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AN ULTRASONIC GUIDED WAVE EXCITATION METHOD AT CONSTANT PHASE VELOCITY USING ULTRASONIC PHASED ARRAY PROBES

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ABSTRACT

High order ultrasonic guided wave modes have more and more applications in nondestructive testing. Controlling the excitation when working at frequencies above the cutoff of the first high-order mode is essential to reduce the complexity of the transmitted wave packet. Papers available in the literature demonstrated that single element transducer associated with an angled wedge could be used to excite high order guided wave modes at a chosen phase velocity corresponding to the wedge angle. Ultrasonic phased array probes typically used in ultrasonic imaging have variable beam steering capability through the control of the elementary delay law. This study investigates the possibility of exciting specific ultrasonic guided wave modes or group of modes at high frequency-thickness products using an ultrasonic phased array probe. The regions of the dispersion curves targeted can be controlled by the input signal bandwidth and the angle of the generated beam. The method of excitation and its theoretical background are described. Finite element simulations are presented to verify the analytical predictions and quantify the unidirectional and diffraction properties of the transmitted beam. Experiments show striking agreement with the finite element simulations including the possibility to excite a single mode in a narrow zone at high frequency-thickness products.

Keywords: Guided Waves, Excitation method, Beam steering, Mode selection, Phase velocity excitation

NOMENCLATURE

α	alpha, angle of excitation
t_0	elementary delay
λ	wavelength
p	elementary pitch
f	frequency
v_{ph}	phase velocity
UGW	ultrasonic guided waves
FE	finite element

1. INTRODUCTION

Most UGW applications use frequencies below the cutoff frequency-thickness product of the first high-order mode in order to reduce the signal processing complexity as only three fundamental modes propagate. However, high-order ultrasonic guided wave modes have recently been attracting interest in a variety of nondestructive testing applications such as long range bond characterization [1], crack monitoring [2] or partially accessible thickness gauging [3]. However, it is difficult to perform the excitation of a single high-order UGW mode using conventional transduction methods [4]. A single-element transducer coupled to an angled wedge [5] transmits a specific phase velocity, but the method requires to change the angle of the wedge when the targeted phase velocity changes. Comb excitation can be used to target a specific wavelength, but the method also does not have the required flexibility to handle a variable wavelengths [6]. An alternative transduction method, initially presented by Nguyen et al. [7], uses ultrasonic phased array probes for the excitation of high-order UGW modes in bone phantoms, but only in view of exciting and receiving multiple modes concurrently.

The aim of this study is to demonstrate the variable beam steering capability of ultrasonic phased array in exciting UGW modes at a chosen phase velocity. Ultimately, the idea would be to target individual high-order UGW modes.

2. THEORY

The analytical demonstration of the phase velocity excitation method is based on the improved comb excitation of Li and Rose [8]. They showed that specific modes can be amplified by the use of a phased array by adding a particular elementary delay t_0 between the elements. It creates a linear delay and the maximum amplitude of the generated harmonic modes then depends on:

$$\lambda = \frac{p}{m \pm f \cdot t_0} \tag{1}$$

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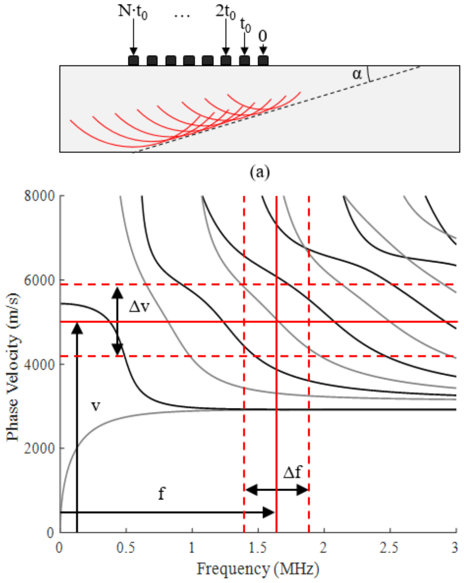
where ± represents the direction of propagation (the other variables are defined in the nomenclature). According to this equation, a comb transducer (having a pitch equal to the targeted wavelength), amplifies various zones in the phase velocity versus the frequency diagram due to the many possible integers m excited around the targeted zone. Using this method, it is therefore difficult to target a single mode.

