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Uncertainty quantification for acoustic nonlinearity parameter in Lamb wave-based prediction of barely visible impact damage in composites

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ABSTRACT

Nonlinear features extracted from Lamb wave signals (e.g., second harmonic generation) are demonstrably sensitive to microscopic damage, such as fatigue and material thermal degradation. While a majority of the existing studies in this context is focused on detecting undersized damage in metallic materials, the present study is aimed at expanding such a detection philosophy to the domain of composites, by linking the relative acoustic nonlinearity parameter (RANP) – a prominent nonlinear signal feature of Lamb waves – to barely visible impact damage (BVID) in composites. Nevertheless, considering immense uncertainties inevitably embedded in acquired signals (due to instrumentation, environment, operation, computation/estimation, etc.) which can adversely obfuscate nonlinear features, it is necessary to quantify the uncertainty of the RANP (i.e., its statistics) in order to enhance decision-making associated with its use as a detection feature. A probabilistic model is established to numerically evaluate the statistical distribution of the RANP. Using piezoelectric wafers, Lamb waves are acquired and processed to produce histograms of RANP estimates in both the healthy and damaged conditions of a CF/EP laminate, to which the model is compared, with good agreement observed between the model-predicted and experimentally-obtained statistic distributions of the RANP. With the model, BVID in the laminate is predicted. The model is further made use of to quantify the level of confidence in damage prediction results based on the concept of a *receiver operating characteristic*, enabling the practitioners to better understand the obtained results in the presence of uncertainties.

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1. Introduction

The use of composites has become ubiquitous in modern engineering applications, ranging from large-scale fuselage panels and wings of commercial airplanes to high-performing bicycle frames and car bogies. Although endowed with numerous merits like high strength-to-weight ratio, corrosion resistance, and design flexibility, composite materials may, under inappropriate use or in harsh environment, suffer various forms of damage that are invisible and difficult to identify,

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primarily due to the susceptibility of composite structures to foreign object impacts [1]. For instance, a low-velocity impact, such as tool dropping during manufacturing and servicing, may result in what is commonly referred to as *barely visible impact damage* (BVID). Typical BVID ranges from indentation and matrix micro-cracks to ply delamination and fiber breakage. On top of this, cyclic loads, both mechanically and thermally, throughout the service life of a composite structure, may also lead to matrix cracking and inter-laminar damage (e.g., delamination). All these have entailed early awareness of BVID in composites and timely remediation, to prevent further material deterioration and weaken the risk of consequent system failure. Effectual damage identification can be conducive to the reliability, integrity, and durability of composite structures.

Over the past few decades, a diversity of well-defined nondestructive evaluation (NDE) methods and later cutting-edge structural health monitoring (SHM) techniques have been developed, some of which are now on the verge of maturity and have been demonstrated to be capable of identifying damage in composites, including BVID, in a cost-effective manner. Of special interest are those methods taking advantage of guided ultrasonic waves (GUWs), with Lamb waves in particular [2–9]. Lamb waves feature the superior ability to interrogate a substantial area promptly with only a few transducers and low energy consumption, the capacity to omni-directionally access hidden components (via multi-path reflections), the prospect of being implemented in an in-situ manner to accommodate the purposes of SHM, and most importantly, the high sensitivity to various types of damage which features a characteristic dimension comparable to the wavelength of a probing GUW (i.e., “gross” damage, such as a notch or a through-hole). A majority of the existing efforts has been focused on exploring what are referred to as *linear wave features*, which derive from linear wave propagation, dispersion, and scattering through a linear elastic medium modified by gross damage [10,11]. As commented elsewhere [1,11], these classical linear feature-based GUW techniques may become deficient once used to evaluate small-scale damage in inhomogeneous materials whose characteristic dimension may be much smaller than the wavelength of a probing GUW, as typified by BVID in composites; this is often the case for composite materials.

In parallel to the mainstream of using linear GUWs for developing various damage detection and health monitoring approaches, there exists a batch of studies exploring nonlinear features concealed in GUWs (e.g., sub-harmonics or second harmonics), based on the recognition that nonlinear features of GUWs, compared with their linear counterparts, can possibly be more sensitive to undersized defects or certain defect types. Representatively, Aymerich and Staszewski [12] and Meo et al. [13], respectively, evaluated BVID in composites using a cross-modulation vibro-acoustic technique (VAT) and nonlinear elastic wave spectroscopy (NEWS)—a group of methods exploiting nonlinear features of GUWs in conjunction with vibration modulation. Ciampa et al. [1] employed the mechanism of second harmonic generation in GUWs to calibrate material and damage-induced nonlinearities in a composite laminate via finite element simulation and experiment validation. Pieczonka et al. [14] also used the second harmonic generation to examine the imaging quality of BVID and further compared the results against those from a local defect resonance (LDR) method. In another instance, Li et al. [15] explored second harmonics of Lamb waves for detecting fatigue damage in a composite panel introduced by a cyclic thermal load. In these studies, the feasibility and effectiveness of using nonlinear features of GUWs (second harmonics in particular) for damage evaluation in composites has been illustrated and validated.

Nonetheless, inherent to the use of any signal feature, whether it is linear or nonlinear, are uncertainties associated with acquired signals. The uncertainties may contaminate or even bias obtained results. Thus it becomes imperative to identify and quantify intrinsic uncertainties in measurement, experimental operation, ambient conditions, and/or computation, any of which may otherwise impair the user's ability in using the signal features properly within the context of interpretive decision-making [16]. In particular, the nonlinear contributions to the overall signal-to-noise ratio tend to be substantially lower (by orders of magnitude) than linear contributions, further complicating the extraction and identification process. Plus, in composites, the nonlinearities can be largely multifold: even in the material's healthy state, features like voids and imperfect bonding between plies may augment the uncertainty of the said nonlinear effects. Thus, to avoid excessive Type I (false alarms) or Type II (missed calls) errors in a detection process, an uncertainty quantification model, rooted in statistical hypothesis testing, is desired. Based on this quantification, appropriate statistical inference can be reached to evaluate the health condition of the structure under inspection.

Given this backdrop, the present study establishes a probabilistic model to quantify the uncertainties of estimates of nonlinearity extracted from Lamb wave signals and to verify the model in the context of predicting BVID in a composite laminate. A brief review of the second harmonics—one of the most representative nonlinear features of Lamb waves to be adopted in the present study—is provided in Section 2, based on which a relative acoustic nonlinearity parameter (RANP) is formulated. Section 3 derives and explores a probabilistic model for RANP estimates. Subsequently, in Section 4, experimental investigation is performed on a carbon fiber/epoxy (CF/EP) laminate plate. Miniaturized piezoelectric lead zirconate titanate (PZT) wafers are employed for actuation and acquisition of Lamb waves, which well suit the purpose of in-situ SHM. Continuous sine waves are generated by the PZT wafers as the input probing GUWs, and steady-state signals are acquired and processed for estimating RANP values before and after the introduction of BVID to the laminate by a drop-weight impact test. With the developed probabilistic model, histograms and predicted distributions of RANP before and after the impact test are compared. Taking a step further, a receiver operating characteristic (ROC) curve is computed using the modeled RANP distributions, as detailed in Section 5, which provides a quantified level of confidence in using RANP for predicting damage in the presence of uncertainty.

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