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Improvement in the predictivity of squeal simulations: Uncertainty and robustness

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ABSTRACT

The objective of this paper is to improve the predictivity of squeal simulations by introducing uncertainty and robustness concepts during simulations. Complex eigenvalue analysis is a traditional way to detect numerically the unstable modes that can be associated with extensive vibration and noise pollution. This simulation, for which associated computational times are compatible with the design phase, is known to be insufficiently predictive. We first propose a complete strategy that relies on the integration of random fields into the contact interface, complex eigenvalue calculations, probabilistic analysis and a robustness criterion. Next, this strategy is applied to study the instabilities of a complete industrial brake system. Experimental comparisons highlight the efficiency of the improved squeal detection methodology.

1. Introduction

Brake noise issues have been investigated since the early 1930s. Yet, they are still barely understood today. According to J.D. Power and Associates surveys published in 2002, more than 60 percent of warranty claims concerning the brake system are due to brake noise. Higher consumer expectations make brake noise a priority topic. Friction induced vibration is the reason behind much of the noise pollution caused by brake noise. The most types of brake noise most frequently cited in the literature are groaning (frequencies under 100 Hz), moaning (100–500 Hz) and squealing (1–16 kHz). In order to avoid these instabilities, the industry has specific tools for performing efficient optimization. To numerically solve this type of problem, two analysis method categories based on the finite element method can be performed: a Complex Eigenvalue Analysis (CEA) [1], in which system equations are linearized around a stationary state whose stability is evaluated according to Lyapunov's theory, or a nonlinear transient dynamic analysis [2,3], which can be used to study the time evolution of mechanical solutions (e.g., velocities, loads, contact node status). CEA requires less computational time. With appropriate computing facilities, a CEA can be of the order of one hour, even for a complete brake system, whereas transient analysis requires systematically many more than a day or can be unreachable for such systems. Therefore, CEA is more frequently used by industrials and is coupled with sensitivity and optimization tools. Nevertheless, the CEA method, which is characterized as a global approach, is known to be insufficiently predictive and highly dependent on a static equilibrium position, whereas

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nonlinear transient analysis can be used to study the phenomenon more locally [1,4]. For the latter method category, Vermot des Roches [2] proposed an interesting reduction technique associated with a modified nonlinear Newmark scheme. This method, which leads to a very compact model, was applied during sensitivity studies required for the development stage of an industrial brake system.

However, brake squeal is a highly fugitive phenomenon [5,6], and this variability is what makes brake squeal so difficult to predict and eliminate [6]. Furthermore, the environmental and operational conditions conducive to squeal are difficult to reproduce (temperature, pressure, excitation or braking history) and manufactured systems do not always have the same characteristics. To account for this variability and uncertainty, nondeterministic theories and methods that can be divided into two categories have been proposed: probabilistic theories [7,8] and non-probabilistic theories (interval [9], convex [10] and fuzzy approaches [11]). From a probabilistic point of view, Nechak et al. [12] and Sarrouy et al. [13] recently proposed introducing uncertainty into stability analysis using a polynomial chaos approach to analyze, for example, the effect of a friction coefficient on unstable modes. For non-probabilistic formalisms, Culla and Massi [5], and then Gauger et al. [14], used fuzzy formalism and a combinatory approach to evaluate respectively the influence of uncertainties on the modal behavior of a beam/disc model and an industrial brake model. The uncertainties were localized to the Young modulus and the friction coefficient of brake pads. The uncertain nature of the phenomenon is one of the main reasons why friction induced instabilities remain tricky to study.

In this paper, a complete strategy based on integrating random fields at the contact interface, eigenvalue calculations, probabilistic analysis and a robustness criterion is proposed to improve the predictivity of squeal frequency simulations in a design phase. The aim is to build different families or classes of unstable modes and to study their robustness. A classification of each family's participation in squeal is proposed. First, previous research on this topic and equations governing the stability problem are reiterated in Section 2. Then, a deterministic stability analysis of an industrial brake system is performed in Section 3. Numerically unstable modes are compared with those observed experimentally. Finally, a complete strategy, called Improved Squeal Detection Methodology (ISDM), is described and applied, respectively, in Sections 4 and 5. Conclusions and remarks about this work are given in Section 6.

2. Simulation of squeal frequency instabilities

2.1. Mode coupling phenomenon

For many years, a decreasing coefficient of friction with increasing sliding velocity was the only explanation for what triggers brake squeal. Thereafter, engineers and researchers suggested that structural mechanisms may also be root causes of friction induced vibration. Today, many theories and models are available in the literature. All these models, which come from various domains, aim to explain the root causes of friction related dynamic instabilities and to predict the conditions under which oscillation may occur.

For example, one of the most famous theories is stick-slip. Observations of the oscillation of the system reveal the existence of two distinct phases. The first phase presents no relative motion of the sliding bodies and is known as sticking. The second phase shows the relative motion of the bodies in contact and is known as sliding. Moving back and forth between these two states leads to stick-slip oscillation. Otherwise, in the sprag-slip theory, vibrations are caused by multiple degrees-of-freedom interactions. The sprag situation leads to component buckling. After the components have been sufficiently deformed, they come loose and return to the original contact situation. Spragging in an elastic system can lead to sprag-slip limit cycles. This structural mechanism highlights the fact that friction induced vibration can be predicted without a decreasing coefficient of friction.

Finally, most articles consider brake squeal to be vibration caused by mode coupling phenomena, which is also discussed in this paper. North developed a two degrees-of-freedom model [15], which considered not only the geometrical characteristics of brake components but also the characteristics of the friction interface. Millner extended [16] North's model and developed a six degrees-of-freedom model for a fixed caliper disc brake system. He observed that brake squeal triggering is dependent on friction coefficients, the mass and stiffness parameters of the brake assembly and the contact properties of the pad–piston interface. Writing the equations of motion of these systems leads to an eigenvalue problem and adding friction to the system leads to the coupling of some degrees of freedom. If an eigenvalue $\lambda = a + ib$ has a positive real part, i.e., $a > 0$, the system becomes unstable and its response to a perturbation is exponentially increasing oscillation. This mechanism is referred to as mode coupling and leads to flutter instability. Roots of couplings are assumed to be stiffness matrix asymmetries resulting from the existence of follower forces.

Today, numerous publications on the frequency analysis of instability can be found in the literature. One cited the works of Fritz et al. [17], which studied the flutter instabilities of a finite element model for a whole automotive brake corner. A complex eigenvalue analysis of the system is undertaken to assess brake stability as a function of the friction coefficient. Different kinds of damping spreading over the modes have been studied and Fritz pointed out that if the ratio of damping between two modes is sufficient, an increase in damping tends to make the brake unstable for a lower friction coefficient value. Lorang et al. [18] studied the squealing behavior of a TGV brake system considering the asymmetry of both the damping and stiffness matrices by means of a complex eigenvalue analysis of the problem. They found good agreement between the numerical analysis and the experiments. However, they stated that the phenomenon is not yet completely explained. Duffour and Woodhouse [19] investigated the linear stability of a pin-on-disc, which contains sliding frictional