Damage Identification in Fiber Metal Laminates with Guided Ultrasonic Wave using Bayesian Inference and Model Order Reduction

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Abstract

Structural health monitoring using guided ultrasonic wave (GUW) in fiber metal laminate (FML) seeks to precisely identify the damage with minimal use of sensors. In this research work, it is accomplished through Bayesian inference method that utilizes the sensor measured data and an accurate finite element model of GUW propagation in FML. The results are found to be promising when detecting and characterizing the damage.

Keywords: Guided ultrasonic wave, Fiber metal laminates, Model-order reduction, Bayesian inference

1 Introduction

Vibration-based structural health monitoring with guided ultrasonic waves (GUW) is one of the eminent techniques for damage identification in layered laminates, as their propagation behavior changes when interacting with a damage [1]. A Bayesian inference via Markov chain Monte Carlo (MCMC) method not only identifies the damage parameters from the measurements but also quantifies their uncertainties. However, the inference problem in a stochastic framework requires a very large number of forward simulations of the process which drastically rises the computational effort. Therefore, this research focuses on two key aspects: (a) generating a low-cost but accurate model through model-order reduction (MOR); (b) employing the produced global reduced-order model (ROM) with Bayesian inference to localize and characterize the damage.

2 Numerical Model of Lamb Wave Propagation

Numerical modeling and analysis of anti-symmetric lamb wave mode (A_0) propagation as well as its interaction with the defect in FML were studied using the FEM on COMSOL-Multiphysics® software. A 16-layered two dimensional carbon fiber reinforced plastic (CFRP)-steel laminate model was considered for further analysis. The excitation was realized by a five-cycle Hanning window with sinusoidal burst of 120 kHz central frequency, applied on the top and bottom left node of the model as shown in Figure 1. The damage was modeled as the loss of stiffness in a localized area within the steel lamina.

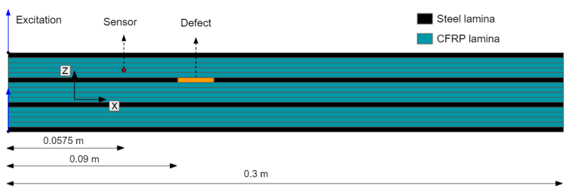

Figure 1: 2D-Model setup in COMSOL®

Although COMSOL implicit solver was used, time step and mesh sizes were calculated using a Courant–Friedrichs–Lewy condition. The finite element simulated GUW signal measured by the sensor embedded in the FML model is plotted in Figure 2. The simulation time for a solve using this high-fidelity (HiFi) numerical model was 66.29 s.

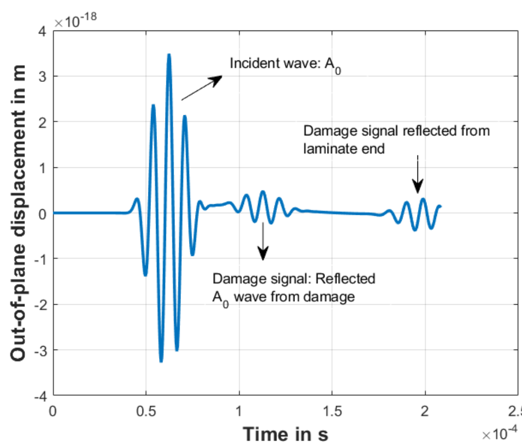

Figure 2: Displacement signal at sensor location

3 Parametric Model Order Reduction

In real-time operation, the construction of ROMs should be robust to parameter changes and needs to be fast such that the precomputed reduced model can be adapted to new sets of modeling parameters. In this research, parametric model-order reduction (PMOR) along with a surrogate model based on [2] was adapted to generate the global ROM. An adaptive POD-greedy algorithm was applied to train the ROM of GUW propagation in the FML. The training was carried out on a 3D parametric space, defined by Young's modulus, position on the x-axis and length of the damage. The comparison of the out-of-plane displacement of FML obtained by the HiFi model and reduced-order model is shown in Figure 3. A detailed methodology of its application on GUW propagation in FML can be found in [3].

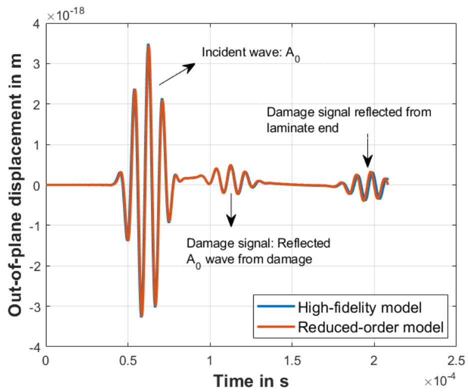

Figure 3: Comparison of HiFi and reduced-order solution

Using the adaptive POD-greedy approach, a speedup factor of 33.82 is achieved. This substantial decrease in the computational effort is very much appreciated in inverse problem analysis for the localization and characterization of the defect in the FML.

4 Damage Identification by Bayesian Inference

Bayesian inference for damage characterization was informed by the ROM instead of the high-fidelity model. A random walk procedure, MCMC method, was performed to draw the samples from the posterior distribution concerning the damage parameters: stiffness, x-position and length of the damage element in the FML. The synthetic measurement data is obtained by adding a zero mean Gaussian-type errors to the model output. Figure 4 and Figure 5 represents the histograms of the samples drawn to characterize the damage with parameters. It can be clearly seen that the true values of different parameters lie close to the bin corresponding to the maximum number of samples in the histogram.

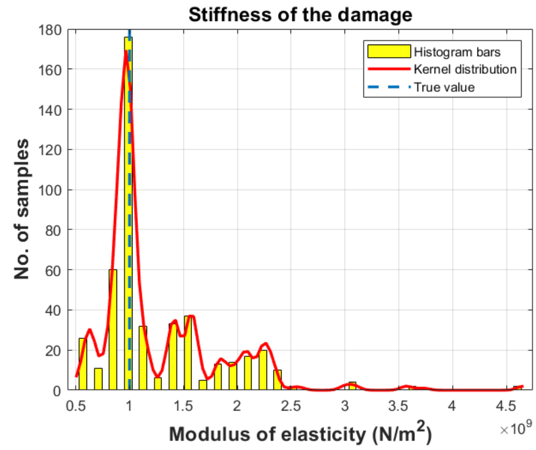

Figure 4: Histogram for stiffness of the damage

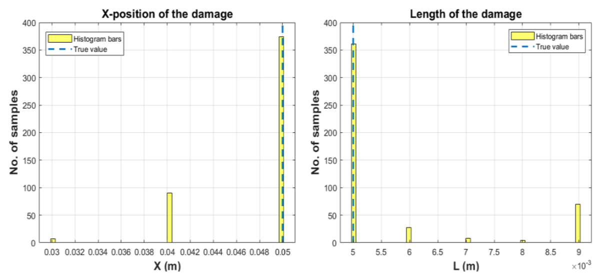

Figure 5: Histogram for the x-position and length of the damage

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