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A multilevel Bayesian method for ultrasound-based damage identification in composite laminates

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ABSTRACT

Estimating deterministic single-valued damage parameters when evaluating the actual health state of a material has a limited meaning if one considers not only the existence of measurement errors, but also that the model chosen to represent the damage behavior is just an idealization of reality. This paper proposes a multilevel Bayesian inverse problem framework to deal with these sources of uncertainty in the context of ultrasound-based damage identification. Although the methodology has a broad spectrum of applicability, here it is oriented to model-based damage assessment in layered composite materials using through-transmission ultrasonic measurements. The overall procedure is first validated on synthetically generated signals and then evaluated on real signals obtained from a post-impact fatigue damage experiment in a cross-ply carbon-epoxy laminate. The *evidence* of the hypothesized model of damage is revealed as a suitable measure of the overall ability of that candidate hypothesis to represent the actual damage state observed by the ultrasound, thus avoiding the extremes of over-fitting or under-fitting the ultrasonic signal.

1. Introduction

Composites are high-performance layered materials that are increasingly used as primary material for engineering structures and mechanisms in the aerospace, wind energy and naval industries, among others [1,2]. However, they are vulnerable to damage during operation, e.g., fatigue-induced damage or impact damage, that can be noticeable from the beginning of lifespan as an alteration of macro-scale mechanical properties like stiffness or strength [3,4]. Unlike metals, damage degradation in composites consists in a complex multi-scale process driven by internal fracture mechanisms distributed through the thickness, such as micro-cracks, delaminations, fibers breakage, etc. [5,3,4]. These damages are hardly ever detectable by visual inspection and typically require advanced nondestructive evaluation (NDE) techniques.

Ultrasound is currently one of the most frequently used NDE inspection techniques mainly due to its efficiency in obtaining indirect measurements of the actual mechanical properties of materials at relatively low cost. In ultrasound-based NDE, the received ultrasonic signal is evaluated and processed to retrieve quantitative information about the state of health of the inspected media. However, given the complexity of the internal structure of composite laminates (e.g., heterogeneity, multiple damage mechanisms, etc.), *ad hoc* signal processing techniques are usually required for a more in depth interpretation of the measured ultrasonic signal [6,7]. The noise arising from the imperfections of both the acquisition system and the propagation path, and the difficulties in understanding and analyzing multiple and overlapping ultrasonic echoes, suggest to directly compare the experimental signal response with theoretical signals obtained from a model of ultrasound wave propagation (UWP), with the purpose of inferring

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quantitative information about the effective mechanical properties of the material. A suitable approach for such comparison is given by the model-based *inverse problem* (IP), in either its deterministic version [8,9] or alternatively in its Bayesian (probabilistic) version [10–12]. The deterministic approach has been previously applied in the context of ultrasound-based damage identification in composites [7,13], although it suffers from a strong practical limitation since it requires the adoption of an *a priori* hypothesis about the through-the-thickness distribution of the damaged layers. However, when dealing with composite materials under fatigue or impact degradation, not only one single hypothesis about damage distribution but numerous candidate hypotheses can be considered, even under nominally identical material and testing conditions [14,15]. Moreover, reconstructing the damage state of a material using a deterministic IP approach neglects not only the uncertainty arising from measurement errors, but also the uncertainty related to the modeler's choice of a particular hypothesis of damage to solve the inverse problem [11,16]. In this context, it seems reasonable to explore the applicability of a probabilistic IP to ultrasound-based damage identification in composite materials, precisely where the benefits of the Bayesian approach can be fully exploited to deal with the aforementioned sources of uncertainty.

There are few papers in the literature dealing with some form of damage identification in composite laminates using Bayesian IP approaches. Gros [17] used several NDE methods (no ultrasound) to detect and size delamination in composites. A Bayesian framework was adopted to fuse various sources of experimental data and assess the probability of a defect to be detected at a particular location. Peng et al. [18] developed a Bayesian imaging method to detect and size delamination damage in composites using Lamb waves. Recently, some authors have made use of recursive Bayesian updating techniques for *on-line* damage identification in the context of fatigue life prediction in composite materials [19–21]. Other researchers have adopted Bayesian IP approaches for ultrasound-based feature identification in biomaterials and soft tissue [22,23]. However, to the authors' best knowledge, the use of a full Bayesian inverse problem for damage assessment based on ultrasound in composite materials is still missing in the open literature.

