A comparison of numerical approaches for predicting the dynamics of a beam with a lap joint

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This work establishes a round robin for comparing different modeling approaches that predict the dynamics of a bolted-joint structure. The goal of the round robin is to calibrate each modeling approach against one set of measured frequency response data and then validate the calibrated models using a different range of frequency response data from the same structure. The calibrated joint models are then assessed on their ability to predict the nonlinear frequency response of the benchmark structure. Two different joint modeling approaches were considered: a time-domain method that uses whole-joint models (hereafter referred to as the whole-joint approach) [1, 2], and a frequency-domain method based on a multi-harmonic balance method that uses 3D contact elements (MHBM approach) [3, 4]. This work is the conclusion of a previous round robin [5], which attempted a purely numerical comparison between the considered joint modeling approaches without model updating against measurements.

The benchmark test structure against which these approaches were examined is the Brake-Reuss beam, a prismatic structure composed of two stainless steel beam components that are bolted to each other in the middle of the assembly via a lap joint with three bolts. Although simple in its construction, the Brake-Reuss beam has been shown to produce ample nonlinear joint behavior in previous tests [6], so it was deemed a suitable structure for this round robin on joints modeling. During the experiments, the bolts were tightened to 20 Nm, and the beam was suspended in a free-free configuration for testing. A shaker was attached in a direction normal to the contacting surfaces, and the beam was excited with a stepped-sine input near the resonance for the first, second, and third bending modes of the beam. The response was collected from an accelerometer placed at the end of the beam, and the frequency response function (FRF) was collected for each mode at four different force levels: 0.1 N, 0.5 N, 1 N and 2 N.

The four FRF curves measured near the peak of the first bending mode were used as the reference data to which the joint models were calibrated. After calibration, simulations were conducted using the nonlinear joint models to predict the frequency response near the peaks of the second and third bending modes at each of the four forcing levels without any further model updating to test the predictive capabilities of the nonlinear models.

The whole-joint approach and the MHBM approach both used the same linear finite element model (FEM) of the Brake-Reuss beam as the base onto which each added their own nonlinear joint model.

The whole-joint approach uses a time-domain solver to simulate any type of response, but the solver tends to struggle if the model includes hundreds of nonlinear elements. By using a whole-joint model, specifically an Iwan element [7], the dynamics of the entire joint is modeled by representing each bolted region on the interface with a single Iwan element. One can then use quasi-static modal analysis to tune the Iwan elements to reproduce the change in the modal damping and resonant frequency with the change in excitation force as measured from experiment [8]. However, there is uncertainty in how best to divide the contact interface amongst multiple Iwan elements. A few configurations were explored in this work, and it was found that dividing the interface into five contact patches allowed the model to flex the Iwan elements enough to produce comparable damping to that measured for the first bending mode. In simulations using this time domain method, the time history of the quasi-steady-state response to a swept-sine input was computed, and a Fourier transform was implemented to bring the response into the frequency domain.

The MHBM approach seeks to predict accurately the response of a structure by modelling the interface in detail though node-to-node coupling of nonlinear elements. As a frequency-domain method, however, the output of a simulation using the MHBM approach is limited to the forced harmonic response. Hence, forced harmonic response data was chosen to compare the approaches. The parameters of the 3D contact element used in this approach can be determined using predictive techniques, such as through calculating the pressure due to the bolts to determine the normal force, and by referencing literature for a local friction coefficient and contact stiffness. The 3D contact element can represent stick, slip, or gap states, but the mesh of the joint interface is required to be refined enough to capture the underlying nonlinear mechanism in the joint. In this work, 86 contact elements were used to obtain a good balance between computational time and accuracy in the nonlinear response. A Voronoi area optimization was applied to divide the interface into areas surrounding each active node so as to compute the bolt load on the node due to the contact pressure in each area.

