Model Correlation to a Nonlinear Bolted Structure Using Quasi-Static Modal Analysis

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Abstract:

Bolted joints are common in many engineering structures, yet they introduce complexity when the interest is predicting the dynamic response of a system. Under large load amplitudes, the joint contact interfaces will slip and cause the response to be nonlinear. A method proposed by Festjens et. al., and later elaborated upon by the authors and dubbed Quasi-Static Modal Analysis (QSMA), has made it feasible to model the contact between structures in detail and thus predict the nonlinear dynamic behavior. Prior works have shown that this is feasible [1] [2], yet no work has rigorously correlated such a finite element model with experimental measurements. This work takes a step in that direction by quantifying the effect of various features in the FEM to the amplitude dependent damping and natural frequency predicted by QSMA. Specifically, the effect of the friction coefficient and the curvature of the contact interface on the QSMA predictions is found and quantified. The results so far show that some of these effects could improve model agreement.

Keywords: Quasi-Static Modal Analysis, Nonlinearity, FEA, Damping, Natural Frequency

Introduction:

Most structures utilize bolted joints to connect critical load bearing components. These bolted joints introduce many complications when modeling the dynamics of a structure because under certain conditions a bolted joint can exhibit nonlinearity with respect to load amplitude. The mechanism causing the nonlinearity is the relative slip that occurs at the contact interfaces between two clamped components. Slip at the contact interface will dissipate energy and reduce the effective stiffness of the structure with increasing load amplitude. This may occur in two regimes. In the micro-slip regime the edges of the contact patch will begin to slip relative to each other, but at least some parts of the joint remains stuck and the joint shows only weak to moderate nonlinearity. The other regime is macro-slip, where the entire interface begins to slide, exhibiting a significant increase in nonlinearity. The focus of this work is to model the nonlinearity restricted to micro-slip.

One of the greatest challenges to solving these problems is the computational cost. Modeling macroscale structural geometry must be balanced with modeling the microscale parameters that dictate the frictional energy dissipation. To address this, Festjens et al. [3] proposed a method that broke up the bolted structure into linear regions away from the joints and nonlinear regions near the joints. Then the mode shapes of the linearized structure could be modeled with a coarse finite element mesh and used as boundary conditions for a much more refined nonlinear model of the joint. Mode shapes would be calculated for the linearized structure, which would be valid at low force amplitudes, and then they could be updated as the mode shapes changed at higher amplitudes. The computational cost was further improved by applying Masing's rules, described in [4] and [5], which assumes that the initial loading curve, or backbone curve, is simply a scaled version of the full hysteresis curve the structure would undergo in a full vibration cycle. Using the backbone curve, one can also calculate the instantaneous natural frequency of the structure, and using the area inside the hysteresis curve, one can calculate the instantaneous damping ratio.

A simplified version of this method [3], was eventually developed in [6]. This method, here referred to as Quasi-Static Modal Analysis (QSMA), included the difference that the structure was not separated into linear and nonlinear regions, so that the nonlinear quasi-static problem could be solved only once on the whole model, and the approach was more amenable to commercial FEA software. Furthermore, in [6] the QSMA method was first used together with model updating to obtain a model that correlated well with experimental data.

QSMA was further developed as a means to create a predictive FEM for damping nonlinearity in [1] and [2]. Where various contact formulations and experimental parameters were explored in both 2-D and 3-D models using Coulomb friction. Physically reasonable results were found in both cases, although they fell short in being truly predictive of the experimentally observed nonlinearity for an experimental benchmark structure called the S4 beam. This work hopes to expand on this progress by creating a high fidelity FEM that uses more accurate measurements of the geometry of the contact surface to create a more accurate model for the S4 beam. Furthermore, since the sub-millimeters scale surface topography is uncertain, parametric studies are used to explore the sensitivity of the modal frequency and damping to the surface curvature.

Preliminary Results:

Experimental measurements [7] showed that two modes of the S4 beam exhibited significant nonlinearity, the second and the sixth. The second mode is the first in-phase bending mode and the sixth mode is the first shearing mode. Shown in Figure 11, the two modes load the contact interface differently; the second begins to slip at the end of the interfaces closest to the center of the beam due to transverse shears from the bending, and the sixth begins to slip in a more circular pattern as the joint is loaded by transverse shear forces and torsional forces. In the cases presented here only mode two is considered, although both modes are being correlated in order to have a thorough validation of the FEM.

