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A global strategy for the stability analysis of friction induced vibration problem with parameter variations

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This paper presents a numerical strategy to reanalyze the modified frequency stability analysis of friction induced vibration problem. The stability analysis of a mechanical system relies on several coupling steps, namely a non-linear static analysis followed by linear and complex eigenvalue problems. We thus propose a numerical strategy to perform more rapidly multiple complex eigenvalue analyses. This strategy couples three methods namely, Fuzzy Logic Controllers to manage frictional contact problem, homotopy developments and projection techniques to reanalyze the projection matrices and component mode synthesis to calculate the modified eigensolutions. A numerical application is performed to highlight the efficiency of the strategy and a discussion is proposed in terms of precision and computational time.

1. Introduction

Besides the pleasant noises as violin's sound, there is a lot of unpleasant noise in the current life such as the noise of ground–wheel contact in aviation [1], rail–wheel contact in railway engineering [2], hip endoprosthesis squeaking noise [3] or brake squeal in automotive [4]. Indeed, vibrations are responsible for a large number of acoustical nuisances. The problem of brake squeal and more generally friction induced vibrations was a subject of great interest for many researchers, summarized in several review papers [5–7]. By the past, many studies focused on the phenomenological aspect of squeal and on dynamic instabilities occurring in sliding contact such as stick-slip behavior, sprag-slip phenomena or lock-in instabilities.

The results of these works are that squeal is a complex phenomenon and is not yet fully controlled. The main reason is due to the contact instability phenomenon, which depends on the dynamics of the system, on the nonlinear contact kinematic and on the contact surfaces topography. Indeed, this multi-scale problem depends constantly on the interaction of effects at macroscopic and microscopic scales. Thus, the phenomenon is related to both the dynamics of every component of the system and the interactions of the two bodies at the contact interface. In summary, this problem is nonlinear (frictional contact), transient (wear of the contact surfaces), multi-scale and multi-disciplinary. Simulations of friction induced vibration problems can be performed considering two main ways, either transient analysis or frequency analysis. The transient analysis [8] takes into account the nonlinear aspect of friction. The instability is characterized by the appearance of adhesion or sliding areas as well as separation of the contact interfaces. This analysis allows us to know the evolution of mechanical quantities (stress, strain) vs. time, and thus the global and local contact dynamic of the system. Acoustic simulations [9] can also efficiently complete this analysis. However, the disadvantage of this analysis is an important

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computing time which makes parametric studies difficult. Moreover, the current simulations do not correspond to real braking but only to steady braking. On the contrary, the frequency analysis relies on a linearization of the nonlinear problem around stationary state. The instability of solutions is studied in Lyapunov's sense and is due to the coalescence of mode shapes of the system. This analysis provides a set of frequencies that may (or not) be unstable and does not give the behavior of the system during the instability. In fact, the validity range is unknown and clearly depends on the stationary state which is directly related to the description of the contact surface not generally well known. Thus, a modification of the contact surface can generate a new distribution of contact pressure, and subsequently a new state of stiffness matrix asymmetry. In addition, nonlinear interactions of the components can lead to squeal thanks to post-bifurcations [10,11], not detected by the frequency analysis. Despite these disadvantages, the frequency analysis can give valuable information in the development process of a brake system. This solution is also less time consuming than the transient one and is thus more compatible with parametric studies for industrial finite element models.

Indeed, brake squeal is a highly fugitive phenomenon [4,12,13], which is difficult to efficiently catch with only deterministic approaches. To improve the predictivity of simulations, several authors have integrated observed variability of input parameters considering multi-parametric analyses, such as designs of experiments, performing sensitivity analyses, non-deterministic analyses or robust optimization, but mainly for the CEA way. Relatively few contributions present multi-parametric analysis for the transient way on industrial brake systems [14]. The recent works of Tison et al. [15] and Renault et al. [16] have highlighted the contribution of uncertainty to improve numerical and experimental correlation in the case of squeal instabilities for several industrial automotive systems. In their papers, they show first the limitations of deterministic simulations to predict squeal phenomenon with efficiency. Second, different studies show that uncertainties on topology of pads, material properties, damping and friction, play a key role in the destabilization of the brake system. Integration of such variabilities in simulation is thus essential to tend to robust designs. In the case of friction induced vibrations problems under uncertainty, Gauger et al. [17] used fuzzy formalism to model respectively the influence of uncertain friction and Young modulus on the modal behavior of a beam/disc model and an industrial brake model. Considering a polynomial chaos approach, Nechak et al. [18] takes the influence of uncertain friction coefficient into account on a dry friction system to predict stable and instable behaviors. In the same way, Sarrouy et al. [19] have determined both uncertain eigenvalues and stochastic limit cycles of a self-excited non-linear system and compute stochastic complex eigenvalues of a simplified brake system with uncertain friction coefficient [20].

To generalize these non-deterministic approaches in design step, it is necessary to reduce the supplementary computational time due to uncertainty propagation as claimed by several authors [10,21]. To achieve this objective, many papers have also been dedicated these last years to the introduction of reduced order models or approximations. Culla et al. [22] employed Monte Carlo simulation and substructured model for investigating contact instability under the influence of uncertainties, which leads to the occurrence of squeal noise. Fazio et al. [23] have studied a friction induced vibration problem through the stability analysis of an industrial brake system. A reduction technique is proposed to create Super-Element to reduce the number of nodes in contact, and consequently the computational time. Nouby et al. [24] and Lu et al. [25] use the response surface method to approximate the implicit relationship between the unstable mode and the system parameters. Nobari et al. [26] and Nechak et al. [27] predict squeal instability of uncertain brake systems through the construction of kriging surrogate model.

In the continuity of our previous works [15,16] we propose in this paper a numerical strategy dedicated to multi-parametric CEA analysis. Instead of using surrogate models to approximate the studied solutions, we propose here to revisit each step of the stability problem using new alternative methods. Contrary to surrogate models, with this methodology, the physical meaning of the well-established sequence is preserved.

Thus, a complete strategy, named CHOC, is proposed by coupling both *C*ontrol approach, *HO*motopy and *C*omponent mode synthesis techniques. The fuzzy logic control approach is used to manage the sliding contact problem. Homotopy perturbation and projection techniques allow perturbed projection matrices, due to model parameter variations, to be efficiently reanalysed. A component mode synthesis is then used to solve the modified undamped coupled eigenproblem. Finally, multi-parametric CEA analysis can be performed with a reduced computational time. Thus, Section 2 summarizes the main equations of a nominal stability problem in a finite element context. The contributions of input parameters' perturbations on different data, such as stiffness matrices, contact conditions, coupling matrices, are highlighted. Section 3 presents the CHOC strategy and details the main ingredients, namely:

- the reanalysis of modified modal basis, static modes and contact projection basis,
- the solving of reduced modified contact problem,
- the calculation of modified modal basis of undamped coupled system,
- the calculation of modified complex eigensolutions.

To verify the efficiency and the robustness of the CHOC strategy, a numerical application is presented in Section 4. Each main step will be validated individually and the effects on input variability on an unstable mode are highlighted. Conclusions and remarks of this work are provided in Section 5.