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Time-Frequency Beamforming for Nondestructive Evaluations of Plate Using Ultrasonic Lamb Wave

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ABSTRACT

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. Here, the lowest anti-symmetric (A0) Lamb wave mode is selectively generated by adjusting the excitation frequency to avoid complex multi-mode wave generation. The measured array signals then include the wave signals generated directly by the excitation and reflected from the defects as well as the boundaries of the plate. 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 to process the measured signals in the time-frequency domain. In addition, a normalized, structurally-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 both 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 decay rates so that they have gained significant interest for many non-destructive evaluation (NDE) applications. In these NDE applications, a guided wave can be generated by using a Piezoelectric Wafer Active Sensor (PWAS)[1], propagating 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. A mode tuning technique[1] is used to 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.

In this article, experimental results obtained with a 1.22 m × 0.92 m × 0.002 m aluminum plate placed on small foam blocks around its edges are presented. For the purpose of simulating structural defects in this experiment, coins are glued on the aluminum plate. A time-frequency, MUtiple Signal Classification (MUSIC) algorithm is applied to identify structural defect locations. A normalized, structurally-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.

2. THEORY

A. Time-Frequency MUSIC Beamforming

Amongst various beamforming algorithms, the MUSIC beamforming algorithm[2,3] is widely used due to high spatial resolution of its resulting MUSIC power maps. Here, the proposed time-frequency MUSIC beamforming algorithm is applied to the time-averaged spectral (i.e., frequency) data obtained by applying the Discrete Fourier Transform (DFT) to a short period temporal (i.e., time) data at a specific time.

A spectral vector **X** at t_n can be expressed as

$$\mathbf{X}(t_n, f_l) = [X_1(t_n, f_l)\ \ X_2(t_n, f_l)\ \ X_3(t_n, f_l) \cdots X_M(t_n, f_l)]^{\mathrm{T}} \ . \tag{1}$$

where M is the number of transducers and l is the frequency index. The $M \times M$ cross-spectral matrix **R** at a specific time, t_n, and a specific frequency, f_l can be obtained from the spectral vector: i.e., $\mathbf{R} = \mathbf{X} \cdot \mathbf{X}^{\mathrm{H}}$. The cross-spectral matrix is then decomposed by using the Singular Value Decomposition (SVD): i.e.,

$$\mathbf{R}(t_n, f_l) = \mathbf{U}(t_n, f_l)\boldsymbol{\Sigma}(t_n, f_l)\mathbf{V}^{\mathrm{H}}(t_n, f_l)\ . \tag{2}$$

The time-frequency MUSIC power is then calculated at each scanning point, $\mathbf{r}_s$, as

$$P_{\mathrm{MUSIC}}(t_n, f_l, \mathbf{r}_s) = \frac{1}{\sum_{i=p+1}^{N} \left| \mathbf{g}^{\mathrm{H}}(\mathbf{r}_s) \cdot \mathbf{u}_i(t_n, f_l) \right|^2}\ . \tag{3}$$

where **g** is the steering vector of the acoustic signals at the transducer locations calculated by placing a free-field source at the scanning location and $\mathbf{u}_i$ is the i-th column vector of the matrix $\mathbf{U}(t_n,f_l)$ in Eq. (2), and p is the dimension of the signal space. When the scanning location is coincident to the source location, the inner product in the denominator of Eq. (3) becomes a small value and the MUSIC power is then locally maximized at this scanning location.

B. Wave Propagation in Models for Steering Vectors

Since the performance of the source localization using a MUSIC beamforming algorithm strongly depends on how well a steering vector represents the spatial distribution of the acoustic field of interest, it is important to precisely model wave propagation characteristics of a plate structure in the steering vector. A cylindrical, 2-D steering vector in Eq. (4) is used since the aluminum panel can be regarded as a 2-D surface.

$$\mathbf{g} = [\frac{1}{\sqrt{r_1}} \exp^{-ikr_1}\ \frac{1}{\sqrt{r_2}} \exp^{-ikr_2}\ \cdots \frac{1}{\sqrt{r_M}} \exp^{-ikr_M}]^{\mathrm{T}}\ . \tag{4}$$

When the measurement and scanning locations are coincident, the assumed acoustic field represented by the steering vectors in Eq. (4) becomes infinity at $r = 0$. Then, the MUSIC power in Eq. (3) becomes zero. For this reason, when a defect locates very close to the array, the resulting MUSIC power has an extremely small value at this defect location, making it impossible to have a local maximum MUSIC power at the defect location. In order to avoid this abnormality, it is proposed that the steering vector is normalized as

$$\mathbf{g}_{\text{normalized}} = \frac{\mathbf{g}}{\|\mathbf{g}\|}. \tag{5}$$

In addition to the geometrical wave decays associated with $1/r^{0.5}$ in Eq. (4), there is also a spatial decay induced by the structural damping. In this paper, a complex wave number is used in place of k in Eq. (4) to describe the structural-damping-induced spatial decay: i.e.,

$$\bar{k} = k(1 - i\beta). \tag{6}$$

The relation between the spatial decay rate β and the structural damping coefficient η can be obtained by assuming that the A0 Lamb wave at a low ultrasonic frequency such as 20 kHz can be regarded as a flexural wave[4]: i.e., $\beta = \eta/4$.

