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Damage detection on an aluminum plate from the cross-correlation of diffuse field using the support vector machine

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ABSTRACT

In order to assess the damage detectability of the structural health monitoring method using diffuse fields, a laboratory experiment is conducted on an aluminum plate where two accelerometers are mounted as receivers. Two types of damages, a nonlinear material attachment and a punctuated hole, are considered. A hand-held impact hammer is used for the excitation, whereby the hammer is moved over grid points drawn on the aluminum plate, and thus the diffuse fields are generated by superposing the wave fields by many excitations randomly sampled. From the cross-correlation of diffuse fields between two receivers, we extract the coherent wave field in cases with and without damages. To detect the damage, a novel damage detection algorithm using a support vector machine is suggested based on the reduced features, transformed from several statistical parameters of damaged and undamaged noise cross-correlation functions, aided by the principal component analysis. The performance of the proposed algorithm is analyzed for the number of sources and damage types.

1. Introduction

Structural health monitoring (SHM) is imperative for safe operation of large structures such as ships, offshore structures, and bridges. Traditionally, the SHM is classified into two groups: active and passive method. The active SHM method detects damages using signals generated by active sources and the passive method only uses ambient signals received by passive sensors to find damages (Davis and Brockhurst, 2015; Farrar and Worden, 2007; Jamalkia et al., 2016; Liu et al., 2017; Yi, 2016).

Recently, a series of studies on ambient noise interferometry have demonstrated that the time-domain Green's function (TDGF) between two receiving points can be reconstructed from the ensemble average of the cross-correlation of ambient diffuse fields (Lobkis and Weaver, 2001; Roux and Kuperman, 2004; Sabra et al., 2005; Snieder, 2002; Wapenaar, 2004; Weaver and Lobkis, 2004). These interesting studies have two implications for the application to the SHM in the plate structure. First, active sensors are not needed for SHM and a pair of passive sensors is sufficient for the recovery of TDGF if the inspected plate creates sufficient diffuse field. Second, in the ambient noise interferometry, the plate structure causing multiple reflections is no longer a hindrance to the SHM since the complexity of the structure rather promotes the diffuseness and randomness of the wave field.

Applications of the ambient noise interferometry to the SHM of the plate structure were first investigated by Sabra et al. (2007). They performed an experiment for a flat plate and a hydrofoil in a cavitation tunnel and reconstructed the TDGF from ambient vibrations induced by turbulent flows. Successively, Sabra et al. (2008) extracted the TDGF in an aluminum plate from the diffuse field generated by random excitations of a Garnet pulsed laser and observed the change of TDGF with and without a hole damage. Duroux et al. (2010) performed similar experimental work on an aluminum plate with two piezoelectric actuators and a scanning laser Doppler vibrometer. They synthesized the diffuse field with multiple measurements based on the source-receiver reciprocity and conducted several theoretical and experimental analyses. Recently, experimental studies were investigated to detect a nonlinear material attachment on the plate (Tippmann et al., 2014; Tippmann and Lanza di Scalea, 2015). The diffuse field needed to obtain the TDGF is artificially made from multiple excitations by the shaker over 576 grid points on the plate. They defined several damage indices (DIs), describing the similarity of forward and backward TDGF, that are expected to be sensitive to the damage with nonlinear behavior (Sohn et al., 2004; Tippmann and Lanza di Scalea, 2015). These DIs were used for the K nearest neighbor (KNN) algorithm with the principal component analysis (PCA) to detect the damage, and showed good damage detectability.

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In this paper, we perform an experimental study on the passive SHM from a diffuse field on an aluminum plate and propose a novel damage detection algorithm using statistical parameters of damaged and undamaged noise cross-correlation functions (NCFs). The experimental procedure of Tippmann and Lanza di Scalea (2015) is adopted in this paper. However, the approach in this paper differs from that by Tippmann and Lanza di Scalea (2015) in a number of ways as follows. (1) Instead of the random noise shaker, a hand-held impact hammer is used as the source. Actually, our source generation technique is closer to the active source interferometry than the ambient noise interferometry. In practice, while the use of natural random noise may be more cost-effective, it renders the stable control of the SHM difficult. The active source interferometry can be suitable for marine system or offshore system, which is usually exposed to wave impact loading (e.g., slamming). In this paper, the effects of number of the active sources on the damage detection are studied. (2) In addition to nonlinear material attachment considered in Tippmann and Lanza di Scalea (2015), a punctuated hole damage is used. (3) New feature vectors characterizing the elastic behavior of the plate are presented based on the statistics of the damaged and undamaged data of the NCF. These feature vectors differ from current feature vectors using the reciprocity of TDGF, and are applicable to all types of damages. The PCA is used to reduce the dimension of the feature vectors and the support vector machine (SVM) is then applied for damage detection.

