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Lamb mode diversity imaging for non-destructive testing of plate-like structures

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ABSTRACT

Several Lamb wave modes can be coupled to a particular structure, depending on its geometry and transducer used to generate the guided waves. Each Lamb mode interacts in a particular form with different types of defects, like notches, delamination, surface defects, resulting in different information which can be used to improve damage detection and characterization. An image compounding technique that uses the information obtained from different propagation modes of Lamb waves for non-destructive testing of plate-like structures is proposed. A linear array consisting of 16 piezoelectric elements is attached to a 1 mm thickness aluminum plate, coupling the fundamental A0 and S0 modes at the frequencies of 100 kHz and 360 kHz, respectively. For each mode two images are obtained from amplitude and phase information: one image using the Total Focusing Method (TFM) and one phase image obtained from the Sign Coherence Factor (SCF). Each TFM image is multiplied by the SCF image of the respective mode to improve contrast and reduce side and grating lobes effects. The high dispersive characteristic of the A0 mode is compensated for adequate defect detection. The information in the SCF images is used to select one of the TFM mode images, at each pixel, to obtain the compounded image. As a result, dead zone is reduced, resolution and contrast are improved, enhancing damage detection when compared to the use of only one mode.

1. Introduction

The use of guided waves in non-destructive testing of plate-like structures and pipes is advantageous because of some characteristics as: they propagate over long distances due to low attenuation, inspecting relatively large areas without the necessity of moving the transducers; the whole cross section of the structure can be inspected; the possibility of testing structures with coating or insulation with no significant loss of sensitivity; the possibility of using several propagation modes, with different sensitivity to each type of defect [1].

Additionally, each propagation mode has its own dispersion characteristic, which should be considered for proper analysis of the results [1–3]. To minimize the effect of dispersion, narrowband signals or techniques of dispersion compensation can be used [4–6]. The propagation modes can be symmetric or antisymmetric, with different orders. They are generally presented in the form of dispersion curves: phase or group velocity (or wavenumber) as a function of the frequency–thickness product ($f \cdot d$), for the various propagation modes. For an aluminum plate, at low $f \cdot d$ values, only the two fundamental modes can propagate: the symmetric S0 mode, which presents low dispersion characteristic, and the antisymmetric A0 mode, which has significant dispersion. At higher $f \cdot d$ values other modes can be coupled. The modes that will be coupled to the structure depend not only on the plate properties, but also on the transducer, frequency range and technique used to generate the guided modes.

Using arrays an image of the structure and its defects can be obtained. An ultrasonic array is a set of transducers, geometrically organized to control the acoustic beam electronically [7]. The quality of the image depends on various parameters, e.g. array configuration, number of elements, transducer geometry, beamforming technique and propagation modes [8–10]. Some images resulting from guided waves may not have 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. An alternative to improve image quality is the use of image compounding or fusion techniques.

Davies and Cawley [11] used an array of piezoelectric shear transducers and different synthetically focused imaging techniques, considering different frequencies for each one, for pipe inspection.

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For each method one image per frequency is obtained. The compounding procedure consists of summing all images for the same technique.

Su et al. [12] proposed three fusion schemes based on probability to estimate delamination in carbon fiber-epoxy composite plates. The perception of each sensor is obtained from a correlation of the signal with a baseline parameter, resulting in the probability of the perception for each combination (transmitter and receiver). Union and intersection probabilities were used, but an intermediate measure of them presents delamination identification with relatively high robustness and reliability.

Michaels and Michaels [13] excited a sparse array with broadband pulses and one image is produced for each frequency. The fusion is made by taking the minimum value of all images for a given pixel. Differential signals are used by subtracting the measured signal from a baseline signal recorded from the undamaged plate. In [14,15], the authors propose to use chirp excitations as an efficient method to generate multimode and multifrequency guided waves. This is followed by post-processing to obtain the best mode purity and echo shape for generating multiple images of damaged plates.

Higuti et al. [16] proposed an image compounding technique based on information obtained from multiapodization and two different arrays which generated the fundamental S0 mode in an aluminum plate. There was improvement in contrast and resolution when compared to the use of only one array, but the use of two arrays increases the system complexity in terms of transducers and electronics.

The main contribution of this paper is an image compounding technique which uses information from two propagation modes generated by the same linear array, without baseline subtraction, resulting in an improved image respect to resolution, contrast, image artifacts and dead zone when compared to the use of only one mode. These improvements are obtained from amplitude and phase information, and from the specific mode interactions with different types of defects.

