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A nonlinear component mode synthesis method for the computation of steady-state vibrations in non-conservative systems

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ABSTRACT

This paper presents an extension to classic component mode synthesis methods to compute the steady-state forced response of nonlinear and dissipative structures. The procedure makes use of the nonlinear complex modes of each substructure, computed by means of a modified harmonic balance method, in order to build a reduced-order model easily solved by standard iterative solvers. The proposed method is applied to a mistuned cyclic structure subjected to dry friction forces, and proves particularly suitable for the study of such systems with high modal density and non-conservative nonlinearities.

1. Introduction

For many years reduced-order modeling of dynamical systems has been a challenging topic in both fundamental and applied sciences, partly due to the rising complexity of modern technologies. The primary objective of order reduction is to cut down the number of parameters describing the system to a much smaller set of variables, while ensuring the capability to predict the behaviour of the initial model with sufficient accuracy. A tremendous diversity of reduced-order modeling techniques applicable to a broad range of engineering problems can be found in the literature. Standard mode superposition, component mode synthesis (CMS) [1–4], and proper orthogonal decomposition [5] methods, widely used in structural dynamics, are classic examples of model order reduction. The efficiency of these methods mainly relies on the ability of the reduction basis to capture and render the intrinsic dynamics of the system. As a consequence, in the presence of nonlinear phenomena, model reduction can become a very tedious task. Recent works [6,7] have however shown that the concept of nonlinear modes can prove to be very efficient in building reduced order models of large scale nonlinear systems, thus paving the way for the development of new reduction strategies well-suited for tackling industrial problematics.

Owing to their growing ubiquity in several industrial fields, cyclic structures have been extensively studied by researchers and engineers during the past century, most of the effort aroused by turbomachinery manufacturers in response

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to a soaring need for efficient power generation for both aeronautical and power plant applications. Facing evermore stringent and conflicting performance and safety requirements, bladed-disk designers have pushed back the limits of these key components to provide industrials with efficient and light structures, while ensuring their integrity in operation. Along with this constant search for an optimal design have emerged new problematics, among which stands out what is commonly referred to as mistuning, which relates to the loss of the cyclic symmetry of the system. A great deal of studies have been dedicated to the understanding and identification of the phenomenon during the last decades, first initiated by Whitehead [8], Wagner [9], Dye and Henry [10], and Ewins [11], and furthered by numerous authors since then. A thorough review is made by Castanier and Pierre in [12], devoted to the state of the art and emerging directions in the modeling and analysis of mistuned bladed-disks.

A practical consequence of mistuning when it comes to modeling is that classic methods taking advantage of the cyclic symmetry property of bladed-disks to reduce the size of the problem [13] cannot be used. Even though basic lumped-parameter models have first allowed to perform various statistical investigations to better understand the phenomenology of such systems [14–16], quantitative analyses on large-scale finite element models have required to summon reduced-order modeling techniques, such as the aforementioned classic or modified CMS methods [1,2,17], as well as mistuning-dedicated methods [18–22]. However, the introduction of nonlinearities in the model makes most of these techniques either inapplicable or ill-suited to the task, whereas nonlinear effects can yet be of primary importance for the study. As a consequence, the development of new methods allowing to efficiently combine nonlinear phenomena with mistuning has been identified as one of the key challenges in bladed-disk dynamics [12].

So far, the classic way to tackle the mistuning of bladed-disks in a nonlinear context is to summon frequency-based formulation such as harmonic balance methods (HBMs), and to proceed to a condensation of the system on the nonlinear degrees of freedom (DOFs) [23,24]. This is conceivable for localised nonlinearities such as contact and friction, and of great interest for the industry. However, for industrial finite element models, the number of nonlinear DOFs easily exceeds a few hundreds per sector, which amounts to thousands overall, resulting in large and cumbersome nonlinear systems, especially when cyclic symmetry cannot or should not be enforced to narrow down the equations to those of one single sector, for instance in case of mistuning or when localised responses are sought. Not to mention the case of non-localised nonlinearities, such as large displacements, for which an exact condensation could amount to keeping all DOFs. As a consequence, the need for fast and reliable design as well as statistical investigations entices both researchers and industrials to endeavour and elaborate new reduction strategies well-suited to such problematics.

In this paper, a new reduced-order modeling technique particularly suitable for the study of nonlinear and mistuned cyclic structures is proposed. The method can be seen as an extension of classic fixed-interface CMS methods, taking advantage of nonlinear complex modes instead of linear modes. This allows to treat internal nonlinear DOFs as slave coordinates, and further the reduction compared to a standard linear CMS. The reduction basis of a superelement is made of nonlinear modes, which must be updated during the computation to properly account for the nonlinear effects, supplemented by a set of static modeshapes through which the substructures are assembled to form the global system. A similar approach was adopted by Apiwattanalunggarn et al. [25] by means of nonlinear normal modes, but is unfortunately limited to weakly nonlinear systems and involves significant analytical developments due to the invariant manifold approach used to compute the modes. The recent and promising works devoted to nonlinear complex modes and their frequency-based formulation, first by Laxalde and Thouverez [6] and later on by Krack et al. [7,26], have highlighted their capabilities to accurately capture and render the intricate dynamics of strongly nonlinear systems subjected to non-smooth and dissipative nonlinearities. This observation makes of them well-fitted candidates in a model order reduction approach, not to mention the flexibility of their computation, inherent to numerical methods. It should be emphasised that even though the development of the method was initiated to answer topical problematics in bladed-disk dynamics, the procedure could be readily applied to all kinds of nonlinear systems, with or without specific symmetry properties.

In Section 2, the methodology used to compute nonlinear complex modes, key elements of the method, is reminded. The equations governing a nonlinear superelement are then derived in Section 3. In Section 4, the method is applied to the lumped-parameter model of a bladed-disk subjected to blade-disk joint friction, first in the absence of structural mistuning to highlight its capabilities to approximate multi-resonant nonlinear responses, before considering a randomly mistuned system to highlight its effectiveness and efficiency in studying such dynamical systems. The performance and limitations of the method are finally discussed in Section 5.

2. Nonlinear complex modes

The reduced-order modeling technique presented in this paper is inspired by classic CMS, and makes use of the rich information provided by nonlinear complex modes to further the reduction. Key element of the procedure, the concept of nonlinear complex modes is first reminded in the following section, along with the main steps of their computation.

2.1. Historical background

Nonlinear normal modes of conservative systems have been extensively studied during the last decades. Since Rosenberg addressed the topic in the 1960s [27], many authors have contributed to build a rich and comprehensive literature,

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