Mechanical Systems and Signal Processing 54-55 (2015) 336–356

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Time–frequency beamforming for nondestructive evaluations of plate using ultrasonic Lamb wave

Je-Heon Han, Yong-Joe Kim *

Acoustics and Signal Processing Laboratory, Department of Mechanical Engineering, Texas A&M University, 3123 TAMU, College Station, TX 77843-3123, USA

A R T I C L E I N F O

Article history:
Received 10 October 2012
Received in revised form
1 August 2014
Accepted 16 September 2014
Available online 14 October 2014

Keywords:
Nondestructive evaluation
Time–frequency MUltiple SIgnal Classification (MUSIC) beamforming
Ultrasonic Lamb wave
Single Lamb wave mode excitation

A B S T R A C T

The objective of this study is to detect structural defect locations in a plate by exciting the plate with a specific ultrasonic Lamb wave and recording reflective wave signals using a piezoelectric transducer array. For the purpose of eliminating the effects of the direct excitation signals as well as the boundary-reflected wave signals, it is proposed to improve a conventional MUSIC beamforming procedure by processing the measured signals in the time–frequency domain. In addition, a normalized, damped, cylindrical 2-D steering vector is proposed to increase the spatial resolution of time–frequency MUSIC power results. A cross-shaped array is selected to further improve the spatial resolution and to avoid mirrored virtual image effects. Here, it is experimentally demonstrated that the proposed time–frequency MUSIC beamforming procedure can be used to identify structural defect locations on an aluminum plate by distinguishing the defect-induced waves from the excitation-generated and boundary-reflected waves.

1. Introduction

Guided ultrasonic waves such as Lamb waves in shell structures can propagate long distances with small spatial dissipation rates so that they have gained significant interest for many Non-Destructive Evaluation (NDE) applications [1]. In these NDE applications, a guided wave can be generated by using a Piezoelectric Wafer Active Sensor (PWAS) [2,3] and then propagates in a shell system. When there is a structural defect in the system, the wave is then reflected from the defect. By measuring the reflective wave, the structural defect location can be identified. The latter procedure can be implemented to scan a large structural area with a relatively small number of transducers due to the long propagation distance of the guided wave.

The guided Lamb wave generation characteristics of piezoelectric actuators were studied by Crawley et al. [4,5] and Giurgiutiu [2]. Giurgiutiu et al. [2,3] suggested a mode tuning technique to dominantly excite a single mode Lamb wave by selecting an appropriate excitation frequency for the given dimensions and material properties of a piezoelectric actuator and a shell structure.

NDE algorithms for processing measured guided wave signals are listed in Refs. [1,6]. A pulse-echo method using a PWAS array referred to as the embedded ultrasonic structural radar was used for detecting cracks on a panel [7].

* Corresponding author. Tel.: +1 979 845 9779; fax: +1 979 845 3081.
E-mail addresses: jeep2000@tamu.edu (J.-H. Han), joekim@tamu.edu (Y.-J. Kim).

http://dx.doi.org/10.1016/j.ymssp.2014.09.008
0888-3270/

Wang et al. improved the conventional pulse-echo and pitch-catch method by applying a time reversal process to suppress boundary effects and thus increase the signal to noise ratio (SNR) [8] although this method required undamaged baseline data [9]. In Ref. [10], Ikegami et al. introduced an aircraft health monitoring system by using embedded-piezoelectric transducers and continuously comparing measured data with undamaged data. Sohn et al. suggested a damage diagnostic procedure that does not require undamaged data by combining a consecutive outlier analysis and a time reversal procedure [11]. Giurgiutiu et al. [12] and Yan et al. [13] found structural defect locations in aluminum and composite plates from two-dimensional (2-D) beamforming power images constructed by using a Delay-And-Sum (DAS) beamforming algorithm. In addition, Choi and Kim modified a Multiple Signal Classification (MUSIC) beamforming algorithm to consider spherical wave fronts in estimating the locations and relative strengths of noise sources [14]. Li et al. applied a MUSIC beamforming algorithm to identify air-filled cylindrical target locations in a water-filled tank at a high spatial resolution [15]. Gruber et al. investigated the performance of a MUSIC algorithm by considering numerically-simulated, second-order scattering between defects with a high spatial resolution of 0.1λ where λ is the wave length [16].

