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A numerical study on the limitations of modal Iwan models for impulsive excitations

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ABSTRACT

Structures with mechanical joints are difficult to model accurately. Even if the natural frequencies of the system remain essentially constant, the damping introduced by the joints is often observed to change dramatically with amplitude. Although models for individual joints have been employed with some success, accurately modeling a structure with many joints remains a significant obstacle. To this end, Segalman proposed a modal Iwan model, which simplifies the analysis by modeling a system with a linear superposition of weakly-nonlinear, uncoupled single degree-of-freedom systems or modes. Given a simulation model with discrete joints, one can identify the model for each mode by selectively exciting each mode one at a time and observing how the transient response decays. However, in the environment of interest several modes may be excited simultaneously, such as in an experiment when an impulse is applied at a discrete point. In this work, the modal Iwan model framework is assessed numerically to understand how well it captures the dynamic response of typical structures with joints when they are excited with impulsive forces applied at point locations. This is done by comparing the effective natural frequency and modal damping of the uncoupled modal models with those of truth models that include nonlinear modal coupling. These concepts are explored for two structures, a simple spring-mass system and a finite element model of a beam, both of which contain physical Iwan elements to model joint nonlinearity. The results show that modal Iwan models can effectively capture the variations in frequency and damping with amplitude, which, for damping, can increase by as much as two orders of magnitude in the microslip regime. However, even in the microslip regime the accuracy of a modal Iwan model is found to depend on whether the mode in question is dominant in the response; in some cases the effective damping that the uncoupled model predicts is found to be in error by tens of percent. Nonetheless, the modal model captures the response qualitatively and is still far superior to a linear model.

1. Introduction

Mechanical joints are known to be a source of considerable energy dissipation in built-up structures [1,2]. The presence of a joint causes the damping in the structure to show amplitude-dependent behavior [3]. That is, the apparent damping in

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the structure tends to increase as the excitation force increases. For years, analysts have modeled amplitude-dependent damping by tuning linear equations of motion for particular levels of excitation. In realistic settings, this method can give erroneous results because the excitations from the environment induce structural responses that cover a spectrum of amplitude levels in a short time frame. A better model is one that can account for the change in damping with amplitude.

One way to account for the change in damping is simply to represent the joint as a local nonlinearity in an otherwise linear finite element model of the structure. Ideally, the joint model would be predictive, describing the friction contact in detail and capturing deformations near the interface due to the clamping load [4–6]. Prior work has shown that, at small amplitudes, the edges of the contact begin to slide relative to one another even though most of the joint remains intact [7,8]. This phenomenon is called microslip. In the microslip regime the stiffness of the joint decreases only slightly, but small slip displacements occur in localized regions in the contact patch that cause significant energy loss [9]. As the excitation amplitude increases, the small slip regions expand and combine until macroslip occurs, where the stiffness of the joint is compromised and relative motion occurs between the interfacing bodies.

To model microslip-macroslip phenomena in detail is exceedingly expensive, and there is still considerable uncertainty regarding which friction models should be used for a given material interface. One alternative is to replace the contacting interfaces with a lumped, hysteretic model such as an Iwan element [10]. This work uses Segalman's four-parameter Iwan model [11], which is capable of capturing joint behavior over both the microslip and macroslip regimes. Segalman's model was developed as a result of an extensive testing campaign and theoretical studies [12], and was shown to capture the physics that were observed in metal-metal contacts. A brief theoretical treatment of the four-parameter Iwan model is given in Appendix A. The four-parameter Iwan model is not predictive, however, so experiments must be conducted to derive its parameters based on the geometry, clamping force, friction characteristics, and other properties of the joint it represents. For bolted structures containing many joints, this could be a challenging task.

In response to this problem, Segalman proposed an alternative approach, the modal Iwan model, which accounts for the net effect of all the joints on each mode of the structure [13]. In Segalman's formulation, a nonlinear single-degree-of-freedom oscillator is used to represent each modal coordinate independently. The nonlinearity is captured with a four-parameter Iwan model so that each mode can exhibit both microslip and macroslip behavior. Many other researchers have proposed similar approaches, although with very different models for each mode (see for example [14,15]).

The key assumption made in these formulations is that nonlinear coupling between the linear modes is negligible, so the nonlinear model for each mode depends only on the native modal coordinate. Eriten et al. [15] used a complexification and averaging method to show rigorously that this assumption holds when the nonlinearity is weak and that the natural frequencies are not close nor integer related. Follow-up works by Deaner et al. [16] and Roettgen and Allen [17] demonstrated experimentally that the modal Iwan model can be used to accurately describe the free response of bolted structures in microslip.

When a single mode is selectively excited (by adjusting the spatial distribution of the force or exciting at a frequency near resonance), the coupling between modes will be relatively small. Segalman used a three-degree-of-freedom mass-spring system with a single Iwan joint to show that, when a mode is selectively excited, an appropriately tuned modal Iwan model can reproduce the modal response of that mode exceptionally well [13]. Segalman did not probe the limits of this assumption, however. When a general input is applied, modal coupling may be more important. Festjens, Chavalliear, and Dion began to explore this in [18], where they showed a case in which a model with uncoupled modes exhibited considerable error compared with their truth simulation. However, their study used an “Iwan joint” with only three slider elements in parallel, so it was not capable of accurately reproducing microslip behavior. This prompts the question: is modal coupling in realistic structures typically small enough to allow a modal Iwan model to be accurate over a significant range of amplitudes in the microslip regime?

This paper seeks to answer that question, exploring the extent to which a modal Iwan model can reproduce the response of a structure to discrete, impulsive excitations. Two structures are considered, a three-degree-of-freedom spring-mass system and a finite element model of a bolted beam, both of which contain discrete Iwan elements to describe joint behavior. The response of these structures is computed for various types of impulsive excitations, and then the effective natural frequency and damping of each mode is compared to that predicted by an uncoupled modal model. The following section presents an overview of the modal Iwan model, followed by a discussion of how to deduce its parameters based on transient ring-down data. The two structures are then studied, first by selectively exciting the linear modes of each structure to deduce the parameters of an equivalent modal Iwan model. Then the effective damping and natural frequency of the modal Iwan model are compared against those that are observed when the original finite element models are subjected to impulsive excitations at various points. The results show that the modal framework can be a good approximation in the microslip region, and they highlight the path-dependent nature of the nonlinear joints.

2. Theoretical background

The objectives of this study necessitate a comparison between the response simulated from a modal Iwan model and that of a realistic system that has discrete joints. In this work, the response due to bolted-joint nonlinearity is interpreted on a mode-by-mode basis, including the modal coupling that is observed. The typical effect that bolted joints have on a structure is such that, as the amplitude of excitation increases, the modal damping of the structure increases significantly and natural