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Hybrid surrogate model for the prediction of uncertain friction-induced instabilities

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ABSTRACT

This paper presents a hybrid surrogate model for the prediction of friction-induced instabilities in uncertain mechanical friction systems. The proposed hybrid meta-model is developed in order to predict the occurrence of mode coupling instabilities submitted to random and interval parameter uncertainties. This predictor is built from the combination of the generalized polynomial chaos formalism, known to be useful to deal with random uncertainties, together with the inclusion function based on Chebyshev polynomials used to deal with interval uncertainties. The feasibility of the proposed approach and its efficiency are assessed by investigating the stability analysis of a four degree-of-freedom model with two sets of uncertain parameters described by probabilistic and interval models. Numerical results are compared with those obtained by applying a classical parametric approach to demonstrate the efficiency of the proposed methodology. The suggested hybrid meta-model is then shown to have an interesting potential to deal with stability analysis of mechanical systems subjected to friction-induced vibration.
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1. Introduction

The prediction of friction-induced instabilities is a well identified problem [1–3]. Two main methods are used in this framework. The first one is based on numerical integration over time of nonlinear differential equations [4,5] while the second is based on the Complex Eigenvalue Analysis (CEA) [6,7]. The CEA based method is often preferred to the first method since the latter occasioned stronger computational difficulties and higher cost in terms of computation time and data storage. In fact, the CEA is based on the linearization of the nonlinear differential system around its static solution then, on the analysis of eigenvalues of the resulting linear system. Instability is then identified when at least one eigenvalue is with a positive real part. The corresponding imaginary part defines the instability pulsation.

Despite the CEA may lead to an underestimation or an over estimation of unstable modes [3–5], it remains the preferred method since it gives a more suitable compromise between the accuracy and the required time calculation comparing to time integration method which is more accurate but computationally so expensive. However, the CEA may lose the convenience of the 'accuracy/cost' compromise when parameter uncertainties are required to be taken into account. In fact, numerous studies have pointed out high sensitivity levels for friction induced instabilities toward design parameters [8–13].

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However, in most cases, design parameters are submitted to dispersions that can be related to manufacture process, operating conditions and/or to intrinsic properties of materials. Thus, it is always necessary to take these dispersions into account for robust prediction and analysis of friction-induced instabilities and, more generally, for robust design of friction systems. In this perspective, using CEA by taking uncertain parameters into account is too costly [8]. Thus, searching for alternative methods is necessary. This is a challenging issue enjoying a great interest by academic and industrial communities. Numerous methods have been then proposed in this field. They differ from each other with respect to models used to describe uncertainties. From this point of view, one can particularly distinguish probabilistic [14,13] and non-probabilistic methods [15,16].

Probabilistic methods, based on propagating uncertainties described by probability density functions, aim to characterize almost-surely friction-induced instabilities. In this framework, the Monte Carlo based approach [17] is considered as the reference method but suffers from strong difficulties regarding its cost induced by a slow convergence. Indeed, a high number of samples and consequently a high number of CEA problems are needed to be solved to ensure convenient accuracy and confidence for the prediction and analysis of friction induced instabilities [8]. The polynomial chaos formalism introduced by Wiener [18], pioneered by Ghanem [14] and generalized by Xiu and Karniadakis [19], was proposed in numerous studies these last years to propagate more efficiently uncertainties onto friction induced instabilities. The main idea of this approach is based on the expression of the system's random eigenvalues or degrees of freedom as truncated expansions in polynomial functions that are orthogonal with respect to probabilistic measures associated to the random parameters. Intrusive and non-intrusive schemes are then used to compute expansions which are then exploited to analyze in an almost-surely way the stability of analytical models [20–22] and [23] and finite element models [24]. All these studies have shown high efficiency for the GPC formalism comparing to MC based techniques. However, the use of probabilistic methods assumes that probability laws governing parameters are identified beforehand. One popular method used for this objective consists of determining the density function which maximizes, under some known statistical constraints, the entropy function defined by Shannon [25]. This task is, unfortunately, not trivial and so difficult that probabilistic methods can be unsuitable. In this case, non-probabilistic methods can be more convenient. One can then distinguish fuzzy and interval approaches [16,15].

The fuzzy approach is based on fuzzy sets which include uncertain parameters with degrees defined by membership functions. These are different in concept from the known probability density functions. Indeed, they define an evasive quantitative measures on imperfect data. In other words, they permit to assign, to proposals or data, truth degrees ranging from zero (false) to one (true) with all possible graduations. The application of fuzzy logic is thus very appropriate to the approximate reasoning [13], particularly in systems analysis where uncertainties arise from inaccuracies rather than the randomness character. For example, the fuzzy formalism is proposed in [26,27] to propagate and quantify fuzzy uncertainties on proper modes (eigenvalues and the associated eigenvectors) of mechanical structures and to analyze the stability of a beam-to-beam structure by taking into account fuzzy data [28]. However, as for probability density functions, the membership functions are not easy to obtain [29]. From this point of view, intervals can be considered as the easiest models that can be obtained for uncertainty description. Indeed, in several cases design parameters can only, but easily, characterized by their lower and upper bounds without any knowledge on how they evolve within the obtained bounds [15]. Interval theory has been proposed these last years to deal with the stability of dynamic systems. It is used, for example, in [30] to determine bounds of eigenvalues of interval matrices, in [31] for guaranteed stability analysis of friction systems and in [32] for proving set inclusion with application to the robust stability analysis. The main drawback of this approach is essentially related to the pessimism phenomenon one of which wrapping effect and overestimation are the two well known symptoms [33]. Interval Taylor series [34,35] and Chebyshev inclusion function [36] define methods helping for decreasing the pessimism drawback.

In fact, most studies recorded in the framework of friction-induced instabilities, have considered the propagation and quantification of uncertainties when represented by models of the same type namely probabilistic, interval or fuzzy models. However, in numerous practice situations, system parameters may be submitted to uncertainties of different levels depending on the available knowledge on parameters. This requires the consideration of different models to represent the uncertain parameters. Consequently, methods to propagate and to quantify simultaneously these uncertainties are needed. At our knowledge, a very small number of studies have considered this problematic. The originality of the proposed paper is then related to the analysis of the potential of an hybrid approach to predict friction-induced instabilities by taking into account random and interval parameter uncertainties. The only study recorded in the same framework is that of Lu et al. [37] who have developed in their recent work the reliability-based design optimization (RBDO) for a disc brake in order to reduce the squeal propensity under hybrid (probabilistic and interval) uncertainties.

In this paper, we propose to deal with the prediction of friction-induced instabilities submitted to hybrid (probabilistic and interval) uncertainties. This approach recently introduced in [38] for the analysis of vehicle dynamics under hybrid uncertainties, is based on the combination of the generalized polynomial chaos formalism for propagating probabilistic uncertainties together with the Chebyshev inclusion functions used for propagating interval uncertainties. The main objective of the present study is then to evaluate the potential of this hybrid approach to be an efficient alternative to the prohibitive parametric approach usually used for the prediction of parameter-dependent friction-induced instabilities. A second objective is also to discuss the impact of hybrid models used to describe uncertainties on the stability analysis. So in this perspective and as in numerous studies in the same field, a minimal model representing a friction system submitted to mode coupling instabilities within random and interval uncertainties is considered, the final goal being the study of the

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