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A probabilistic crack size quantification method using in-situ Lamb wave test and Bayesian updating

Jinsong Yang [a], Jingjing He [a,*], Xuefei Guan [b], Dengjiang Wang [a], Huipeng Chen [a], Weifang Zhang [a], Yongming Liu [c]

[a] School of Reliability and System Engineering, Beihang University, Weimin Building, No. 37, Xueyuan Road, Haidian District, Beijing, China
[b] Siemens Corporation, Corporate Technology, 755 College Rd.E., Princeton, NJ 08540, USA
[c] School for Engineering of Matter, Transport and Energy, Arizona State University, Tempe, AZ 85287-9309, USA

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ABSTRACT

This paper presents a new crack size quantification method based on in-situ Lamb wave testing and Bayesian method. The proposed method uses coupon test to develop a baseline quantification model between the crack size and damage sensitive features. In-situ Lamb wave testing data on actual structures are used to update the baseline model parameters using Bayesian method to achieve more accurate crack size predictions. To demonstrate the proposed method, Lamb wave testing on simple plates with artificial cracks of different sizes is performed using surface-bonded piezoelectric wafers, and the data are used to obtain the baseline model. Two damage sensitive features, namely, the phase change and normalized amplitude are identified using signal processing techniques and used in the model. To validate the effectiveness of the method, the damage data from an in-situ fatigue testing on a realistic lap-joint component are used to update the baseline model using Bayesian method.

1. Introduction

Guided ultrasonic waves have shown great potential in non-destructive evaluations (NDE) and structural health monitoring (SHM) systems. Lamb waves are among the most important guided waves and are a form of elastic perturbation, guided between the parallel free surfaces [1–3]. It has two modes: the symmetric mode and the anti-symmetric mode. With features including strong penetration, minimal attenuation over a long distance, omnidirectional dissemination and high sensitivity to discontinuities (cracks, delamination, corrosive degradation, etc.) in their propagation paths, Lamb waves have been intensively investigated for damage identification in both composite and metallic materials [4–7]. The underlying mechanism for Lamb wave detection is to monitor the changes of the characteristics of the transmitted/deflected waves. The changes of the characteristic are due to the discontinuities introduced by cracks or flaws in the path of the wave propagation. The discontinuities can disperse and reflect energy of the original Lamb wave and cause changes in wave characteristics. The changes, in principle, can be detected and used to locate the damage and quantify the damage size [8–10]. The velocity of Lamb wave is a function of the product of the frequency and thickness of the material, called dispersive nature of Lamb waves [11,12]. Furthermore, the mode conversion occurs when Lamb waves interact with damage or boundary. These properties are undesirable in SHM applications because of the modes

* Corresponding author. Tel.: +86 10 82314879.
E-mail address: hejingjing@buaa.edu.cn (J. He).

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overlap and amplitude decrease which make it difficult to extract features associated with cracks. In addition, these properties make it a challenge to quantify the crack size directly using characters that have physical meaning (amplitude, phase change, energy, etc.) due to that the transmission mechanism for Lamb wave remains obscure. For damage evaluation, most studies adopted damage indexes to quantify the crack size [13–16]. Damage indexes can be extracted from Lamb wave signals in the time domain, frequency domain and time–frequency domain by different signal processing method. Ihn proposed a damage index defined as the ratio of the monitoring signal energy to the baseline signal energy [14]. The energy can be obtained by the time integration of the power scatter spectral density. In Michaels' study, a damage index called time domain difference scaled the Lamb wave signal to unity energy to evaluate the amplitude difference between the damage signal and the baseline signal [16]. This study proposes a quantification model to correlate damage features with clear physical meaning (phase change and normalized amplitude) to the actual crack size instead of damage index.

