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Data-driven fatigue crack quantification and prognosis using nonlinear ultrasonic modulation

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ABSTRACT

In this study, an online monitoring technique for continuous fatigue crack quantification and remaining fatigue life estimation is developed for plate-like structures using nonlinear ultrasonic modulation and an artificial neural network (ANN). First, multiple aluminum plates of different thicknesses are subjected to cyclic loading tests at a constant amplitude, and the ultrasonic responses are obtained from the piezoelectric transducers attached to each specimen. Second, an ANN is constructed by defining (1) the specimen thickness; the elapsed fatigue cycles; and two features extracted from the ultrasonic responses, namely, the cumulative increase and decrease in the nonlinear beta parameter, as inputs and (2) the crack length and remaining fatigue life as outputs. Then, the architecture and learning parameter of the ANN are optimized using the data obtained from the specimen tests. Finally, the performance of the trained ANN is examined using the blind test data obtained from additional specimens. The results of the blind tests indicate that the proposed technique can estimate the crack length and remaining fatigue life with a maximum error of 2 mm and 3 k cycles, respectively, for the tested aluminum plates. The uniqueness of this technique lies in (1) the fatigue crack quantification and remaining fatigue life estimation using nonlinear ultrasonic modulation and (2) the data-driven crack quantification and prognosis using an ANN for online monitoring.

1. Introduction

Fatigue crack, which initiates from a damaged precursor at an unperceivable level under repeated loading, is one of the primary reasons for the failure of metallic structures. It is reported that up to 90% failures of in-service metallic structures are a result of fatigue cracks [1]. Therefore, detecting a fatigue crack in early stage is an important issue for ensuring the safety and integrity of structures, and there are various ongoing structural health monitoring (SHM) and nondestructive testing (NDT) research activities evolving in regard to this topic [2–5]. However, because the formation of an initial fatigue crack does not necessarily lead to an immediate failure of a structure, it also becomes important to continuously monitor the growth of the crack length (quantification) and estimate the remaining fatigue life (prognosis).

Numerous monitoring techniques have been proposed for crack quantification. Acoustic emission (AE) technique is widely used for continuous fatigue crack monitoring [6]. AE-based fatigue crack length estimation techniques are developed based on counting the number of AE signals induced by the crack propagation [7,8]. The scattering and attenuation of linear

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ultrasonic at the fatigue crack is applied to crack quantification [9–11]. A technique for monitoring the fatigue crack length and depth inside the surface of a pressurized pipe is proposed [12,13]. The elastic strain at the outside surface is modified due to the crack growth, and it is monitored using multiple strain gauges.

In general, fatigue crack prognosis can be performed based on Paris' law [14]. The parameters of Paris' law can be obtained experimentally by measuring the fatigue crack length and applied loading cycles [15–17]. Numerically, the remaining fatigue life of a fatigue crack in a simple plate structure is probabilistically estimated by the Bayesian interface [18,19]. A fatigue crack prognosis technique using a linear ultrasonic technique is proposed and experimentally validated for aluminum plate specimens [20]. Combining with a particle filter, the damage index obtained from the linear ultrasonic response is used to evaluate the statistical distribution of the crack length under uncertainties and update the prognosis results.

Among various damage quantification and prognosis approaches, data-driven approaches are gaining prominence because of the recent advances in computing and breakthroughs in artificial intelligence [21,22]. Examples of data-driven approaches include artificial neural network (ANN) [23,24], fuzzy logic [25–27], Gaussian process (GP) [28,29], support vector machine [30,31], and hidden Markov model [32,33]. As a representative research for fatigue crack prognosis, Li et al. [26] developed a fuzzy logic-based fatigue prognosis technique using the crack length and elapsed fatigue cycles. In addition, a GP-based fatigue crack quantification and prognosis technique is proposed for an aluminum compact tension fatigue specimen using the elapsed fatigue cycles, maximum and minimum loadings, and load ratio [29].

One of key issues of data-driven approaches is to determine the property to be measured. Ultrasonic measurements have tremendous potential for online fatigue crack quantification and prognosis because the (1) transducers used for ultrasonic wave generation and sensing are inexpensive and can be easily installed on a target structure for online monitoring [34,35], (2) ultrasonic waves can travel a long distance and have a wide sensing range (1–2 m for metals) [35,36], and (3) nonlinear characteristics of ultrasonic waves are highly sensitive to the initial micro cracks in the range of sub-millimeters length and width [37,38].

For example, the relationship between the nonlinear ultrasonic harmonic and modulation components and fatigue crack length is examined using the Nazarov–Sutin crack model [39], whereas a fatigue crack prognosis technique is proposed by combining Paris' law [40,41]. The relationship between the modification of the nonlinear modulation components and crack length is investigated by Li et al. [42]. A strong correlation between the modulation components and crack length is observed when the crack length is less than 5 mm. However, no specific pattern is observed once the crack becomes larger than 5 mm. An imaging technique for fatigue crack growth monitoring is developed using nonlinear ultrasonic waves [43]. A feature named nonlinear metric is defined considering the energy shift of the fundamental waves to nonlinear components, and it is assumed that the maximum value is observed at the crack tip. Subsequently, the propagation of the crack is traced by following the position of the crack tip, and the crack growth is visualized using a phase array. It is reported that the nonlinearity increases until approximately 70% of the fatigue life is reached.

This study proposes a data-driven online monitoring technique for the fatigue crack quantification and prognosis for plate-like structures using nonlinear ultrasonic modulation and ANN. First, cyclic loadings with a constant amplitude are applied to multiple aluminum plates of different thicknesses, and the ultrasonic responses are obtained from the piezoelectric transducers (PZTs) attached to each specimen. Next, an ANN is established, and the specimen thickness, elapsed fatigue cycles, and cumulative increase and decrease in the nonlinear β parameter extracted from the ultrasonic responses are used as inputs, whereas the crack length and remaining fatigue life are used as outputs. Subsequently, the architecture and learning parameter of the ANN are optimized using the data from the previous specimen tests. Finally, for the validation of the trained ANN, blind tests are performed using the data obtained from additional specimens. The uniqueness of this technique lies in the (1) quantification and prognosis of the fatigue using nonlinear ultrasonic modulation and (2) data-driven crack quantification and prognosis using an ANN for online monitoring.

This paper is organized as follows. In Section 2, the proposed fatigue crack quantification and prognosis technique are presented, including a brief introduction to the nonlinear ultrasonic modulation and ANNs. In Section 3, the application of the proposed technique for the crack quantification and prognosis in aluminum plate specimens is described. Finally, the conclusion and discussions are provided in Section 4.

2. Data-driven fatigue crack quantification and prognosis

2.1. Overview

Fig. 1 presents an overview of the proposed data-driven fatigue crack quantification and prognosis technique. First, fatigue tests with a constant-amplitude cyclic loading are performed for multiple aluminum plate specimens of different thicknesses. Here, the ultrasonic response is obtained using the three PZTs attached to each specimen, as shown in Fig. 2. Two excitation PZTs are used for applying two high-frequency (HF) and low-frequency (LF) signals at distinct frequencies ω_a and ω_b ($\omega_a < \omega_b$), respectively, to the specimen. The ultrasonic response is obtained using the sensing PZT. When the HF and LF signals are applied to a structure with a fatigue crack, additional frequency components (harmonics at n times the input frequency and modulation at the sum of and difference between the input frequencies) are generated owing to the opening and closing of the crack surface. In this study, the first modulation components at $\omega_b \pm \omega_a$ are used for the fatigue