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Updating structural models containing nonlinear Iwan joints using quasi-static modal analysis

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Structures with bolted joints are known to exhibit amplitude-dependent shifts in the natural frequency and damping of its modes that are challenging to model accurately. These two properties could be derived from dynamic simulations (for example, by computing the response of the structure to an impulsive force), but such simulations are expensive. Any updating strategy based on dynamic simulation therefore becomes cumbersome. A solution was provided by Festjens et al. (2013) whereby the joint is treated as a static subcomponent in an otherwise dynamic global model. This work proposes a few modifications to their theory, resulting in a highly-efficient quasi-static algorithm that can be used to compute the amplitude-dependent frequency and damping by loading the finite element model in the shape of one of its modes. This new quasi-static method was then utilized to update a set of Iwan joint parameters so that the shift in the frequencies and damping seen in the finite element model matched those from measurements on an experimental beam containing three bolted joints. The updated model was then verified to be capable of capturing with good accuracy the effects of modal coupling seen in the impact response of the beam.

1. Introduction

Much of the uncertainty in finite element models for built-up structures comes from the interfaces (e.g. bolted joints, riveted connections, press-fits, etc.). They often cause the structure to behave nonlinearly, making experiments more challenging, and to model them accurately requires a nonlinear model that can be dramatically more expensive. See [1–3] for a review of these issues. This work focuses on methods by which joints are represented in a simplified way, so that the structure's response can be simulated quickly and the model updated to correlate with experimental measurements.

In most industrial applications, the bolts are designed to retain integrity, so most of the joint nonlinearity is attributed to microslip friction in which the joint remains intact yet partial slipping occurs for some material near the edges of the contact region [4,5]. Commercial finite element codes typically include the ability to simulate the static and dynamic response of flexible structures with Coulomb friction between contacts. For example, Abaqus [6] includes the capability to model friction using Penalty and Lagrange methods. However, once the contact interfaces are meshed with sufficient resolution to capture micro-slip and the penalty stiffness and stabilization are set to acceptable levels, the simulations become very expensive for static response [7] and are completely prohibitive when a dynamic response is desired that spans many cycles of oscillation. To address this, harmonic balance methods have been developed that compute the frequency response directly [8,9]. Other

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works have proposed 2-D zero-thickness elements [10,11] or 3-D thin-layer elements [12,13], both of which implement a tangential stick–slip condition in a continuum element, and have demonstrated their implementation in joints modeling with frequency-domain solvers. In order to model microslip behavior accurately, such models typically require hundreds of friction elements per interface [14]. The resulting simulations are still quite expensive and may be impractical if the model contains many joints. Furthermore, when updating a model to correlate with measurements, one must typically run many simulations while varying the parameters for the joint, a daunting prospect with current models.

A recent work by Festjens et al. [15] presented an alternative to traditional time and frequency domain methods. They computed the quasi-static response of the structure to a loading representative of a certain mode, and then used the results of that simulation to compute the effective natural frequency and damping for the structure when it vibrates in that mode. Their predictions were validated by comparing them to the transient response computed by integrating a full-order nonlinear finite element model, which included the preload in the fastener and the resulting Coulomb friction between the contacting surfaces. Their methodology was found to provide good estimates of the effective damping and natural frequency, however the costs are still quite high if many iterations on the model must be run such as for model updating applications.

One way of reducing the computational burden associated with joints is to replace the joint region with a simpler element that captures its effective stiffness and damping. Then, instead of enforcing frictional contact between individual nodes or element faces, those degrees of freedom can instead be tied (e.g. by multi-point constraints as in Fig. 2) to two ends of a single nonlinear element whose constitutive formulation is designed to reproduce microslip behavior internally. Such a modeling approach is the premise of Segalman's "whole-joint" model [16]. The nonlinear element may be a hysteretic model such an Iwan model [17,18] or a Bouc-Wen [19] model. A whole-joint representation is appealing because joints are often only one small part of a complicated, assembled structure. Various experimental studies have shown that the presence of one or more bolted joints induces only a slight softening in the natural frequencies, accompanied with a large increase in the damping, as the structure is excited to higher response amplitudes [14,20–23]. Unfortunately, no methods exist in literature that can predict the parameters of these hysteresis elements based on joint geometry, surface roughness, material, etc. This work instead uses a model updating approach to determine the parameters. An experiment is performed in which the transient free response is measured and then the instantaneous natural frequency and damping for each mode are extracted from those measurements [24–27]. The model updating approach can then be used to find the joint parameters that bring the model into agreement with the measurements.

Specifically, this work presents a few extensions to the quasi-static method introduced by Festjens et al., creating a highly efficient tool for extracting the amplitude-dependent natural frequency and damping from a finite element model containing discrete (localized) nonlinearities. The structure of interest is reduced to a Hurty/Craig-Bampton model [28], which contains only the nodes at each end of the nonlinear elements representing the joints. Here, Iwan elements are considered for the nonlinear representation, and the approach is optimized for those but it could be extended to other nonlinear elements. Then, a variation of the method by Festjens et al. is presented, here referred to as the method of quasi-static modal analysis (QSMA), which is used to compute and update the amplitude-dependent natural frequency and damping. By iterating on the parameters of the nonlinear Iwan joints, one can obtain a model that reproduces the measurements very well, including damping that varies in a power-law fashion with respect to response amplitude. The updated model is then validated using additional transient measurements taken from the structure, and, in the application presented here, the method showed favorable results.

2. The method of quasi-static modal analysis

The method of quasi-static modal analysis (QSMA) implemented in this work is a modification on the method in [15]. In that work, Festjens, Chevallier, and Dion solved a quasi-static problem in which a quasi-static, distributed force was applied representing the inertial loading when the structure vibrates in the mode of interest. Then, the nonlinear response of that quasi-static model was used together with Masing's rules to relate the load–deflection behavior to the dynamic response when the structure vibrates in that mode. This allowed them to compute the effective natural frequency and damping as a function of vibration amplitude from a single quasi-static solution.

To further accelerate the computations, Festjens et al. also divided the structure into two domains, a nonlinear domain including the joint (or joints) and a linear domain comprising the rest of the structure. The assumed deformation of the linear domain (i.e. into the shape of the mode in question) provided the boundary conditions for the nonlinear static solution on the joint domain. However, because the deformation of the rest structure changes as the joint slips (and its stiffness decreases), they had to use an iterative procedure to adjust the boundary conditions. To circumvent the additional complexity that this step introduces, in this work a single reduced-order model is created of the entire structure (i.e. a Hurty/Craig-Bampton model) and the distributed inertial load is applied to the entire reduced model. It is important to note that when a force is applied rather than a displacement, the structure is free to adjust quasi-statically in response to small changes in the stiffness of the joint. Hence, it is not necessary to update the displacement field near the joint. This approach does, however, neglect any change in the mode shapes with vibration amplitude, but because joints are typically designed to retain their integrity, changes in stiffness (and hence changes in the mode shapes) are therefore small within the operating regime of interest.