The phase velocity excitation method proposed in this paper, and shown in Figure 1, is a specific case of the improved comb excitation. Indeed, in ultrasonic phased array probe the elementary pitch p is selected to be much smaller than λ. Thus, taking the positive +z direction of propagation as $\frac{p}{\lambda} \ll 1$, the value of m is also much smaller than 1, and the closest integer to m is 0. Therefore, with m=0, the excitation no longer depends on the frequency, and the amplified region corresponds to a single phase velocity:

$$v_{ph} = \frac{p}{t_0} \tag{2}$$

For a transducer array with a fixed elementary pitch p, a delay t_0 in emission can be selected between each element in order to excite the desired phase velocity. Figure 1 shows that the excited area of the dispersion curve can be controlled via f the center frequency of the input signal and Δf the bandwidth of the input signal. Then v corresponds to the targeted phase velocity and is controlled by the delay implemented between the elements. Δv corresponds to the phase velocity bandwidth and is related to the aperture of the probe. Therefore, flexible control of the transmitted modes is possible at high frequency-thickness products by adapting the elementary delay between the elements.



(a)

(b)

FIGURE 1: (a) PHASE VELOCITY EXCITATION METHOD USING AN ULTRASONIC PHASED ARRAY PROBE. (b) PHASE VELOCITY DISPERSION CURVES FOR A 4.76 MM ALUMINUM PLATE.

3. FINITE ELEMENT SIMULATIONS AND EXPERIMENTAL RESULTS

In order to assess the feasibility of the excitation method and verify the analytical predictions, 2-D finite element simulations were used. The model simulated a 64-element transducer by applying loads to nodes corresponding to the transducer elements, and the displacement field was monitored along a line to identify the propagating modes by performing a 2-D FFT [9]. Different excitation scenarios were modelled. They showed that the phase velocity excitation method is able to transmit a single high-order mode in a very narrow zone as shown in Figure 2 and the possibility of targeting the non-dispersive frequency region where the fundamental modes are propagating.

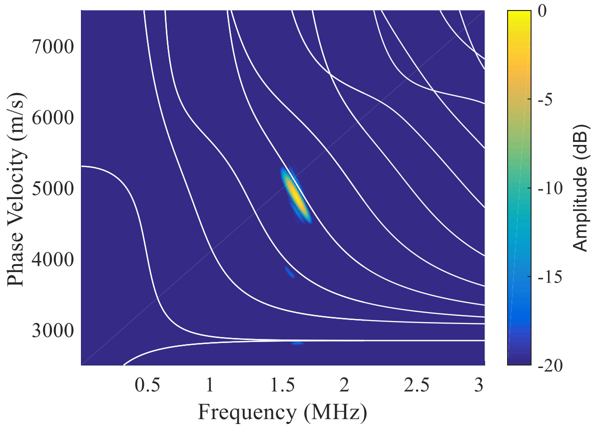


FIGURE 2: 2-D FOURIER TRANSFORM OF SIGNALS EXTRACTED FROM FE SIMULATION: 5000 M/S PHASE VELOCITY EXCITATION WITH A 20-CYCLE HANN-WINDOWED TONEBURST CENTERED AT 1.6 MHZ.

A 3-D finite element model was also used to quantify the beam directivity and divergence (Figure 3). The diffraction angle at -6 dB was approximately 20°.

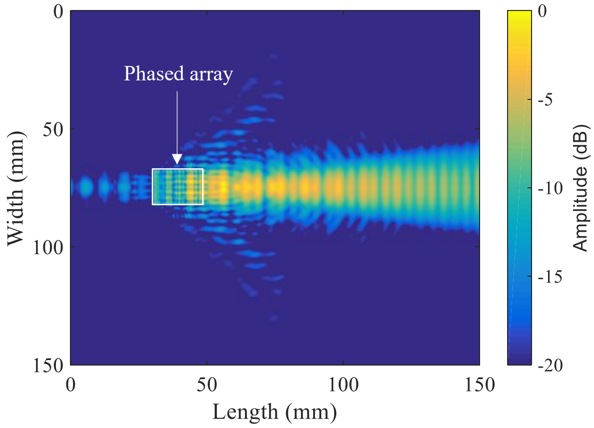


FIGURE 3: DIFFRACTION PATTERN OF THE PHASE VELOCITY EXCITATION METHOD USING A ULTRASONIC PHASED ARRAY PROBE OF 64 ELEMENTS, 19.2 MM APERTURE AND 15 MM PASSIVE APERTURE. THE EXCITATION WAS A 20-CYCLE HANN-WINDOWED TONEBURST CENTERED AT 1.6 MHZ.