The damage identification using Lamb wave method originally proposed by Chang et al. [17,18]. They used built-in piezoelectric materials as actuators to generate Lamb waves as well as sensors to receive signal. Various cracks diagnostic technologies based on this method have been demonstrated to be effective in detecting cracks in metallic structures. Lu et al. [13,19] numerically and experimentally investigated the forward- and back-scattering of Lamb waves by through-thickness cracks of varying length and orientation. Crack orientation was quantitatively determined by evaluating amplitudes of energy peaks in the Hilbert spectra. Victor Giurgiutiu et al. [20,21] proposed an embedded ultrasonic structural radar algorithm for Lamb wave damage detection in thin-wall structures by using piezoelectric wafer active sensors (PWAS) phased arrays. Wang [22] developed a synthetic time-reversal method for a distributed sensor network to investigate the inhomogeneity caused by a bonded mass on an aluminum plate. Paul Fromme [23] monitored cracks at rivet holes by finite difference methods. They model the amplitude change of the A_0 mode of Lamb wave scattered around the hole. Emmanuel Le Clézio [24] discussed the propagation of the S_0 mode and its interaction with different crack thickness in an aluminum plate. Ihn and Chang [25] monitored the hidden fatigue crack growth using a damage index (DI) defined as the ratio of the scatter energy contained to the baseline energy in the S_0 mode wave packet with a built-in piezoelectric sensor/actuator network. Chao Zhou [26] developed a retrofitted probability-based diagnostic imaging approach in conjunction with an active sensor network in a pulse-echo configuration.

Despite a number of approaches have been proposed to perform the damage detection using Lamb wave method, there are still some challenges remaining for engineering applications [27–29]. Reliable acquisition and interpretation of Lamb wave signal is not a trivial task. The difficulty in the signal acquisition and analysis lies in several aspects: (1) Different structure geometries and working conditions require different Lamb wave sensor configurations, (2) the physical model which describes the relationship between damage sensitive features and the crack size is varied with structure geometries and working conditions. Therefore, the Lamb wave crack detection experiment is required in order to establish the crack size quantification model, which is extremely difficult for real engineering application, (3) noise and irrelevant signals can introduce difficulties in damage sensitive feature extraction, (4) data interpretation of the Lamb wave signal and crack size quantification model requires highly specialized knowledge [30–32]. Most of researches reported in existing literatures are mainly focus on specific target systems such as plate and beam structures, with a hole or a cut to represent the damage [33–36]. It is therefore for significant interest to develop an overall methodology for reliable, efficient and accurate crack quantification for different structures using only coupon tests. This paper presents a general procedure for a probabilistic crack size quantification method using in-situ Lamb wave testing and Bayesian updating.

The coupon test results are employed to establish the baseline crack quantification model. In order to make the baseline model also suitable for realistic engineering application, the Bayesian method is employed to update baseline model parameters. To demonstrate the proposed method, Lamb wave testing on simple plates with artificial cracks of different sizes is performed to obtain the baseline model. The damage detection data from an in-situ fatigue testing on a realistic lap-joint component is used as a validation to verify the effectiveness of the proposed method.

This paper is organized as follows. First, the framework of the proposed probabilistic crack size quantification method is introduced. Next, a brief introduction of the coupon test for Lamb wave crack detection in laboratory is given. Two damage sensitive features, namely, the phase change and normalized amplitude are extracted from raw data using signal processing techniques. A multivariate regression model is proposed to correlate damage features to the actual crack size. Following this, experimental testing data from the coupon test are used to establish the crack quantification model and construct the prior distribution of model parameters. In-situ Lamb wave data from the fatigue testing on a realistic lap-joint component are used to update the baseline model parameters using Bayesian method. Finally, some conclusions are drawn based on current study.

2. Methodology development

The objective of this study is to develop an overall methodology for reliable, efficient and accurate crack quantification for different structures using only Lamb wave coupon test data. The proposed probabilistic crack size quantification framework is shown in Fig. 1. Lamb wave crack identification experiments for coupon test are used to capture the underlying mechanism for Lamb wave damage detection and acquire the baseline model for crack quantification. In this study, Lamb wave detection on simple plates with artificial cracks of different sizes is used as coupon test for demonstration purpose. Surface-bonded piezoelectric wafers are used as actuators to generate Lamb waves as well as sensors to receive Lamb signal. The pitch-catch method is used for Lamb wave damage detection. A pulse signal is sent across the specimen to interrogate the integrity of the specimen. At the same time, a sensor is placed at the other end of the specimen to receive the signal. Several signal processing techniques are employed to extract damage sensitive features from received Lamb wave signal. A correlation model between the crack size and damage