3. NUMERICAL SIMULATIONS FOR DETERMINATION OF ARRAY SHAPE

For the purpose of determining an array shape, numerical simulations with linear, circular, and cross-shaped arrays are performed. In the simulations, a point acoustic source is assumed to be placed at each of its source locations at x = 0.21 m and y = 0.7 m to generate a transient cylindrical wave field. The source locations are indicated by using the red "x" marks in Fig. 1. A burst sinusoidal signal with a center frequency of 20 kHz and a SNR of 10 dB is used to drive the point source. The wave speed at this excitation frequency is assumed to be 615 m/s that is corresponding to the A0 Lamb wave speed in a 2 mm aluminum plate. The structural damping coefficient for this cylindrical wave is set to 0.01. A linear, circular, or cross-shaped array of identical 20 sensors is then used to measure the radiated cylindrical wave field. These three arrays have the sampling space of 1 cm between two adjacent sensors except that the outer four sensors of the cross-shaped array are placed 2 cm apart to increase its measurement aperture. The radius of the circular array is then set to 3.2 cm. For all simulation cases, the sampling frequency is set to 10 MHz.

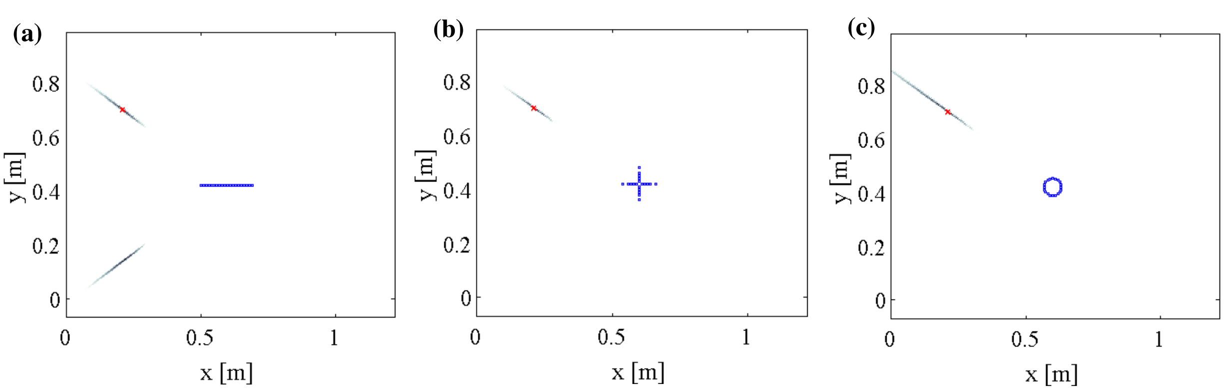

Figure 1: MUSIC power results of transient, cylindrical point source simulations with three different array sizes and shapes.

Fig. 1 shows the simulation results. In the cases of the linear array (see Fig. 1(a)), there is a mirrored virtual MUSIC power maximum around (x,y) = (0.21,0.14) m since the linear array cannot be used to distinguish the cylindrical waves generated from both the original and mirrored source locations. When comparing Figs. 1(b) and 1(c), the spatial resolution of the cross-shaped array is higher than that of the circular array since the measurement aperture size of the cross-shaped array is larger than the circular array: i.e., the x-direction aperture size of the cross-shaped array is 12 cm, while that of the circular array is only 6.4 cm.

4. EXPERIMENTAL SETUP

A cross-shaped array of 21 PWASs (APC-851 manufactured by APC International, Ltd.) is attached on the 2.03 mm thick aluminum panel by using superglue (see Fig. 2). The size of each PWAS is 7 × 7 mm and the sampling space between two adjacent PWASs is 10 mm except the outer four PWASs placed 20 mm apart from the closest PWASs to have a bigger array aperture. Then, three quarter coins at three different distances (i.e. 10 cm, 20 cm, and 30 cm) from the array center are glued on the aluminum panel to simulate structural defects. A National Instruments (NI) system equipped with a PXIe-5122 ultrasonic data acquisition (DAQ) module, a PXI-5421 signal generator, and an in-house LabView code is used to generate a burst sinusoidal wave with the center PWAS and measure the direct and reflective waves with the other PWASs. The excitation center frequency of 20 kHz is determined by using the criterion described in Ref. [1] to generate a single mode Lamb wave. A Brüel & Kjær Type 2693 Nexus conditioning amplifier is used to amplify the measured ultrasonic wave signals before the signals are fed to the NI DAQ system. The measured ultrasonic wave signals are recorded for 0.1 seconds at the sampling frequency of 10 MHz.