In this paper, a multilevel Bayesian framework is proposed for identifying the through-the-thickness position and the effective mechanical properties of the damaged layers in composite laminates using ultrasound. As a key contribution, the proposed methodology does not require any predefined hypothesis on the damage distribution for solving the IP. Instead, several candidate damage hypotheses or *model classes* [11] are formally tested and ranked through relative probabilities within a Bayesian model selection framework. The chosen UWP model is based on a digital representation of the laminate recently developed by Bochud et al. [13], which is particularly suitable for the proposed Bayesian methodology due to its high efficiency and low computational complexity. In this context, Bayes’ Theorem is applied at three hierarchical levels: first, to deal with the posterior information about the model parameters for a specific *damage hypothesis*; second, to assess the relative plausibility of each damage hypothesis within a set of candidate hypotheses defining a particular *damage pattern*, and third, to obtain the degree of plausibility of a given pattern of damage among a set of candidates. In this work, the concept of damage hypothesis is physically associated with the type of damage and its through-the-thickness distribution within the laminate, whereas damage pattern is defined as a set of damage hypotheses that share the same amount of damaged layers, regardless of their position. An algorithm is proposed to efficiently explore the set of possible damage hypotheses, thus avoiding an exhaustive search across an intractable number of combinations of model parameters and making the identification problem computationally feasible. In this sense, it constitutes a major contribution of this research.

To serve as a validation, the proposed Bayesian framework is initially applied to a set of synthetic signals with increasing levels of noise and complexity, which are intended to serve as *ground-truth* data. Additionally, a case study is presented using ultrasonic signals obtained from a post-impact fatigue damage experiment in a cross-ply carbon fiber-reinforced polymer (CFRP) laminate. Results show that the proposed methodology is able to detect and locate the damaged layers and estimate their effective mechanical properties through probabilities that measure and rank the extent of agreement between the measured ultrasonic signal and the modeled signal. It is also shown that more complex damage hypotheses (i.e., model parameterizations that involve more updatable model parameters) do not necessarily yield higher probabilities in explaining the observed ultrasonic signature even for severe damage scenarios. The last is an instance of the Principle of Model Parsimony or *Ockham's razor* [24,25] which is shown to appear in a natural and principled way from the computation of the *evidence* of each damage hypothesis [26,11]. Thus, it is a key aspect in favour of the proposed Bayesian approach over commonly used methods for hypotheses assessment like the Maximum Likelihood Estimation (MLE), or the *information criteria* like the Akaike's Information Criterion (AIC) [27] and the Bayesian Information Criterion (BIC) [28,29]. The MLE approach is purely based on the goodness of the data-fit of the hypothesized model, thus favouring unnecessary complex damage hypotheses [11] (i.e., those that lead to only slightly better agreement with the data). The AIC and BIC criteria were proposed to attempt to correct for the bias of MLE by the addition of a penalty term to compensate for the over-fitting of more complex models. However, despite their simplicity, they may give biased identifications favouring excessively simple hypotheses [26,11]. In this context, the *evidence* of each damage hypothesis is revealed as a suitable measure of the overall ability of the candidate damage hypothesis to represent the actual damage state observed by the ultrasound, since it explicitly builds in a trade-off between the goodness of fit of the hypothesized model and its information-theoretic complexity, thus avoiding the extremes of over-fitting or under-fitting the ultrasonic signal.

The paper is organized as follows. Section 2 presents the formulation adopted for modeling ultrasound waves in layered media. Key mathematical definitions for damage hypothesis and damage pattern are also introduced in this section. In Section 3, the proposed Bayesian framework for damage identification is presented. This section also provides a pseudocode implementation of the proposed search algorithm. Section 4 illustrates the proposed methodology using both, a set of synthetically generated signals and experimental ultrasonic signals. Section 5 discusses the results, and finally Section 6 provides concluding remarks.