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Mode perturbation method for optimal guided wave mode and frequency selection

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ABSTRACT

With a thorough understanding of guided wave mechanics, researchers can predict which guided wave modes will have a high probability of success in a particular nondestructive evaluation application. However, work continues to find optimal mode and frequency selection for a given application. This "optimal" mode could give the highest sensitivity to defects or the greatest penetration power, increasing inspection efficiency. Since material properties used for modeling work may be estimates, in many cases guided wave mode and frequency selection can be adjusted for increased inspection efficiency in the field. In this paper, a novel mode and frequency perturbation method is described and used to identify optimal mode points based on quantifiable wave characteristics. The technique uses an ultrasonic phased array comb transducer to sweep in phase velocity and frequency space. It is demonstrated using guided interface waves for bond evaluation. After searching nearby mode points, an optimal mode and frequency can be selected which has the highest sensitivity to a defect, or gives the greatest penetration power. The optimal mode choice for a given application depends on the requirements of the inspection.
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1. Introduction

Historically, optimal guided wave mode and frequency selection has been mysterious. A rise in the understanding of guided wave mechanics and the ability to calculate mode solutions using modern computing power has illuminated the subject. However, there are still situations for which the best mode choice is unknown or the material properties are unknown and proper mode and frequency selection choice still remains a mystery. For example, Hosten et al. [1] have shown that the elastic constants of composite materials can be measured. However, the technique can be cumbersome so often only estimates of composite material properties are used.

For these reasons, a novel mode and frequency perturbation method for mode selection is presented. A phased array is used to sweep through available modes to find mode points with optimal characteristics for an inspection, be it for greatest defect sensitivity, penetration power, or another characteristic. Gao and Rose [2] have plotted goodness curves to show mode sensitivity to defects, which changes even along a single mode. The mode and frequency perturbation method implicitly accounts for this effect by testing the available modes in a region. This new method can be used to remove the mystery about which mode activation points are most desirable and base the decision on clear, quantifiable characteristics.

A variety of studies have used different array shapes and signal processing methods for guided wave mode selection and directional control in defect-detection applications. Wilcox et al. [3,4] used circular coil EMATs in a phased array. The transducer array was used to excite the guided wave A0 and S0 plate modes for defect detection, and performance characteristics were considered based on the number of elements and special design. Leleux et al. [5] use a 2-d phased array for beam steering in an NDT setting. The square array contained square elements which were used to excite guided wave modes in both aluminum and carbon epoxy composite plates. Fromme et al. [6] use a ring-shaped array of circular transducers to generate a radial-angular B-scan. The array was bonded to 5-mm thick steel plate and excited the A0 mode for the purpose of structural integrity monitoring of corrosion-like defects. Velichko and Wilcox [7] describe a general approach for processing array data from linear and circular arrays. Their approach is implemented using the S0 mode in 5-mm thick aluminum plate and achieved increased resolution at the expense of sensitivity to noise.

Salas and Cesnik [8,9] used wedge-shaped guided wave SHM transducers which they called CLoVER transducers. CLoVER sectors

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were activated individually to perform an angular scan. Glushkova et al. [10] used a multi-element annular array to perform mode selection between A0 and S0 modes in a plate by applying different amplitude factors and phase delays to the different elements. Michaels et al. [11] used chirp excitations to excite A0 and S0 modes at multiple frequencies in a 3.2 mm plate to achieve the sensitivity benefits of different modes while reducing measurement time and the quantity of data.

Several other studies considered the use of phased arrays with a particular emphasis on precise mode control in both piping and plate structures. Li and Rose [12] used a phased comb array to excite different order axisymmetric modes in pipes. They noted that a simple ring piezoelectric element did not provide control over the relative excited amplitude of $L(0,1)$ and $L(0,2)$ modes, but that the application of time delays to a comb array of ring elements could. Li and Rose built on the previous work of Quarry and Rose [13], who noted that manual adjustment of comb array spacers on pipe can produce different sets of modes.

Zhu and Rose [14] used multiple, overlapping linear comb delays to form what they called a time-delay periodic linear array (TDPLA). They demonstrated directional control for guided waves in plates. Hay and Rose [15] used a phased comb array for fatigue crack detection using the A0 mode at 2 MHz in a 3.2 mm aluminum plate. They noted that since different mode points have different characteristics (displacement wave structures), different modes should be sensitive to different defect types. They mentioned that phase velocity dispersion curve tuning is a powerful experimental technique to locate useful guided wave modes for a given testing application.