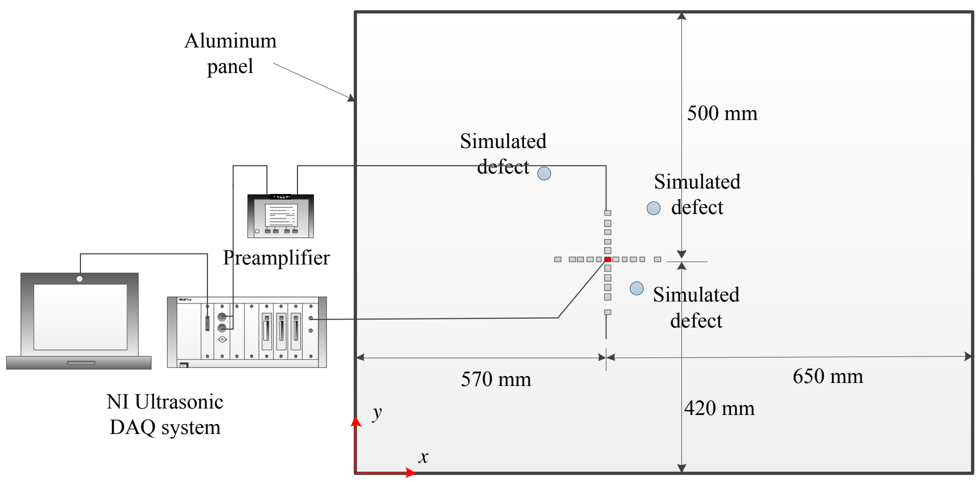

Figure 2: Sketch of experimental setup.

5. TIME-FREQUENCY MUSIC BEAMFORMING RESULTS

The time-frequency beamforming results are calculated by applying the time-frequency MUSIC algorithms to the measured array data. They are represented as the function of time and space. The time-frequency MUSIC power results at t = 0.2521 ms, 0.4102 ms, and 0.5836 ms are presented in Fig. 3 in terms of the maximum MUSIC power locations, coin locations, and -0.5 dB contour lines (i.e., 0.5 dB lower than a local maximum MUISIC power level). By comparing the contoured areas at t = 0.2521 ms, 0.4102 ms, and 0.5836 ms in Fig. 3(a), it is shown that the spatial resolution of the proposed algorithms is getting low as the defect distance increases. Figure 3 also show the effects of the spatial decay induced by the structural damping (see Eq. (6)) in the cylindrical, 2-D steering vectors. The highest spatial resolution results can be achieved at the structural damping coefficient of 0.03 as shown in Fig. 3 (in particular, see the -0.5 dB contour lines around Defect 3).

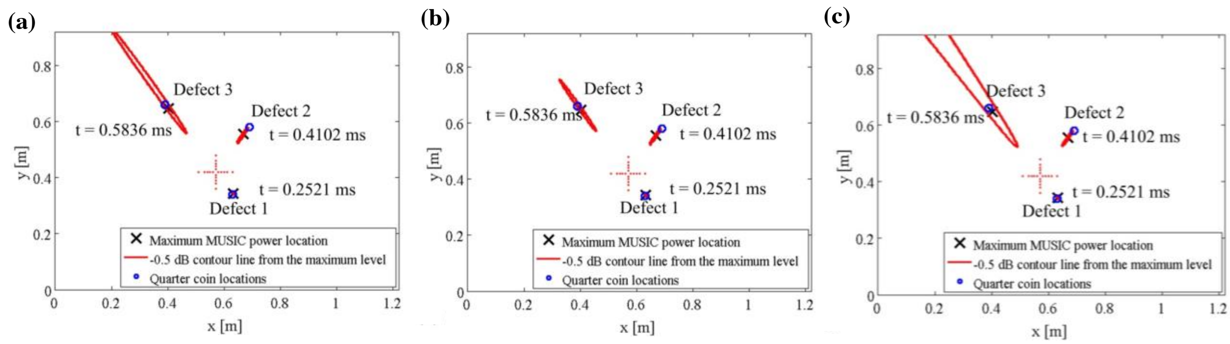

Figure 3: Time-frequency MUSIC power results with normalized, cylindrical 2-D steering vectors including structural damping, η: **(a)** $\eta = 0$, **(b)** $\eta = 0.03$, and **(c)** $\eta = 0.05$.

6. CONCLUSIONS

In order to non-destructively locate structural defects in plates by using a single-mode ultrasonic Lamb wave, the time-frequency MUSIC beamforming procedure, that can be used to distinguish the effects of the direct excitation and boundary-reflected waves, is proposed in this paper. In the proposed procedure, a burst sinusoidal signal is used to excite a plate with a single-mode Lamb wave. Then, the resulting ultrasonic wave signals are measured using a sensor array. The proposed time-frequency MUSIC beamforming algorithm is then applied to the measured array data to obtain the beamforming maps, as a function of time and scanning location, whose local maxima at specific time instants (between the arrival times of the direct excitation wave and the boundary-reflected waves) can be identified as structural defect locations.

In order to improve the spatial resolution of the time-frequency MUSIC algorithm, the structural-damping-induced spatial decay is considered in the steering vectors. When the structural damping of $\eta = 0.03$ is applied to the steering vectors, the highest spatial resolution of the time-frequency MUSIC results can be achieved. A cross-shaped array is selected to further improve the spatial resolution and to avoid mirrored virtual image effects. Finally, it should be noted that the proposed time-frequency MUSIC beamforming procedure does not require undamaged state data as a baseline.

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