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Nonlinear Material Characterization in Dynamic Testing: Part I – Experiments

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1 ABSTRACT

Sources of nonlinearities are ubiquitous in real-world structures and include interfacial mechanics, bolted joints, complex materials, and large deflections. For example, nonlinear behavior of a system under dynamic loading conditions may be directly caused by nonlinear material properties. These features pose challenges in the design, testing, and analysis of systems as they result in amplitude-dependent structural properties (e.g. natural frequency, damping, and mode shape). Los Alamos National Laboratory (LANL) and Sandia National Laboratories (SNL) engaged in a collaboration to investigate and develop testing, analysis, and uncertainty quantification techniques to capture the relevant physics resulting from these nonlinear compliant materials and their corresponding influence on the structural response. The present work is Part I of a three-part series and discusses the experimental approach taken to excite and identify the properties of a nonlinear material. The set-up, testing techniques employed, and results obtained from each lab are presented and compared. A variety of excitation methods were employed, including white noise, stepped sine, and force appropriation. The results from these experiments are used in Parts II and III to, respectively, update the finite element model and provide data for uncertainty quantification.

2 INTRODUCTION

This effort is motivated by the need to reduce uncertainty in simulations and tests for complex systems and models [1]. To do so, "single-feature" testbeds are designed to isolate a characteristic of interest and identify sources of uncertainty due to the specified feature, such as nonlinear, compliant materials. Real-world structures often contain sources of nonlinearities that are sufficiently significant to render a linear framework inadequate to capture the true structural or dynamic response. As such, the testbed discussed herein was designed to have relatively simple geometry, such that characteristics of the compliant material are nearly isolated. Los Alamos National Laboratories (LANL) and Sandia National Laboratories (SNL) established a collaboration to investigate testing, analysis, and uncertainty quantification techniques which can characterize the dynamic response of a stiff material sandwiched between nonlinear, compliant foam materials. For the closed-cell foams of interest, their stress-strain relationship is nonlinear in nature [2] and is broken up into three distinct regimes: (1) low strain stage in which foam deforms in a linear elastic manner due to cell wall bending, (2) plateau of deformation at nearly constant stress caused by elastic buckling of cell walls, and (3) region of densification where the cell walls crush together, resulting in a rapid increase of compressive stress. These regimes and their effect on the response of the overall structure are studied here. This extended abstract is Part I of a three-part series which discusses the testing aspect of this work.

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3 APPROACHES

The test hardware utilized by both labs are nominally identical copies of a testbed comprised of a Top Cap, Center Mass, and Baseplate with compliant foam materials separating each, see Figure 1a. A Threaded Rod holds the assembly together and a Load Ring provides a method to measure and control the preload applied. The applied preload affects the localized stiffness of the compliant materials, leading to overall changes in the dynamic response of the component of interest: the Center Mass. LANL and SNL test set ups reflect their initial approach to the research of complex response of a component due to nonlinear materials. LANL is utilizing an explicit framework whereas SNL is utilizing a nonlinear normal modes (NNM) perspective. A side-by-side comparison of their respective test set ups are shown in Figure 1. LANL bolted the test article directly to the shaker table whereas SNL utilized a traditional modal test set up by suspending the hardware by bungee cords.

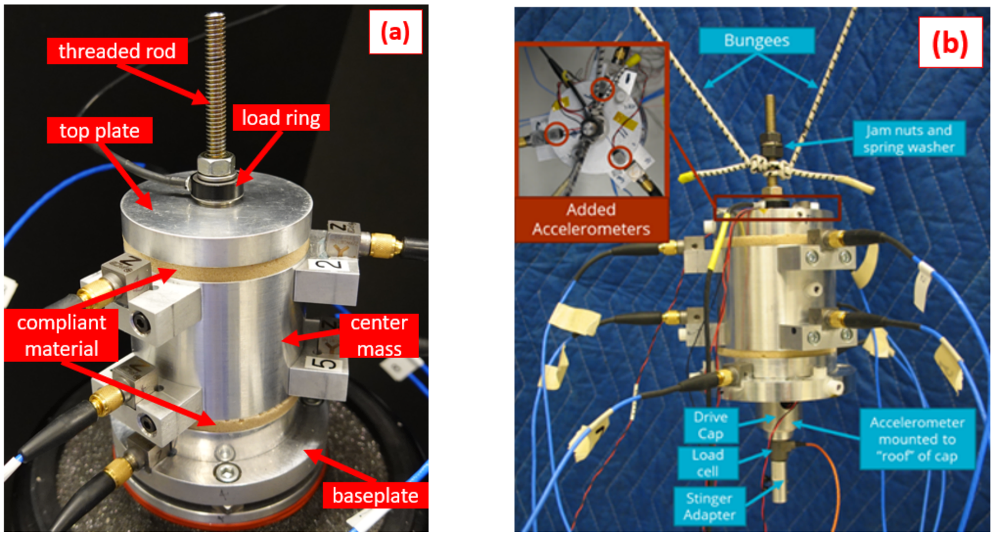


Figure 1. (a) LANL test set up, and (b) SNL test set up.