This paper is organized as follows: Section 2 summarizes the theoretical background of the extraction of the coherent fields from the cross-correlation of the diffuse field. In addition, a few statistical parameters using the NCF are given for damage detection. Section 3 describes the laboratory experiment for the active source interferometry in two cases of nonlinear attachment and hole damage and measurement data. The damage detection using the SVM with the PCA is given in Section 4. Section 5 is a summary and conclusions.

2. Theoretical background

2.1. Extraction of coherent fields from the diffuse field generated by a number of sources

As shown in Fig. 1, consider the elastic field generated by a source arbitrarily located over the structure at N points. The cross-correlation of the signals received at two receivers is defined as (Duroux et al., 2010)

$$C_{12,i}(t) = \int_0^T s_{1,i}(\tau) s_{2,i}(t+\tau) d\tau, \tag{1}$$

where $s_{m,i}(t)$ is the signal acquired at sensor m (m = 1, 2) from a source located on the ith position of the structure in time $[0, T]$ (Bendat and Piersol, 2011). The averaged NCF for the N excitations is expressed as (Duroux et al., 2010)

$$< C_{12}(t) >_N = \frac{1}{N} \sum_{i=1}^{N} C_{12,i}(t), \tag{2}$$

where the operator $< \cdots >_N$ refers to the ensemble averaging of N cross-correlation functions. It has been demonstrated that, when the N sources are uniformly distributed in space and time and the resultant field is fully diffused, the TDGF is reconstructed from the time derivative of Eq. (2). However, the real environment is not ideal, since many of the noise sources have a band-limited spectrum and their distribution is not always uniform in space and time. The loss is always present in the structure and the receivers have their own transducer response characteristics. Considering such factors, the averaged NCF can be theoretically stated as (Roux et al., 2005)

$$< C_{12}(t) >_N \approx Q(t) * [G_{12}(t) - G_{21}(-t)], \tag{3}$$

where $G_{12}(t)$ is the TDGF from sensor 1 to sensor 2 in the positive time domain, while $G_{21}(-t)$ is the TDGF from sensor 2 to sensor 1 in the negative time domain, and * refers to the convolution operator. Here, $Q(t)$ is a function that considers the integrated effect of the source spectrum, the source distribution, the transducer characteristics, and the property of the medium, yet is independent of the positions of each N source excitations.

In this paper, rather than its time derivative, the averaged NCF of Eq. (3) is used for damage detection. This is because a non-ideal environment is created by finite number of sources having not perfectly uniform distribution to simulate a realistic structure (Chehami et al., 2014).

In practice, the averaged NCF is not a deterministic function. When the diffuse field is not fully generated due to an insufficient number of sources, the averaged NCF shows random fluctuations from the mean field. These fluctuations act as noise, interfering with the damage detection from the cross-correlation of the diffuse field. To compare the two extracted signals as a function of the number of sources, a metric defined as the cross-correlation coefficient at zero delay is given by (Tippmann and Lanza di Scalea, 2015)

$$Corr(0) = \frac{\int_{-\infty}^{\infty} < C_{12}(t) >_{N_1} < C_{12}(t) >_{N_2} dt}{\sqrt{\left| \int_{-\infty}^{\infty} < C_{12}(t) >_{N_1}^2 dt \right| \left| \int_{-\infty}^{\infty} < C_{12}(t) >_{N_2}^2 dt \right|}}, \tag{4}$$

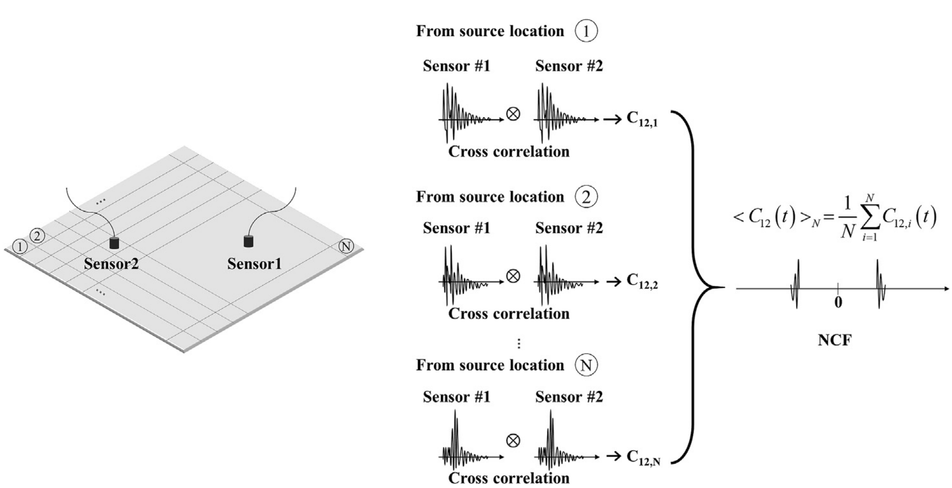

Fig. 1. Extraction of the noise cross-correlation function (NCF) from ambient vibrations. Separate N noise sources are used, denoted as circled text 1, 2, … N to produce the diffuse field.