In order to carry out comparisons with the simulations, experimental measurements were performed with the same plate thickness, material and excitation parameters. Signal generation was performed with a Verasonics Vantage 64 LE controlling an array of 64 elements centered at 1.5 MHz, with a 0.3 mm elementary pitch and 0.2 mm element interspace. The reception was carried out using a laser Doppler vibrometer (Polytec OFV-505, Polytec controller OFV-2570) and a high-definition 4-channel DSO9024H oscilloscope. The same excitation scenarios as the FE simulations were tested, and 2-D FFT were performed on the signals acquired. The experimental results are in striking accordance with the simulations (Figure 4). However, a few spots of energy can be observed outside the targeted zone. This is due to the assumption that all elements have identical performances. Nevertheless, because of fabrication and/or coupling deviations, the response of each element is slightly different, and as a result, the targeted region is not perfectly controlled, as is in the simulations.

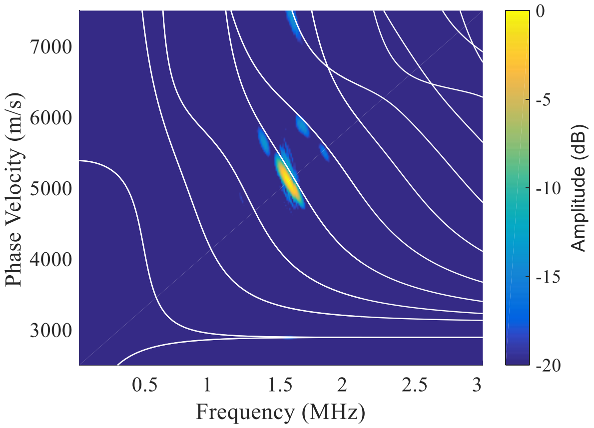


FIGURE 4: 2-D FOURIER TRANSFORM OF SIGNALS EXTRACTED FROM EXPERIMENTAL MEASUREMENTS: 5000 M/S PHASE VELOCITY EXCITATION WITH A 20-CYCLE HANN-WINDOWED TONEBURST CENTERED AT 1.6 MHZ.

4. CONCLUSION

The possibility of exciting specific regions in the phase velocity frequency diagram using an ultrasonic phased array probe was investigated. An analytical demonstration was conducted to determine the difference with the improved comb excitation: the elementary pitch must be small relative to the wavelength in the targeted zone for this technique to work well. The elementary delays equation necessary to transmit a specific phase velocity was provided. 2-D FE simulations were performed to verify the mode selectivity and showed good agreement with the analytical developments. 3-D FE simulations were used to quantify the beam directivity and divergence. Experimental measurements were performed with the same parameters as in the simulations and showed striking agreement with simulations, confirming that the method is able to transmit a single high-order mode by adapting the delays between the elements during the excitation.

REFERENCES

[1] Yu, X., Zuo, P., Xiao, J., and Fan, Z., 2019, "Detection of damage in welded joints using high order feature guided ultrasonic waves," Mechanical Systems and Signal Processing, 126, pp. 176-192.

[2] Travaglini, C., Bescond, C., Viens, M., and Belanger, P., 2017, "Feasibility of high frequency guided wave crack monitoring," Structural Health Monitoring, 16(4), pp. 418-427.

[3] Belanger, P., 2014, "High order shear horizontal modes for minimum remnant thickness," Ultrasonics, 54(4), pp. 1078-1087.

[4] Khalili, P., and Cawley, P., 2016, "Excitation of Single-Mode Lamb Waves at High-Frequency-Thickness Products," IEEE Trans Ultrason Ferroelectr Freq Control, 63(2), pp. 303-312.

[5] Rose, J. L., 2004, Ultrasonic waves in solid media, Cambridge University Press, Cambridge, UK.

[6] Monkhouse, R., Wilcox, P., and Cawley, P., 1997, "Flexible interdigital PVDF transducers for the generation of Lamb waves in structures," Ultrasonics, 35(7), pp. 489-498.

[7] Nguyen, K.-C. T., Le, L. H., Tran, T. N., Sacchi, M. D., and Lou, E. H., 2014, "Excitation of ultrasonic Lamb waves using a phased array system with two array probes: Phantom and in vitro bone studies," Ultrasonics, 54(5), pp. 1178-1185.

[8] Li, J., and Rose, J. L., 2001, "Implementing guided wave mode control by use of a phased transducer array," IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 48(3), pp. 761-768.

[9] Alleyne, D., and Cawley, P., 1991, "A two-dimensional Fourier transform method for the measurement of propagating multimode signals," The Journal of the Acoustical Society of America, 89(3), pp. 1159-1168.