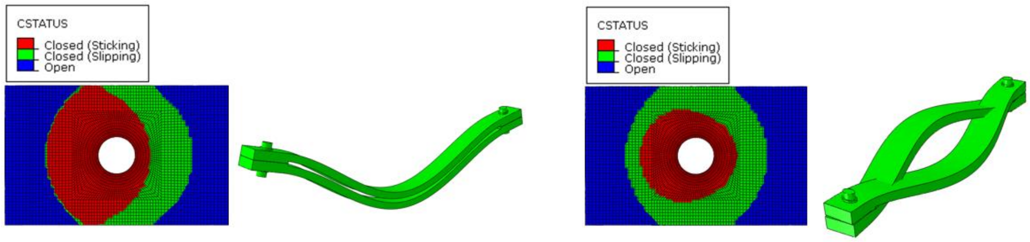

Figure 1: Joint interface slip contours and mode shapes for mode 2 (left) and mode 6 (right).

To reach agreement between the model and the experimental measurements, two parameters are considered here: The coefficient of friction between the two clamped members and the curvature of the contact surfaces. The coefficient of friction is varied over a range of possible values. A cylindrical convex curvature is applied in the direction perpendicular to the length of the beam. Curvatures with a radius of 1.27 m and 2.54 m are considered here, which produce a difference in height of about 508 microns (20 mil) and microns 254 (10 mil) across the width of the S4 Beam. This is in the range of the non-flatness that was measured in the S4 Beam that was tested. Cylindrical curvature was chosen in order to determine how curvature in different directions effected the response.

Figure 22 and Figure 33 show two parameter studies compared with experimental data. No linear damping mechanism was included in the FEM so the magenta line indicates the approximation made for the amount of linear damping in the experimental system. This value was subtracted from the raw experimental damping curve to calculate the nonlinear damping curve in green. The approximation for the linear damping value was made by choosing the value that made the nonlinear curve match the expected power-law form in micro-slip [8]. The bottom plot shows the difference between the linear natural frequency and that computed at each amplitude, revealing how much the natural frequency of the structure would change as the modal amplitude increases. Modal velocity has been expressed as the velocity of the point on the structure that has the largest velocity in the mode in question.

Figure 22 shows how the curvature of the interface changes the structure. The flat model distributes the bolt preload over a larger surface, so it has a lower pressure in the joint, it also shows the most nonlinearity. This agrees with previous findings in [1] that show that lower joint pressure increases nonlinearity, presumably because there is a lower threshold to slip. The models tend to over predict the change in damping and natural frequency and go completely into macroslip well before the experimental data, which does not allow us to compare the models for higher amplitudes.

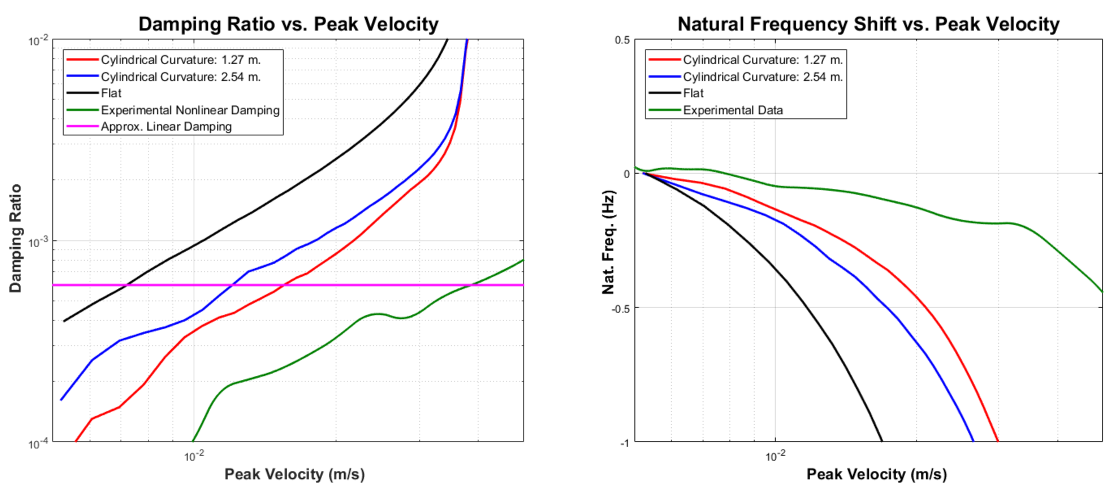

Figure 2: Effective Natural Frequency and Damping of flat and curved interfaces compared to experimental data.

