry is reluctant to do many deterministic analyses. This paper, instead, proposes an efficient method of uncertainty propagation via surrogate modelling. A surrogate model of a brake system is constructed in order to reproduce the outputs of the large-scale finite element model and overcome the issue of computational workloads. The probability distribution of the real part of an unstable mode can then be obtained by using the surrogate model with a massive saving of computational time and cost. The established model can be used subsequently for design, reliability analysis and optimisation.

1. Introduction

Noise, vibration and harshness (NVH) of frictional brake systems have been an active research topic for many years. Car manufacturers are leading the investigations in order to deliver their customers' quality expectations and meet their commitments to environmental issues. Customer satisfaction surveys reveal that a significant number of warranty claims

* Corresponding author.
E-mail address: h.ouyang@liverpool.ac.uk (H. Ouyang).

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concerning brake systems are related to friction noise. Therefore, any improvement in predicting noise propensity during the design stage will improve the manufacturer's quality and profitability.

Frictional brake systems can generate different types of noise and vibration. According to the noise and vibration characteristics, they can be categorised as groan, judder, squeal, wire brush, etc. The one which is the main concern of this study is brake squeal. In terms of vibration characteristics, brake squeal usually ranges from 1 to 20 kHz, and its frequency is fairly independent of the rotor speed and it occurs when the stick–slip motion is largely absent. While out-of-plane modes of the disc are usually responsible for generating squeal, in-plane modes are often involved. If such single tone noise is measured one metre away from the brake and its sound pressure level equals or is greater than 78 dB, it is called squeal and can be heard in a vehicle [1].

Early research on brake squeal was mostly dedicated to the source of squeal while the remainder was on its effects. The fugitive nature of brake squeal often obscures its root cause, so there is not a single mathematical model or expression which is capable of giving an absolute explanation for squeal. Therefore, several squeal mechanisms such as stick–slip [2], sprag–slip [3], hammering [4] and mode-coupling, are attributed to squeal instability. Kinkaid et al. [5] discussed these frictional mechanisms in a comprehensive review paper. More recently, moving loads [6] were suggested as a squeal mechanism for disc brakes. Friction force in both circumferential and radial directions and its moving-load nature were considered in [7]. Time delay was also suggested as responsible for squeal in reciprocating sliding friction [8].

Of these mechanisms, mode-coupling which is also called binary flutter has attracted the most attention in the literature. By means of a minimal model, Hoffmann et al. [9] demonstrated that friction can disturb the symmetry of the stiffness matrix and cause instability at certain values of the friction coefficient. Through increasing the friction coefficient, the imaginary parts of the system eigenvalues merge and simultaneously the real parts of the eigenvalues bifurcate. At the bifurcation point, the system eigenvalues are purely imaginary, but further increase of the friction coefficient causes one of the real parts of the eigenvalues to become positive. This is thought to generate noise since the amplitude of vibration in the linearised system will grow boundlessly due to this term. Kang et al. [10] studied the mode-coupling instability for a reduced-order analytical model consisting of the disc and pad.

Mode coupling instability has been studied in different friction-induced problems. The sign of the real parts of the eigenvalues in the linearised system can determine whether its steady-state solution is stable or not [11,12]. The linearised stability analysis is performed around an equilibrium point determined from a nonlinear static contact analysis. However, nonlinear dynamic contact and nonstationary behaviour cannot be investigated by CEA. Massi et al. [13] emphasised the significance of the stability analysis in predicting the onset of squeal and also stated that the nonlinear time solution was an essential part in attaining squeal limit cycles. D'Souza and Dweib [14] determined the limit cycle of a nonlinear pin-on-disc system and Coudeyras et al. [15] studied limit cycles of unstable vibration of a pad-disc brake model. Von Wagner and Schlagner [16] investigated excitation mechanism of brake squeal and more importantly explored its active suppression by means of pads with integrated piezoceramic actuators. Ouyang et al. [17] discussed the pros and cons of analysing brake squeal via numerical methods: complex eigenvalue analysis (CEA) and transient analysis. In brief, the computational efficiency of the former approach is appreciated although more realistic results can be achieved via the latter one if the system model is sufficient. Sinou et al. [18,19] pointed out that CEA may lead to under- or over-estimation of unstable modes. In [18], it was shown that additional unstable modes appeared during transient and steady-state oscillations, which were not predicted by CEA, because CEA excludes dynamic contact that a dynamic transient analysis includes. It is expected that more realistic models of brakes will be analysed by dynamic transient analyses. In this paper, complex eigenvalue analysis (CEA) is used.

Uncertainties in structures are typically classified into two categories: variability and uncertainty. In the literature, variability is referred to those sorts of uncertainties which are caused by the deviation of material properties from the nominal values, the imperfection of component geometries and the variation in manufacturing process. The second category is mostly due to the lack of knowledge. In the case of brake systems, friction and contact are the major sources of uncertainty. Several experimental and numerical investigations have been carried out for studying the pressure distribution at disc-pad contact interface [20], thermal effects [21,22], wear and roughness [23,24] and the friction coefficient [20,25]. These studies deepen understanding of friction-induced vibration of brakes.

Statistical approaches to the brake squeal problem have received the attention of car manufacturers recently. Statistical interpretations of experimental data [26] and stochastic simulations of brake models can provide more reliable predictions of squeal. In order to conduct an uncertainty analysis, probabilistic, non-probabilistic or mixed uncertainty methods can be used [27]. Of the probabilistic methods, Monte Carlo simulation is known as the most reliable technique, in particular for highly nonlinear problems. Culla and Massi [28] implemented Monte Carlo simulation to propagate the uncertainty of contact instability. The computational inefficiency of Monte Carlo simulation has encouraged researchers to use some smarter probabilistic methods such as the perturbation methods and polynomial chaos expansions. Butlin and Woodhouse [29] applied the 1st-order perturbation method to study the uncertainty of a friction-induced problem. Sarrouy et al. [30] improved the efficiency and accuracy of stochastic simulations of brake squeal by using polynomial chaos expansions. Interestingly, Grange et al. [31] used a stochastic approach to establish a linearised model of a brake with unilateral contact between brake disc and pads.

This paper aims to implement a statistical method for uncertainty analysis of brake squeal with a significant saving of computational workloads. Industrial brake models are typically composed of different components, whose degrees of freedom are in the order of millions. Their computational time can range from 12 to 36 h depending on the computational