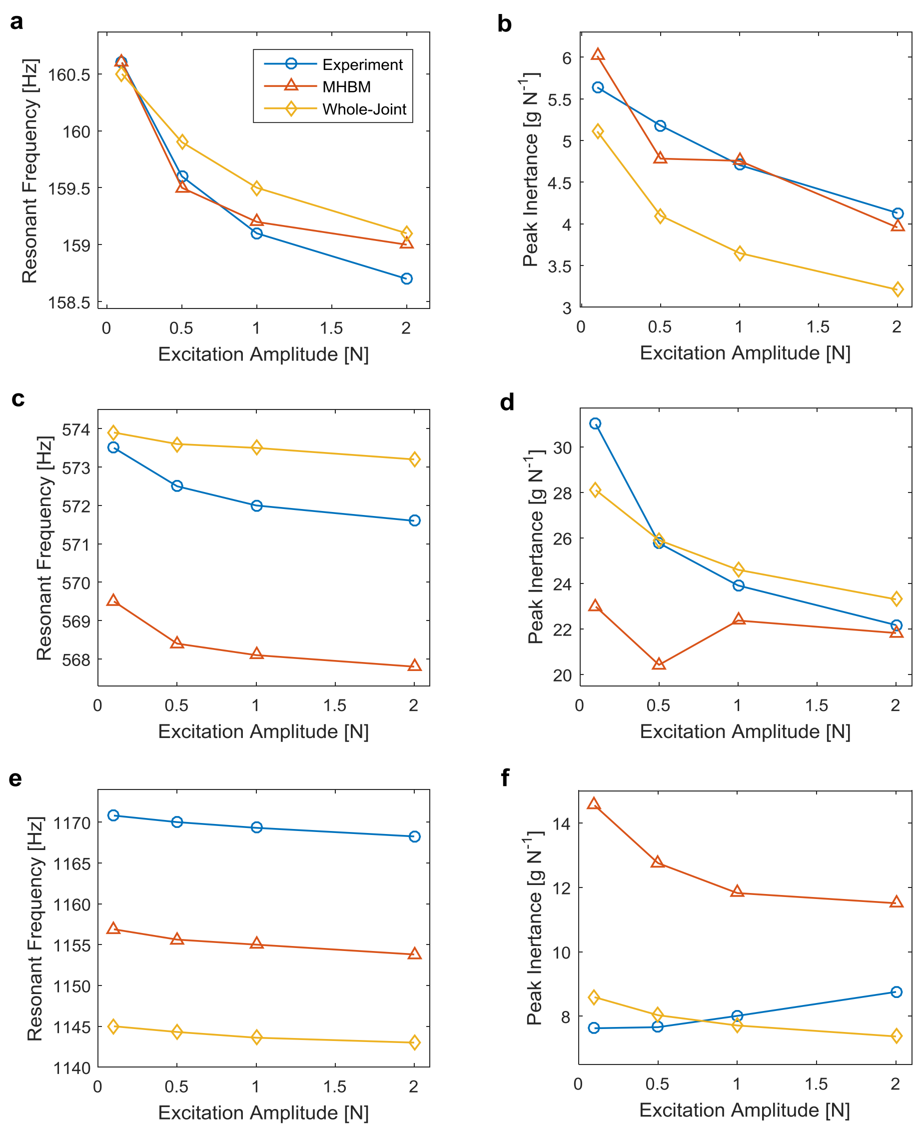

Fig. 1 Comparison between experiment and the modeling approaches of (a,c,e) the resonant frequency and (b,d,f) peak intertances in the (a,b) first, (c,d) second, and (e,f) third bending modes of the Brake-Reuss beam.

Both models were tuned to match the first bending mode at the four excitation levels as closely as possible. Simulations were then conducted for both joint models to produce the nonlinear FRFs at each of the four forcing levels for the second and third bending modes. Figure 1 compares the resonant frequencies and peak FRF values for the three modes in both modeling approaches. It can be observed that both modeling approaches represented the joint behavior of the Brake-Reuss beam very well. The MHBM model calibration produced a closer fit to the FRF curves for the first bending mode than the whole-joint model calibration. The whole-joint model was closer to the natural frequencies and peak intertances of the second bending mode. Both models also predict the correct trend of decreasing natural frequency and decreasing peak inertance with increasing excitation. For the third bending mode, the resonance frequencies predicted by the MHBM model are closer to those of the experiment, though both modeling approaches predict the same amount of frequency shift. Neither approach was able to replicate the trend of increasing peak inertance (i.e. decreasing damping) with increasing excitation in the third bending mode, but the physical mechanism behind this phenomenon was not well understood so the joint models were not expected to predict this trend.

Given the complexity of the motion at the joint interface, and the uncertainty in the measured data, the achieved agreement between the models and the experimental data is very satisfying. This is especially so for the second and third bending modes because they were not considered during the updating of the joint models, which demonstrates the reliability of both approaches. The joint models in this work were produced from the engineering judgement of the specialists behind each modeling approach, and they represent the current state-of-the-art in lap joints modeling. Future research in this work will seek means to improve the models even further.

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