Figure 33 shows the amplitude dependent damping and natural frequency curves for various coefficients of friction and a single cylindrical curvature of 1.27 m. The coefficient of friction has less effect than the curvature but driving it higher does tend to push the predicted damping curve slightly closer to the experimental results.

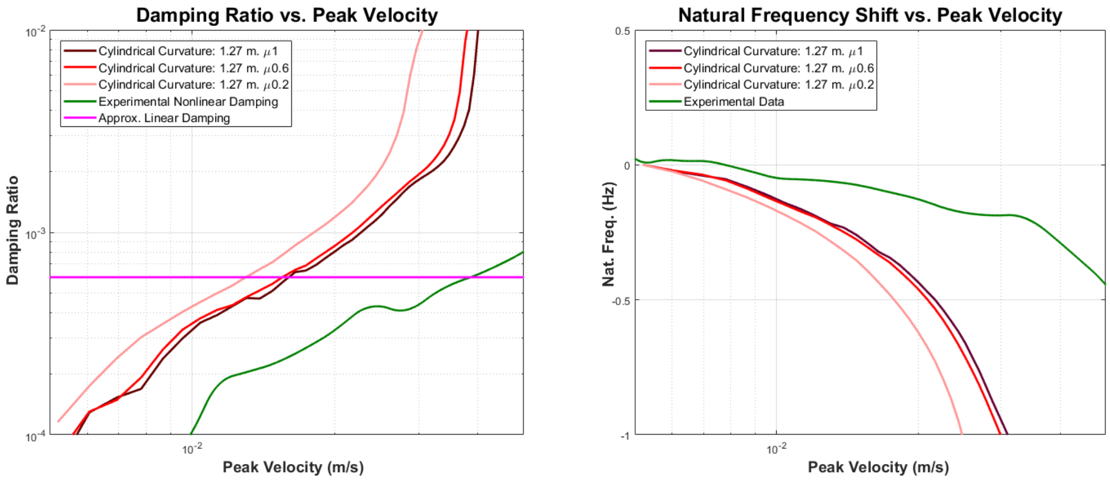

Figure 3: Various coefficients of friction for a given cylindrical curvature of 1.27 m.

Moving Forward

The cylindrically curved surfaces used here were implemented in order to obtain insight into how sensitive the structure is to surface curvature. The actual surface is more spherical or elliptical, or may even have islands that deviate from the otherwise flat or curved surfaces by 10's to 100's of microns (up to a few thousandths of an inch). Findings emphasize the need to accurately predict the preload and joint pressure distribution. To simulate the real surface, precise surface roughness and surface topology measurements are being acquired and will be used to update the FEM. To make a definitive conclusion on the ability of this FEM to replicate the measured behavior, subsequent results will use this more accurate surface representation of the structure.

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References

[1] M. Wall, A. Matthew S., and Z. Iman, "Predicting S4 Beam Joint Nonlinearity Using Quasi-Static Modal Analysis," *IMAC XXXVII*.

[2] E. Jewell, M. S. Allen, I. Zare, and M. Wall, "Application of Quasi-Static Modal Analysis to a Finite Element Model with Experimental Correlation," *J. Sound Vib.*, vol. Submitted for Publication, Jan. 2019.

[3] H. Festjens, G. Chevallier, and J.-L. Dion, "A numerical tool for the design of assembled structures under dynamic loads," *Int. J. Mech. Sci.*, vol. 75, pp. 170–177, 2013.

[4] D. J. Segalman, "A Four-Parameter Iwan Model for Lap-Type Joints," *J. Appl. Mech.*, vol. 72, no. 5, pp. 752–760, Sep. 2005.

[5] G. Masing, "Eigenspannungen und verfestigung beim messing (self stretching and hardening for brass)," presented at the 2nd Int. Congress for Applied Mechanics, 1926, pp. 332–335.

[6] R. M. Lacayo and M. S. Allen, "Updating Structural Models Containing Nonlinear Iwan Joints Using Quasi-Static Modal Analysis," *Mech. Syst. Signal Process.*, vol. Volume 118, no. 1 March 2019, pp. 133–157, 2019.

[7] A. Singh *et al.*, "Experimental Characterization of a new Benchmark Structure for Prediction of Damping Nonlinearity," presented at the 36th International Modal Analysis Conference (IMAC XXXVI), 2018.

[8] D. J. Segalman *et al.*, "Handbook on Dynamics of Jointed Structures," Sandia National Laboratories, Albuquerque, NM 87185, 2009.