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Review

Nonlinear hybrid modal synthesis based on branch modes for dynamic analysis of assembled structure

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ABSTRACT

This paper describes a simple and fast numerical procedure to study the steady state responses of assembled structures with nonlinearities along continuous interfaces. The proposed strategy is based on a generalized nonlinear modal superposition approach supplemented by a double modal synthesis strategy. The reduced nonlinear modes are derived by combining a single nonlinear mode method with reduction techniques relying on branch modes. The modal parameters containing essential nonlinear information are determined and then employed to calculate the stationary responses of the nonlinear system subjected to various types of excitation. The advantages of the proposed nonlinear modal synthesis are mainly derived in three ways: (1) computational costs are considerably reduced, when analyzing large assembled systems with weak nonlinearities, through the use of reduced nonlinear modes; (2) based on the interpolation models of nonlinear modal parameters, the nonlinear modes introduced during the first step can be employed to analyze the same system under various external loads without having to reanalyze the entire system; and (3) the nonlinear effects can be investigated from a modal point of view by analyzing these nonlinear modal parameters. The proposed strategy is applied to an assembled system composed of plates and nonlinear rubber interfaces. Simulation results have proven the efficiency of this hybrid nonlinear modal synthesis, and the computation time has also been significantly reduced.

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1. Introduction

In the context of engineering structural dynamics, the systems are generally large-sized and of nonlinear nature. A typical nonlinear industrial case consists of assembled structures containing nonlinearities located along interfaces between substructures. To analyze the nonlinear effects and calculate the steady state responses of these systems under a constrained computation time, fast and efficient methods are needed.

To obtain a reduced-order model of industrial structures, the linear mode synthesis (LMS) theory has been developed into a powerful tool by various authors for analyzing mechanical systems. A brief review of dynamic substructuring can be found in Klerk et al. [26]. For systems with flexible physical interfaces, a clarification about component mode synthesis methods has been provided in Ohayon and Soize [33], namely: (1) attachment modes were first introduced to describe substructures by Hurty [18]; (2) a method combining static response modes (constraint modes) and free vibration modes of the substructure clamped on its interface (internal modes) was proposed by Craig and Bampton [12]; (3) branch modes, which are the first boundary modes obtained by condensing the modes of the structure on its interface thanks to the global structure's static response modes, were investigated by Jézéquel et al. [21,9,16]; and (4) model reduction techniques for structural dynamics were compared in Besselink et al. [7]. These techniques are all limited to linear systems. Whereas the nonlinear effect on global structural dynamics cannot be neglected in most cases and linear assumptions in these cases may lead to considerable discrepancies.

In order to solve the nonlinear problem, numerical time integration methods, such as the Newmark method and Runge-Kutta method, are often used [3]. These methods yield quite accurate results though appear to be time-consuming, especially when analyzing large nonlinear systems containing many degrees of freedom (DOFs) and when the steady state responses are required. To overcome this drawback, Rosenberg proposed the nonlinear normal mode (NNMs) concept to study nonlinear systems [37]. His premise was that resonance occurs in the neighborhood of the normal mode vibration regardless of whether the system is linear or nonlinear; moreover, the response around the main resonance can be represented by this main resonant mode response. The NNMs concept has been further developed by various authors based on theoretical aspects [32,5], numerical aspects [17,24,36] and experimental aspects [39,13,14,25,34,11]. A thorough review of theoretical developments of NNMs based on the determination of modal lines in configuration space and the computation of invariant manifolds of motion is conducted in Mikhlin and Avramov [29]. A certain summary of NNM applications is furthermore given by Avramov et al. [4]. A single nonlinear mode approach has been legitimized by Szemplinska-Stupnicka [41] to solve steady state responses of nonlinear differential equations by using approximate methods, *e.g*. the harmonic balance method, averaging method and asymptotic method [30]. In relying on this single nonlinear mode approach, Jézéquel and Lamarque have normal form theory to describe the forced response of harmonically excited systems for a two-DOF system [20]. Following this, Neild and Wagg [2] have then applied the normal form method to forced nonlinear vibration problems with the system equations expressed in the second-order form. Setio et al. [40] extended this normal form method to express general transient responses as the algebraic addition of nonlinear modal responses of general systems.

These generalized nonlinear modal analysis methods are efficient in reducing the computation time when analyzing nonlinear systems, yet prove to be still time-consuming since the iterations are integrated into the numerical approaches. Reduction techniques are therefore required. Reduced-order modeling techniques relying on nonlinear modes are presented in Touzé and Amabili [42], Lülf et al. [28]. Kuether et al. have developed a reduction technique for geometrically nonlinear models [27]. A reduction method, based on the enrichment of reduction basis constituted of vibration modes with modal derivatives, is presented in Wu and Tiso [43] for flexible multibody systems. In general, these methods are devoted to analyzing complex nonlinear phenomena. While set up for weak, large nonlinear systems, the nonlinear problem may be simplified under appropriate assumptions and lead to a faster algorithm. Nonlinear models can subsequently be reduced by integrating reduction techniques that are analogous to those employed in the LMS method. Various reduction techniques in component mode synthesis can be used to extend the normal form theory [26]. The chosen reduction technique should comply with the concrete nonlinear problem. A discussion on all reduction techniques available has not be included herein, and special attention has been paid to Craig & Bampton reduction and double modal synthesis based on branch modes.

Since the reduction techniques developed in LMS theory are often applied to analyzing engineering systems and since the NNMs obtained from free vibrations can be employed to calculate the forced responses, we propose herein to integrate reduction techniques with the NNMs concept in studying the dynamic performance of assembled systems. Before calculating nonlinear modes, the reduction technique is first applied to the nonlinear model in the case of free vibrations: physical displacements of the system are projected onto the generalized modal coordinates. A second reduction proceeds by selecting the dominant nonlinear modes obtained by solving the reduced order nonlinear problem with numerical iteration methods. The nonlinear modal parameters, *i.e*. mode shapes, natural frequencies and damping ratios, are deduced based on the