ABSTRACT

This paper describes a general approach for processing data from an omni-directional guided wave transducer array for the rapid inspection of large plate structures. A basic phased array algorithm is presented that can be applied to any array geometry. The beam forming is the method in which the phase-coherent signals at different sensors are superimposed such a way that the sum will have maximum amplitude. This phase-coherent line in fact coincides with the front line of the propagating wave and thus the shape of the wave front is determined to be similar to the spatial shape of the array. Because the circular array which must be in general uses due to its symmetricity to all directions has the different shape to the wave front, its beam pattern is poor with high sidelobe levels. By projecting the array onto the wave front, the compensating weights are proposed to reduce the sidelobes. The proposed beam enhancement weights improve the inspection performance with well designed and established beam pattern. For guided waves on plate, beam steering algorithm is derived and the corresponding beam pattern to the array shape is well obtained. The processing algorithms are sufficiently investigated by applying to some simulation and experimental cases. The results show well the usefulness of the proposed methods in guided wave phased array for structural inspections.

Keywords: phased array, guided wave, projected array signals, compensating weights.

INTRODUCTION

Phased arrays have been widely used in ultrasonics for many years. Medical B-scan as one popular example sends and receives bulk waves in various directions by steering the narrow beam with different time-delay inputs to the transducer elements. The beam forming capabilities and acoustic fields generated by the transducer array have been studied very carefully. In recent years, ultrasonic arrays have been used in many areas of nondestructive evaluation. In particular, guided wave phased arrays are being increasingly studied and used in variety of inspections.

Inspection of large plate-like structures using traditional nondestructive evaluation methods is both time consuming and difficult, especially if the monitoring has to be done in situ. Lamb wave based inspection methods have been shown to be well suited for monitoring such structures, because Lamb waves have the capability of travelling large distances without much attenuations. However, Lamb waves are dispersive in nature and hence the velocity of propagation becomes a function of the frequency and the thickness of the plate though the medium is isotropic. Hence, to deal with Lamb waves becomes difficult and complicated for the nondestructive evaluation of structural integrity.

For two-dimensional inspections in plate-like structures, direction finding algorithms as well as distance finding algorithms which are used for most of traditional one-dimensional inspections are required to be developed. The suitability of an array based approach for achieving directionality and the applicability of an array based system for rapid inspection of plate structures have been well demonstrated. Beam steering and forming algorithms were used to process data obtained from multiple omni-directional guided wave transducers.

In this paper, guided wave phased array algorithm is theoretically established in detail that can be applied to any array geometry. Dispersive propagation model of Lamb wave was incorporated with the delay-and-sum algorithm. Far-field approximation introduced a simple mathematical expressions and leakage problems in beam patterns. Beam pattern design is prerequisite for enhancing the inspection performance by reducing the leakage.

The beam forming is the method in which the phase-coherent signals at different sensors are superimposed such a way that the sum will have maximum amplitude. This phase-coherent line in fact coincides with the front line of the propagating wave and thus the shape of the wave front is
determined to be similar to the spatial shape of the array. Because the circular array which must be in general uses due to its symmetricity to all directions has the different shape to the wave front, its beam pattern is poor with high sidelobe levels. By projecting the array onto the wave front, the compensating weights are proposed to reduce the sidelobes. The proposed beam enhancement weights improve the inspection performance with well designed and established beam pattern.

For guided waves on plate, beam steering algorithm is derived and the corresponding beam pattern to the array shape is well obtained. The processing algorithms are sufficiently investigated by applying to some simulation and experimental cases. The results show well the usefulness of the proposed methods in guided wave phased array for structural inspections.