The aforementioned MUSIC beamforming algorithms can be applied to identify structural defects in “ideal” and “simple” shell structures such as infinite-size and uniform-thickness shells. However, in a “real” shell structure, high-level waves are reflected from many discontinuous features such as boundaries and stiffeners. In general, the waves reflected from the structural defects have much weaker signal strength than direct excitation waves and reflective waves from the structural boundaries or stiffeners. Then, it is almost impossible to identify the structural defects using the aforementioned, steady-state beamforming algorithms due to the strong direct excitation and reflective wave signals. In order to overcome this problem, a time-gating approach removing reflection time data from boundaries is generally applied [17]. For an embedded structure health monitoring system installed in the middle of a structure, the latter method can be useful since the measured time signals of boundary-reflected waves are appeared at the end of the time data and can be thus easily distinguished from the defect-induced waves that are measured before the boundary-reflected waves. However, this approach is difficult to be applied when defect-induced reflective waves appear later than or at the same time with boundary-reflected waves.

In this article, experimental results obtained with a 1.22 m × 0.92 m aluminum plate placed on small foam blocks around its edges are presented. For the purpose of simulating structural defects in this experiment, coins or washers are glued on the aluminum plate, which is similar to the cases in Refs. [8,9] where mass blocks are glued on an aluminum plate. A cross-shaped array of 7 mm × 7 mm piezoelectric transducers is also installed on the plate. One of the transducers is excited with a Lamb burst signal and the transducer array is then used to measure direct and reflective wave signals. In order to avoid multi-mode wave generation and spatial aliasing, the excitation frequency is set to 20 kHz. Then, a single anti-symmetric A_0 Lamb wave mode whose the wavelength is long enough to avoid the spatial aliasing is excited selectively at this excitation frequency.

By applying the conventional, steady-state MUSIC beamforming algorithms to the measured array signals, it is shown that these algorithms are unable to identify the locations of the simulated structural defects in the aluminum plate due to the multiple wave reflections. Thus, it is proposed to improve the beamforming algorithms by exploiting the temporal information of the reflective wave signals from the simulated defects and boundaries and the spatial information that the defect locations are not coincident with the boundaries. In order to realize this idea, a “time–frequency” MUSIC algorithm is proposed in this article.

Belouchrani et al. and Johnson et al. introduced the concept of a time–frequency beamforming procedure [18,19]. However, its applications are limited to estimate the “direction of arrival (DOA)” of active sources. In this article, the proposed time–frequency MUSIC algorithm is applied to identify the “locations” (i.e., directions and distances) of “structural defects” by measuring reflected waves from the defects on a plate, which does not require any specific time filtering or gating to distinguish defect- and boundary-induced reflective wave events. The proposed algorithm is expected to be useful, in particular, when boundary-reflected waves are measured earlier than or at the same time with defect-reflected waves. In the latter case, it is difficult to filter out the boundary-reflected signals unless the locations of the boundaries and defects are visualized on temporal beamforming power maps obtained by using the proposed time–frequency beamforming algorithm. For example, when the defect- and boundary-induced reflective waves are measured at the same time, the proposed algorithms can separate these waves based on their reflection locations identified on the resulting MUSIC beamforming power map.

One additional advantage of the proposed approach is that it does not require the information on the undamaged baseline structure and its boundaries prior to conduct the NDE. In particular, a simple free-field steering vector can be used in the proposed algorithm since the effects of the boundary reflections can be considered in the temporal and spatial information of the measured array signals. The steering vector does not need to be modeled or experimentally measured from the undamaged baseline structure to accurately include the effects of the boundaries without any structural defects. In most NDE applications, it is difficult or impossible to model or test an undamaged baseline structure to obtain the steering vector including the boundary effects of the structure.

Additionally, normalized, damped, 2-D cylindrical steering vector is proposed to increase the spatial resolution of time–frequency MUSIC power results to accurately pinpoint structural defect locations. A cross-shaped array is here selected to further improve the spatial resolution and to avoid mirrored virtual image effects.

Through the experimental results obtained by applying the proposed time–frequency MUSIC beamforming algorithm to the measured array data, it is shown that the proposed algorithms can be used to successfully locate the simulated defects.