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On the potential of uncertainty analysis for prediction of brake squeal propensity

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ABSTRACT

Brake squeal is a source of significant warranty-related claims for automotive manufacturers because it is annoying and is often perceived by customers as a safety concern. A brake squeal analysis is complex due to changing environmental and operating conditions, high sensitivity to manufacturing and assembly tolerances as well as the not so well understood role of nonlinearities. Although brake squeal is essentially a nonlinear problem, the standard analysis tool in industry is the linear complex eigenvalue analysis (CEA) which may under-predict or over-predict the number of unstable vibration modes. A nonlinear instability analysis is more predictive than CEA but is still computationally too expensive to be used routinely in industry for a full brake finite element model. Also, although the net work analysis of a linearised brake system has shown potential in predicting the origin of brake squeal, it has not been extensively used. In this study, the net work of an analytical viscously damped self-excited 4-dof friction oscillator with cubic contact force nonlinearity is compared with the instability prediction using the CEA and a nonlinear instability analysis. Results show that both the net work analysis and CEA under-predict the instability because of their inability to detect the sub-critical Hopf bifurcation. Then, the uncertainty analysis is applied to examine if it can improve instability prediction of a nonlinear system using linear methods and its limitations. By applying a variance-based global sensitivity analysis to parameters of the oscillator, suitable candidates for an uncertainty analysis are identified. Results of uncertainty analyses by applying polynomial chaos expansions to net work and CEA correlate well with those of the nonlinear analysis, hence demonstrating the potential of an uncertainty analysis in improving the prediction of brake squeal propensity using a linear method.

1. Introduction

Brake squeal is a friction-induced phenomenon and a major concern to automotive manufacturers [1]. The standard industrial tool to predict brake squeal propensity is based on the complex eigenvalue analysis (CEA) [2]. However, the CEA is a linear tool which may over-predict [3] the number of unstable vibration modes compared to experimentally recorded squeal occurrence. On the other hand, the CEA may also under-predict the number of unstable modes when nonlinearities play an important role in initiating instabilities. Hochlenert [4] showed using an analytical model that the CEA

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under-predicts instabilities caused by sub-critical Hopf-bifurcations. Oberst and Lai [5] applied transient nonlinear time domain analysis (TDA) to a finite element pad-on-disc brake model and showed the CEA both over- and under-predicts instability, and that the not predicted instantaneous pad modes instabilities are triggered by intermittency type II chaotic motions, caused by subcritical Hopf bifurcations. By using a nonlinear time domain analysis for a FE brake model consisting of a rotor and a pad, Sinou [6] showed that the under-prediction of unstable modes by the CEA is due to the contributions of the nonlinearities (such as nonlinear contact) and suggested both CEA and time domain analysis need to be considered in brake squeal analysis.

For an analytical model, the nonlinear instability analysis using the multi-scales method to predict the existence of bifurcations has been shown to be more predictive than a CEA [4]. Due to its computational expense, the nonlinear instability analysis is rarely used for a full brake model. Unlike mathematical instability predictions such as the CEA or nonlinear instability analysis, net work relates physically to the origin of brake squeal because it sustains the self-excitation of a brake system [7]. Yet, the principle of energy generation via net work (friction work [5,8] plus damping work) for determining instabilities in friction-induced vibrations has been rarely used. This is because it is difficult to precisely quantify the positive friction work, owing to the fugitive nature of friction and the dissipating mechanisms.

A number of mechanisms have been identified for triggering brake squeal such as mode-coupling, stick–slip, sprag–slip, instantaneous mode squeal, hammering [1,9–13] and they might interact dynamically [5]. As a brake system is complex [14] and inherently nonlinear (e.g., material properties, boundary conditions), chaotic structural vibrations and radiated sound have been observed even though the squeal is tonal [15–17]. In addition, uncertainties in material properties, friction characteristics, contact interface, environmental and operating conditions as well as sensitivities to loading conditions [18] would further reduce the reliability of the prediction of instabilities using deterministic techniques [19].

Recently, more research has been aimed at applying uncertainty analyses to vibration and acoustics by treating brake system's parameters as fuzzy numbers [20], or by conducting sensitivity analyses [21] combined with Monte Carlo simulations [22] or polynomial chaos expansions [23,24] to estimate the probability of brake squeal. Néchak et al. [25], Sarrouy et al. [26] were among the first to use polynomial chaos expansions and the CEA for brake squeal propensity estimations. Tison et al. showed that squeal predictions could be improved using uncertainty calculations with a stochastic field approach [27,28] for a realistic brake system. However, no general conclusions were made on whether and why CEA's prediction could be improved by considering uncertainty and how the improvement would be influenced by the strength of the nonlinearity. The objective of this study is, therefore, to explore the potential of the uncertainty analysis in improving the instability prediction of linear methods for a nonlinear system and to provide some insights into the improvement from the theoretical perspective. For this purpose, a general-purpose 4-dof friction oscillator is considered; it is derived from an extensively used minimal model of Hoffmann et al. which has been found by Hanselowski and Hanss [29] to be a reasonable alternative to a simplified finite element brake model for the investigation of brake squeal (also cf. [30,31]). Recent studies indicate that frictional contact is multi-scaled [32], highly sensitive to changing parameters with non-uniform contact pressure [33] and is significantly influential for brake squeal generation [14]. Therefore, in this study, the contact force is modelled with nonlinearity and the strength of the nonlinearity is varied by adjusting the contact stiffness. A variance-based global sensitivity analysis is then used to identify the most important sources of uncertainties. Uncertainties related to the CEA's instability predictions and net work calculations are quantified with respect to the strength of nonlinearity using polynomial chaos expansions. Finally the potential of applying a stochastic approach by prioritising uncertainties and estimating instability predictions is discussed.

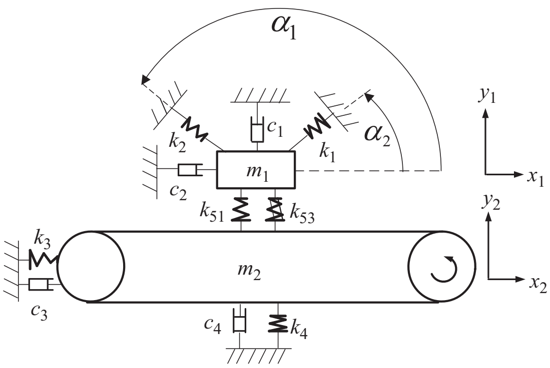

Fig. 1. A 4-dof nonlinear self-excited friction oscillator.