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Nonlinear characterization of a bolted, industrial structure using a modal framework

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ABSTRACT

This article presents measurements from a sub assembly of an off-the-shelf automotive exhaust system containing a bolted-flange connection and uses a recently proposed modal framework to develop a nonlinear dynamic model for the structure. The nonlinear identification and characterization methods used are reviewed to highlight the strengths of the current approach and the areas where further development is needed. This marks the first use of these new testing and nonlinear identification tools, and the associated modal framework, on production hardware with a realistic joint and realistic torque levels. To screen the measurements for nonlinearities, we make use of a time frequency analysis routine designed for transient responses called the zeroed early-time fast Fourier transform (ZEFFT). This tool typically reveals the small frequency shifts and distortions that tend to occur near each mode that is affected by the nonlinearity. The damping in this structure is found to be significantly nonlinear and a Hilbert transform is used to characterize the damping versus amplitude behavior. A model is presented that captures these effects for each mode individually (e.g. assuming negligible nonlinear coupling between modes), treating each mode as a single degree-of-freedom oscillator with a spring and viscous damping element in parallel with a four parameter Iwan model. The parameters of this model are identified for each of the structure's modes that exhibited nonlinearity and the resulting nonlinear model is shown to capture the stiffness and damping accurately over a large range of response amplitudes.

1. Introduction

Joints have long been known to be a significant, if not the most significant, source of damping in built up assemblies. They are also frequently the source of nonlinearity in what would otherwise be a linear structure. However, even when joints behave linearly, their linear stiffness and damping properties are difficult to predict. Hence, when updating a finite element model a significant fraction of the effort is focused on the joints. This work seeks to address the challenge of testing structures with weakly nonlinear joints by using a recently proposed framework that models the structure as a collection of uncoupled, weakly nonlinear (in the case of micro-slip) oscillators. A set of tools is presented that can be used to characterize the nonlinearity in each mode due to the joints. These tools are applied, for the first time, to measurements from an assembly from an automotive exhaust system that contains two joints with realistic geometry, gaskets, and bolt torques.

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This work builds on the efforts of Segalman, and his colleagues at Sandia National Laboratories, who pursued a multi-year project in which models for mechanical joints were derived and calibrated to match experimental force-dissipation measurements [1,2]. They showed that one can determine the parameters for each joint in a structure and employ nonlinear time integration to compute the response including the effects of the joints. This greatly increases the cost of the response predictions so model reduction strategies were explored. In applying this framework to simulate various structures, it has been noted that the resulting response is usually very nearly linear, causing one to question whether there might be an easier, less expensive way to model them. For small enough loads, mechanical joints tend to exhibit micro-slip, a phenomenon in which the joint as a whole remains intact but small slip displacements occur at the outskirts of the contact patch causing frictional energy loss in the system [1].

Towards this end, Segalman recently proposed to model each mode of a structure as independent but with an Iwan joint in parallel with the modal stiffness to capture the nonlinear damping (and to a lesser extent nonlinear stiffness) of the joint [3]. A rigorous theoretical foundation for models with uncoupled modes such as this was developed by Eriten et al. [4], who showed that energy transfer between modes can be negligible in the presence of weak nonlinearity unless their frequencies are close. Using this framework, one can identify or model the weak nonlinearity of each mode individually. Allen and Deaner later extended Segalman's work by adding a viscous damper in parallel with the Iwan element account for the linear material damping that dominates for each mode at very small amplitudes [5] and began to more thoroughly explore the extent to which this modal approximation is accurate for real structures with several joints [6]. They used two new tools, namely the Hilbert transform algorithm developed by Sumali et al. [5,7] and the Zeroed Early-Time FFT (ZEFFT) algorithm by Mayes and Allen [8] to characterize each mode of the structure. The ZEFFT algorithm is a simple time-frequency decomposition comparable to the short time Fourier transform or wavelet transform that allows one to quickly interrogate each mode to detect those modes that exhibit nonlinearity.

Once one has determined which modes might be behaving nonlinearly, a Hilbert transform analysis can be used to extract the instantaneous frequency and damping of each harmonic in the signal. This analysis is only applicable to single-frequency signals, and so the measurements must first be band-pass filtered to isolate a single frequency. Other researchers have instead employed empirical mode decomposition or other variants [4,9,10], but these algorithms are far from straightforward to use and are sometimes ineffective at separating close frequencies, so they were not pursued in this work. Once a single frequency signal has been obtained, the Hilbert transform can be computed and then the output of the Hilbert transform must be smoothed in some way so that its derivative can be found and used to estimate the time varying oscillation frequency and damping. The authors smooth the signal by fitting a polynomial to the amplitude and phase as a function of time, similar to what was done in [5,7]; others have instead filtered the Hilbert transform [11]. Sapsis et al. recently presented another interesting alternative, in which the local maxima in the velocity and displacement were fit to a spline function and then energy measures were derived to extract the instantaneous stiffness and damping [12].

The approach used here is similar to that which was first used by Deaner et al. [5] to characterize a beam with a bolted joint. However, this work presents a new means of interpreting the dissipation in the modal Iwan model that allows one to more clearly see how the damping ratio changes with response amplitude, while still allowing power-law behavior to be identified. Specifically, while previous works [2,5] characterized the damping in an Iwan model using the energy dissipation versus cycle versus velocity amplitude (or force), this work shows that superior information can be obtained by computing the effective damping ratio and displaying it versus log velocity amplitude. This work also builds on the previous works by exploring whether these tools and the modal Iwan modeling framework are effective for a real industrial structure with several joints, with gaskets in the interfaces, bolts tightened to the recommended specifications, and with complicated, three-dimensional modal deformations. The effect of the input location is explored in more detail here, presenting much stronger evidence that the modal Iwan model is valid for a wide range of inputs.

It should be noted that other frameworks have been proposed for modeling structures with joints. Of particular note is the harmonic balance approach employed, for example, in [13] and the associated methods reviewed there and in related works [14]. The harmonic balance can be very computationally efficient, especially when seeking to simulate stepped-sine measurements or nonlinear frequency responses. However, some of those gains may be lost when the joint is modeled by an Iwan model with many slider elements, and harmonic balance is, of course, not as useful when impulsive loads are of interest.

2. Nonlinear model characterization – theory

In order to develop a nonlinear model for a structure, one must first find a means of detecting nonlinearity in measured experimental data. In this work this is done in a two step process. First, the data is analyzed using the zeroed early-time fast Fourier transform (ZEFFT) [8] to determine which modes might exhibit nonlinearity. The ZEFFT applies the following window $w(t)$ to the time history $x(t)$, and then the FFT is computed for various truncation times t_n.

$$w(t) = \begin{cases} 0 & t \le t_n \\ 1 & t > t_n \end{cases} \tag{1}$$

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