2. Image compouding technique

2.1. Amplitude images

Consider a linear array of N elements and amplitude time domain data $v_{ij}(t)$ from all transmitter (i) and receiver (j) combinations. The image value at point (x,z) can be obtained by the Total Focusing Method (TFM) [17]:

$$I(x,z) = \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} v_{ij}(\tau_{ij}(x,z)), \tag{1}$$

where $\tau_{ij}(x,z)$ is the time of flight between the transmitter (i), the point (x,z) and the receiver (j).

2.2. Phase images

The use of synthetic aperture imaging technique using TFM has the advantage that it generates the maximum lateral resolution available at each imaging point, producing high quality images. However, as the individual signals have low signal-to-noise ratio, there is a limitation in detecting defects or objects that are far from the array. The study of the beamforming process based on the analysis of partial characteristics, such as the energy balance or the signals phase distribution, provides a new source of information that can help to overcome these limitations and improve system response.

Under this perspective, the study of the coherence of the energy balance at each point of the image to improve the beamforming process was proposed by Hollman [18] and employed in adaptive beamforming process by Asl [19]. However, the most interesting results are obtained if the analysis of the phase distribution is introduced in the beamformer. This analysis can be based on many descriptors with different degrees of computational complexity but with similar results as the polarity and the variance of the distribution of phases [20], or the spectral analysis of the phase distribution [21]. In this sense the most complete work based on the analysis of the phase variance has been developed by Camacho [20], where the properties of the phase coherence beamformer are studied, showing a high degree of robustness to noise, to side and grating lobes. Among the alternatives proposed in [20], the Sign Coherence Factor (SCF) descriptor has been chosen because of its good results. The efficiency of coherence estimators based on phased distribution has been tested in [22,23].

The SCF image is a method based on the analysis of phase variance at the aperture data. It can be computed as [20]:

$$I_{\mathrm{SCF}}(x,z) = 1-\sigma, \tag{2}$$

where σ is the standard deviation of the polarity $b_{ij}(t)$ of the aperture data:

$$\sigma^2 = 1-\left[\frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} b_{ij}(\tau_{ij}(x,z))\right]^2, \tag{3}$$

and $b_{ij}(t)$ is the polarity or algebraic sign of the aperture data:

$$b_{ij}(t) = \begin{cases} -1 & \text{if } v_{ij}(t) < 0 \\ 1 & \text{if } v_{ij}(t) \geq 0 \end{cases}. \tag{4}$$

The SCF measures the coincidence in algebraic sign of the received delayed signals, which are fully coherent if all of them have the same polarity ($I_{\mathrm{SCF}}(x,z) = 1$). In other cases the value of $I_{\mathrm{SCF}}(x,z)$ is in the range [0, 1[. Dispersion, random noise, signal interferences between multiple rebounds in the specimen (multi-path) and spurious propagation modes can affect the degree of coherence between signals. Under these assumptions, a defect could be detected at a determined position if the sign coincidence is maintained for at least 75% of the received signals, for example, which means that the SCF is valued by at least 50% at that point.

The SCF image is used in two situations in this work: (i) as a weighting factor, being multiplied by the TFM image and resulting in contrast improvements [20,21]; (ii) If the SCF image is above a determined threshold (e.g. 50%), this information can be used to indicate the presence of a defect [16]. So, the novelty of the work is related to the image compounding technique using two propagation modes generated by the same aperture, which is described in Section 2.4.

2.3. Dispersion compensation

At low values of the frequency–thickness product the A0 mode presents high dispersion. However, when the dispersion curves are known this effect can be compensated. Wilcox [24] presents a technique that maps the signals from the time domain to the spatial domain (propagated distance). Considering $g(t)$ the signal with dispersion, the compensated signal is given by:

$$h(x) = \int_{-\infty}^{\infty} H(k)e^{-jkx}\,dk, \tag{5}$$

where

$$H(k) = G(\omega)c_g(\omega), \quad \omega = \omega(k), \tag{6}$$

$G(\omega)$ is the Fourier transform of $g(t)$, ω is the angular frequency, k is the wavenumber ($k = \omega/c = 2\pi/\lambda$), and λ is the wavelength. The phase and group velocities (c and c_g, respectively) are obtained by