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Damage localization in aluminum plate with compact rectangular phased piezoelectric transducer array

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ABSTRACT

In this work, a detection method for the damage in plate-like structure with a compact rectangular phased piezoelectric transducer array of 16 piezoelectric elements was presented. This compact array can not only detect and locate a single defect (through hole) in plate, but also identify multi-defects (through holes and surface defect simulated by an iron pillar glued to the plate). The experiments proved that the compact rectangular phased transducer array could detect the full range of plate structures and implement multiple-defect detection simultaneously. The processing algorithm proposed in this paper contains two parts: signal filtering and damage imaging. The former part was used to remove noise from signals. Continuous wavelet transform was applicable to signal filtering. Continuous wavelet transform can provide a plot of wavelet coefficients and the signal with narrow frequency band can be easily extracted from the plot. The latter part of processing algorithm was to implement damage detection and localization. In order to accurately locate defects and improve the imaging quality, two images were obtained from amplitude and phase information. One image was obtained with the Total Focusing Method (TFM) and another phase image was obtained with the Sign Coherence Factor (SCF). Furthermore, an image compounding technique for compact rectangular phased piezoelectric transducer array was proposed in this paper. With the proposed technique, the compounded image can be obtained by combining TFM image with SCF image, thus greatly improving the resolution and contrast of image.

1. Introduction

Structural health monitoring systems employing guided waves are being considered for civil, mechanical, and aerospace applications. Guided ultrasonic waves, such as Lamb waves, are the primary options for structural health monitoring of plate-like structures, pipes, and beams components [1–3]. Lamb waves are widely used to detect and locate the damage according to the information from signal attenuation [4] and wave reflection [5] because it can travel long distance while maintaining the sensitivity to damage [6–8]. Although a variety of transducers, such as EMATs [9] and air-coupled transducer [10], can excite and detect Lamb waves, the piezoelectric transducer is the most commonly used transducer in guided waves detection.

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A single transducer cannot meet the requirements of sensitivity and information processing, so ultrasonic transducer arrays, which can provide the increased flexibility and superior performance compared to conventional monolithic transducers [11], are adopted for NDE. The arrays can be grouped into two different families: sparse arrays and compact arrays [12]. In general, sparse transducer arrays are mounted on the detected structure and the interrogation is performed with the pitch and catch approach, electro-mechanical impedance change, or pulse-echo measurements [13–15]. Sparse transducer arrays were extensively studied by many researchers. For example, Michaels et al. [16] localized the damage in plate-like structures by analyzing the signals recorded from sparse transducer array. Anthony et al. [17] applied sparse transducer array in the SHM to locate the damage with two algorithms: ellipse algorithm and hyperbola algorithm. Konstantinidis et al. [18] described the effects of temperature on Lamb waves, and detected the defect in plates via Lamb wave with a sparse array. The received signals from the sparse array not only contain direct arrivals but also the forward- and back-scattered echoes. The images obtained by the sparse array were mainly dominated by these direct arrivals and coherent structural reflections and this phenomenon reduced the contrast of images unless there was a baseline subtraction [19].

However, sparse transducer arrays have to be distributed in a large area when detecting defects in the structure with a large area, thus making the system complex to some degree. Furthermore, because the distribution area of transducers is wide, the sparse transducer arrays are not suitable for detecting the complex structures which usually do not have enough space for mounting transducers. In order to minimize the footprint of transducers, various compact transducer array configurations have been proposed, such as linear, cross-shaped, circle shaped and rectangular shaped configurations [20]. The linear phased array is the simplest and most widely used one-dimensional (1-D) ultrasonic phased array. Some parameters in linear phased array including the number of elements, element spacing, element dimensions, and aperture size, as well as their effects on the directivity had been studied by Wooh and Shi [21] and Clay et al. [22]. Yan and Rose [23] applied the linear phased piezoelectric transducer array to composite aircraft panels, suppressed the influence of anisotropy by a modified delay-and-sum algorithm, and introduced a quasi-isotropic mode neighborhood concept based on a wave mechanics study for multilayer anisotropic plates.

In addition to positioning transducers along a line, transducers can also be positioned along other shapes, like planar arrays. The arrays can be located in the center of the interrogation area to interrogate the whole detection area. Wilcox [24] employed an omni-directional Lamb wave compact EMAT transducer array which contained a circular pattern of elements to detect the defects in plate structures and presented the method, basic phased addition algorithm, for processing data from omni-directional guided waves array. Yu and Giurgiutiu [20] presented 2-D array for avoiding the detection angle limitation of 180° in linear phased array, evaluated the directionality of several 2-D phased piezoelectric transducer arrays with the generic beamforming algorithm, and compared the imaging effects of linear array and rectangular array with embedded ultrasonic structural radar (EUSR) algorithm. Recently, Han and Kim [25] detected the defects in a plate with a cross-shaped array of 21 piezoelectric transducers and found that the time-frequency Multiple Signal Classification (MUSIC) algorithm could be used to identify the structural defect located beyond the shortest boundary distance from the array. Various damage detection and location approaches with compact phased transducer arrays had been applied and improved, such as phased-addition algorithm [24] and synthetic aperture technique [26]. In this study, both the amplitude and phase information were used to locate defects, thus greatly improving the imaging quality.

The images based on the Lamb wave technique have no good resolution and/or contrast due to some limitations imposed by spurious propagation modes, main lobe width, side and grating lobes, and signal-to-noise ratio. Data fusion can improve image quality by taking advantages of information from all transducers. Su et al. [27] utilized three different data fusion schemes (disjunctive, conjunctive and compromise fusion) to estimate mono- and multi-delamination in carbon fiber-epoxy composite structures in terms of their effectiveness. Prado et al. [26] located the defects in an aluminum plate with the compounding technique, in which the utilized signals were the signals in fundamental symmetry mode generated by two different arrays. However, the adoption of two arrays had increased the system complexity to some degree.

Liu et al. [28] adopted three types of image compounding algorithms, namely, full summation, full multiplication, and the combination of summation and multiplication, to realize the image compounding and found that the combination of summation and multiplication could effectively highlight the discontinuity position. Besides, Liu et al [29] also put the former two image compounding algorithms, full summation and full multiplication, into the no-contact defect inspection in composite plate and improved the reliability and accuracy of the inspection. Prado et al. [30] employed the image compounding technique, in which the adopted signals from two propagation modes were generated by linear arrays, and obtained an image with the good resolution and contrast. However, the system could not realize the detection in the full range when the linear array was located in the middle of the plate. Wandowski et al. [31] located the defects in an aluminum alloy plate with four different signal filtering approaches and compared the four different imaging results. However, limited by the design of the transducer array, the obtained signals were not enough for accurately positioning the defects.

In this paper, a compact rectangular phased piezoelectric transducer array was used to detect defects in plate structures. During the Lamb wave inspection of plate-like structures with compact phased transducer arrays, it is often not required to subtract baselines [20,24,32]. Therefore, the inspection with the arrays is very convenient for data post-processing. In recent years, various shapes of compact phased transducer arrays, such as linear, circular, square, spiral, and star-shaped arrays, had been reported [33–35]. This compact rectangular phased piezoelectric transducer array allows the 360° full-range damage detection and can avoid the mirrored virtual image generated during the defect detection with linear arrays. Although linear phased piezoelectric transducer arrays can interrogate the large area in the structure, the detection range is the 180° due to the geometric symmetry of array. The mirrored virtual image may occur when linear arrays are adopted for imaging, thus