3.1 LANL Testing Approach

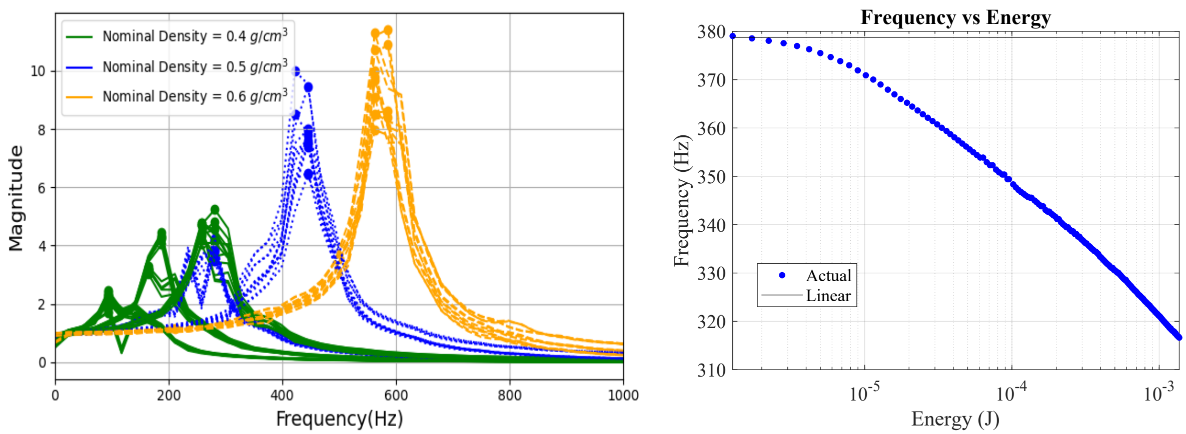
The LANL testbed setup consists of three main components: the controller, the signal amplifier, and a shaker. Eight triaxial accelerometers and a load cell are attached to the motion arm, see Figure 1a. Accelerometers 1, 2, and 3 live on the upper set of flanges, spaced 120 degrees apart. Accelerometers 4, 5, and 6 reside on the lower flanges, directly below the upper accelerometers. Finally, accelerometers 7 and 8 are on the baseplate. The purpose of these accelerometers is to record the motion of the shaker before it reaches the test article. The purpose of the load cell is to read the preload applied to the testbed. It is mounted below the top bolt, such that the user can manually tighten or loosen the bolt. Then, different kinds of signals, such as single-tone, swept frequency, and white noise can be sent through the hardware. Following the conducted experiment, the accelerometer, amplifier, and load cell data can be processed to generate the frequency response of the testbed.

3.2 SNL Testing Approach

SNL is utilizing an NNM framework for this work. The hardware was set up in a free-free configuration typical of modal tests, see Figure 1b. The hardware itself was a copy of the LANL structure, except for additional instrumentation on the Top Cap and Baseplate for increased modal observability as well as additional jam nuts and a spring washer on the Threaded Rod to keep the bungees in place. Low-level hammer impacts were first applied to the structure to identify its linear modes. Nonlinear force appropriation was then conducted using a modal shaker targeting the axial mode of the structure where the Baseplate and Top Cap translate in unison and out of phase with the Center Mass along the axis of the Threaded Rod. Nonlinear force appropriation is a testing technique used to characterize NNMs and utilizes closed loop control to maintain the structure at resonance, which is defined as when the excitation force and acceleration response have a relative phase of 90 degrees [3]. The measurements from the nonlinear force appropriation test were used to characterize the amplitude-dependent nature of the stiffness and damping of the material samples.

4 RESULTS AND DISCUSSION

This work is still in the preliminary phases and, given the different boundary conditions and test approaches taken by each lab, there are currently no common data sets to directly compare. However, LANL performed a study to evaluate the effects of the foam density, see Figure 2a. These results show the acceleration magnitudes for different foam samples of various thicknesses (1mm to 10 mm). In all cases, the same preload was applied to the testbed. It was found that increasing the density of the foam specimens led to an increase in the fundamental frequency. While this seems counterintuitive, higher density foams in this class have higher localized stiffnesses for the same strain state. Therefore, they cause the effective response of the testbed to become stiffer. Figure 2b shows the frequency energy plot from the SNL force appropriation test. The frequency changes approximately 16% from its linear value, demonstrating a strong nonlinear response. The damping (not shown for brevity) remained relatively constant within the response amplitudes achieved. The results from Figure 2 along with other measured data were then used to update the finite element model and uncertainty quantifications for each respective lab, as discussed in Parts II and III of this series. Additionally, in the live presentation, more experimental results will be presented that compare similar findings from each lab, such as the restoring force of each foam pad utilizing measured data and a simplified three-mass model of the test structure.



(a) (b)

Figure 2. Experimental results for the TRUST ND testbed (a) LANL foam density study and (b) frequency energy plot from SNL force appropriation test.

5 CONCLUSIONS

This extended abstract is Part I of a three-part series of collaborative efforts between LANL and SNL to characterize the dynamic response of a stiff component sandwiched between compliant materials with inherently nonlinear material properties. Thus far, the experimental efforts have focused on foam density and thickness, stepped-sine tests, white noise tests, and force appropriation tests using a NNM framework. The work is ongoing and will include further efforts in experiments, finite element modeling, and uncertainty quantification

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