Yan and Rose [16] consider phased array transducers in both isotropic and anisotropic plates. They describe the excitability spectrum and demonstrate the effect of phasing individual elements to change the excited guided wave modes. They use a time delay tuning process where a linear time delay is incrementally increased from zero, and an "optimum" time delay is chosen by looking at the maximum received amplitude for direct arrival signals. Borigo et al. [17] describe considerations for mode selection using phased annular array transducers.

Previous studies demonstrate the use of phased arrays with specific time delays for mode selection and directional control, or the use of a frequency sweep (e.g., chirp signal) to excite modes with different sensitivities. However, none of these studies examine how both element phasing and excitation frequency can be used in tandem to adjust both the phase velocity and frequency to selectively excite and then optimize mode excitation. This paper describes a method whereby different points in dispersion curve space may be activated in order to select an optimal mode and frequency activation for defect detection. This multi-mode and frequency perturbation method can be used to select useful modes even in situations with limited *a priori* knowledge of the waveguide's material characteristics.

In this paper, this method is detailed conceptually and demonstrated experimentally using ultrasonic guided interface waves for bond evaluation. The features analyzed here are those shown previously to correlate with bond length [18,19]. Although the mode sweep technique is applied to only one inspection problem in this paper, note that it is a general technique, and has potential applications in flaw detection characterization and other areas.

2. Approach

Two common guided wave mode excitation methods are the angle beam and linear comb transducers. Both of these excitation methods have unique excitation patterns, and their own strengths and weaknesses. Consider the excitation regions by these two methods in phase velocity-frequency (c_p–f) space.

We discuss the transducer excitation patterns in terms of activation lines and points, for simplicity of discussion. However, note that complex excitation patterns occur depending on the transducer type, dimensions, and other settings.

An angle beam transducer gives an excitation line at a c_p defined by Snell's law. Changing the transducer excitation frequency allows a user to sweep along a horizontal line in c_p–f space. If an adjustable angle wedge block is used, the angle may be manually changed, and the user may then excite at a different c_p and horizontal line.

The linear comb array transducer excites waves at a constant wavelength, given by the comb element spacing s, and the main excitation lobe has a diagonal activation line in c_p–f space. The line starts at (0,0), and extends outward at an angle, φ (from the horizontal) determined by the element spacing as

$$\varphi = \tan(s) = \tan(\lambda_s) = \tan(c_p/f), \tag{1}$$

where φ is the angle of the activation line in c_p–f space from the positive horizontal axis, s is the element spacing, and λ_s is the wavelength of waves excited by the comb, which is equal to s.

A diagonal line is activated when the elements are excited in-phase. However, if the elements are excited out of phase, and more specifically, with a linear time delay to successive elements (0, 1τ, 2τ, 3τ, ...), the activation line curves. Using this property, we can effectively sweep through a region of c_p–f space with a single transducer by applying different time delays (and frequencies), without changes in the physical location, set up, or couplant condition of the transducer. An example of straight (no delay) and curved (linear delay) activation lines are shown in Fig. 1 for s = 8.43 mm and τ = 1 μs. The activation lines are plotted with the phase velocity dispersion curves for a 25 mm (1 in.) steel plate, which will be used in the experimental section of this paper. Note that the location of the no delay activation line is dependent solely on the transducer array spacing. The location of the (curved) phase delay activation lines are dependent on the applied time delay in reference to the array spacing.

We now derive the equations needed to adjust time delay for a mode sweep. Consider the wavelength that will be excited with a phased comb transducer,

$$\lambda = \lambda_s \pm \lambda_{change-TD}, \tag{2}$$

where λ_s is the wavelength excited based on the physical dimension of the transducer ($\lambda_s = c_p/f = s$), and $\lambda_{change-TD}$ is the change in the

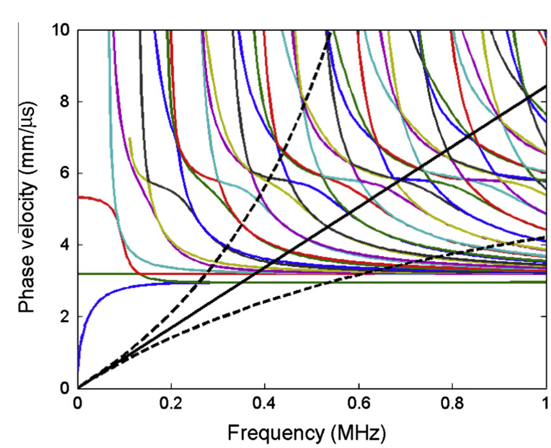

Fig. 1. Activation lines for linear, multi-element comb transducer with in phase (thick solid line) and 1 μs linear time delay (dashed curved lines) element excitation. The curved dotted lines represent the forward and backward traveling wave activation lines from the comb transducer. Phase velocity dispersion curves for a 25 mm steel plate are also shown.

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