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Nonlinear modeling of structures with bolted joints: A comparison of two approaches based on a time-domain and frequency-domain solver

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ABSTRACT

Motivated by the current demands in high-performance structural analysis, and by a need to better model systems with localized nonlinearities, analysts have developed a number of different approaches for modeling and simulating the dynamics of a bolted-joint structure. However, it is still unclear which approach might be most effective for a given system or set of conditions. To better grasp their similarities and differences, this paper presents a numerical benchmark that assesses how well two diametrically differing joint modeling approaches – a time-domain whole-joint approach and a frequency-domain node-to-node approach – predict and simulate a mechanical joint. These approaches were applied to model the Brake-Reuß beam, a prismatic structure comprised of two beams with a bolted joint interface. The two approaches were validated first by updating the models to reproduce the nonlinear response for the first bending mode of an experimental Brake-Reuß beam. Afterwards, the tuned models were evaluated on their ability to predict the nonlinearity in the dynamic response for the second and third bending modes. The results show that the two joint modeling approaches perform about equally as well in simulating the Brake-Reuß beam. In addition, the exposition highlights improvements that were made in each method during the course of this work and reveal further challenges in advancing the state-of-the-art.

1. Introduction

Mechanical joints are a fundamental element of many built-up structures ensuring structural integrity, component alignment, and often sealing. The presence of a bolted joint in a structure can also introduce additional energy dissipation and lead to a change in the overall stiffness, which directly influences the damping and natural frequencies of the structure. Given that most structures are expensive to construct and test, it is important to be able to generate models beforehand that can accurately predict the vibrational amplitudes of such structures in order to ensure accurate performance and life predic-

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tions. Experience shows that structures with bolted joints exhibit damping that changes with the amplitude of excitation [1–7]. This adds an additional layer of complexity to their analysis since linear models are insufficient to capture the overall forced response of such a system. The addition of nonlinear constitutive models that give a better description of bolted joint mechanics is therefore needed for such analysis.

However, a bolted joint model that includes too detailed a description of the nonlinear tribological processes occurring at the interface is far too expensive to be used for nonlinear dynamic analysis of a complicated structure. Such models are typically studied by the solid mechanics community, and would involve separate and highly-refined meshes between the interfacing surfaces and other fixture mechanisms (bolts, washers, nuts, etc.), which are coupled with nonlinear friction and contact models [8–10]. Other works within the same community investigate the fundamental science (friction, adhesion, fretting, elastic deformation, etc.) underlying contact mechanics, and typically involve simplified models such as a punch on a semi-infinite plane [11–14]. These methodologies, however, cannot currently be scaled to three-dimensional dynamic analysis of engineering structures such as that studied here. Further, the length scale of the whole structure (where stresses are of interest to engineers) differs very greatly from that of the joint and so it seems wise to simplify the representation of the joint. Hence, the current state-of-the-art in dynamic joint modeling reflects a compromise between the level of detail in modeling joint kinematics versus the computational effort required to estimate the dynamic response.

The past few decades have seen the development of a number of alternative bolted joint modeling approaches that fall somewhere between low-cost and high fidelity. In the most simple case the assembled structure can be represented as linear mass-spring models, connected by one or a few nonlinear macro-elements composed of a parallel or series arrangement of springs, dashpots, and Coulomb sliders [1,15,16]. At the other end of the spectrum are the high-fidelity joint models produced by the solid mechanics community [8–10]. A modeling approach that also leans heavily towards the detailed side is one that incorporates zero-thickness elements [17–19] and thin-layer elements [20–22] in the contact interface. Originally proposed by the geomechanics community, these elements capture the stick-slip condition as they undergo shear deformation. Most approaches are somewhere in between these extreme cases, and are either based on time [2,23,24] or frequency [25–28] domain solvers that simulate the nonlinear dynamic response of structures containing bolted joints.

Despite the research effort, there are currently no predictive models for joint dynamics and the current benchmark is in error of around 25% in terms of frequency estimation and two orders of magnitude for the damping predictions [2,7]. In this work, two joint modeling approaches have been selected for a detailed evaluation of their prediction capabilities: the whole-joint approach based on a time-domain solver, and a frequency-domain approach based on the multi-harmonic balance method (MHBM).

The whole-joint approach, introduced by Segalman in [2,29], represents an area of contact surrounding a bolt as a coupling of two rigid surfaces by a single nonlinear constitutive element, typically an Iwan element [30,31], which models microslip in a joint interface. Since it is difficult to predict the parameters of an Iwan element for a given geometry and material, an Iwan element is traditionally tuned to capture measurements of the hysteresis of the joint as a function of loading amplitude [2,32]. However, in structures that contain more than one joint, it becomes difficult to isolate the contribution of each joint to the hysteresis observed in the measurements. As a result, subsequent works have measured the net effect of all of the joints on each mode of vibration and have tuned an Iwan element to model each structural mode, which is assumed to be uncoupled from all other modes [33,5,6]. This approach is often justified in structures that exhibit weak nonlinearities such that there is negligible change in the mode shapes of the structure [5,6] yet the natural frequency and the damping of each mode vary with amplitude. Hence these modal Iwan models have been tuned to capture this amplitude-change in frequency and damping of each mode.

However, the work of [34] has demonstrated that the uncoupled modes assumption can lead to error in the predicted modal damping as amplitudes become large, and a systematic method has yet to be developed that reintroduces coupling to these modal Iwan models. Hence, a different tactic is pursued in this work that returns to the whole-joint formulation using discrete Iwan elements for modeling the physical joint, but still updates those Iwan elements so that the change in modal frequency and damping predicted by simulation matches that which is measured. Even then, despite the model containing only a few Iwan elements, it is still expensive to compute the transient response, and one would have to perform lengthy simulations of the nonlinear ring-down response of a structural model in order to extract these amplitude-dependent properties[34]. To address this, a quasi-static technique was recently developed in [35] that was later simplified in [36] to create a highly efficient and accurate algorithm for computing amplitude-dependent frequency and damping for models containing Iwan elements. The authors of [36] then used the algorithm to update the Iwan parameters in a finite element model to match the nonlinearity seen in experimental measurements on the transient free-response of a bolted structure. It is not clear, however, whether the algorithm could be used for updating against forced sinusoid response measurements, and this paper seeks to address that.

The second selected joint modeling approach is based on a multi-harmonic balance solver [37–39]. The forced response of the system is obtained through a frequency-domain solver, which uses a multi-harmonic description of the displacements and nonlinear contact forces. When the MHBM is used, the contact forces are computed in the time domain by following an alternating frequency-time procedure [40,41], which allows for a wide variety of contact nonlinearities, including Coulomb friction, to be computed. The linear components are thereby represented via reduced finite element models [42] that only maintain the information at the contact nodes, thus significantly reducing the computational time. This modeling approach was successfully applied to a series of industrial test cases, including underplatform dampers [43,44] and flange joints [45], where a highly-detailed model was able to capture the amplitude-dependent damping and frequency under high-level exci-