GUIDED WAVE PHASED ARRAY ALGORITHM

Consider scattering of a time-harmonic guided Lamb wave by a small object located at \( x_s \) in a thin isotropic plate. The scattered guided wave detected by a transducer placed at \( x \) can be expressed as

\[
s(x,t) = A(\omega) e^{j(\omega t - \mathbf{k} \cdot \mathbf{x}_s)} = A(\omega) \frac{e^{j(\omega t - \mathbf{k} \cdot \mathbf{x}_s)}}{\sqrt{\mathbf{r}}}\tag{1}
\]

where \( \omega (= 2\pi f) \) is the angular frequency, \( \mathbf{k} (= \omega / c_{\rho}) \) is the guided wave number, and \( \mathbf{r} = \mathbf{x} - \mathbf{x}_s \) is the distance from the scattering object to the receiver. \( c_{\rho} \) is the phase speed. Due to the dispersion of Lamb waves in plates, the phase speed is considered a function of frequency. Here, we define a unit direction vector in which the receiver looks at the source: \( \mathbf{u} = -\mathbf{r} / r \). Note that the frequency dependent amplitude \( A(\omega) \) can also be a function of angular direction in general, but we assume that the radiation characteristics of the source and the scattering object as well as the medium are perfectly isotropic in this paper.

Now consider \( M \) receivers that detect the scattered guided wave, all located and populated compactly in a small region far from the scattering object. An objective function is defined that is the sum of the signals from all \( M \) sensors, each signal delayed with an appropriate time-delay \( \tau_m \) and weighted with \( w_m \):

\[
y(t) = \sum_{m=1}^{M} w_m s_m(t - \tau_m) \tag{2}
\]

Here, \( s_m(t) \) indicates the guided wave signal detected by a m-th sensor at \( x_m \). By adjusting the weights and time-delay, one can shape and steer the “beam” in the direction (beam forming) where this objective function takes its global maximum and this direction is regarded as the direction of incidence of the scattering wave. This is the well-known delay-and-sum technique and the
present paper employs this technique with some modifications in the consideration of guided wave dispersion. A basic beam forming technique uses a constant weight, $1/M$.

For convenience in deriving expressions, we introduce the phase centre $x_o$, defined as a geometric centre of the array sensors, and use this to define the position of a sensor relative to the phase centre:

$$x_O = \frac{1}{M} \sum_{m=1}^{M} x_m, \quad r_O = |x_j - x_O|.$$  \hspace{1cm} (3)

Then, the location of $m$-th sensors relative to the phase centre is

$$\xi_m = x_m - x_O.$$  \hspace{1cm} (4)

Within far-field approximation, finally, one obtains the delay-and-sum output signal

$$y(t) = \frac{A(\omega)}{M \sqrt{r_O}} e^{j\omega t - k(r_O - r_j)} \sum_{m=1}^{M} e^{j(k(u_m - u_j)\xi_m)}.$$  \hspace{1cm} (5)

The delay-and-sum output signal has no sensitivity to the source-to-receiver distance. In other words, the distance information is missing in the array signal processing algorithm when using the far-field approximation. And also Eq. (5) gives the true direction to the source, $u_j' = u_j$. The summation term in Eq. (5) takes a general form of the discrete Fourier transform and the relative locations of the sensors determine the spatial sampling intervals. The sampling is in general uneven and the uneven sampling can significantly affect the beam forming output as will be shown later.

In order to identify both the direction and position of the scattering source, the above-described array processing algorithm needs to be combined with an appropriate ranging algorithm. We use the traditional time-of-flight algorithm for estimating the distance to the scattering source from the phase centre. A tone-burst signal can be used to estimate the travelling time.

**PROJECTED ARRAY SIGNALS AND COMPENSATING WEIGHTS**

The phased array output signal adds all time-delayed versions of transducer signals. It indicates virtual rotation of transducer array to steer the beam, which is called projected array. The projected array has uneven sampling and its sampling is irregular. Moreover it is varied with the direction as shown in Figure 1. Such irregularity of projected array invokes the worse beam pattern with increased sidelobe levels. In order to regularize the projected array, compensating weights are introduced. By weighting the array signals, the array density can be uniform.

The proposed beam enhancement weights improve the inspection performance. Some simulation and experimental results confirm the usefulness of the proposed compensation algorithm in guided wave phased array for structural inspections.

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**REFERENCES**