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ULTRASONIC-BASED DETERMINATION OF IMMERSED PHASED ARRAY SETUP VARIABLES

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ABSTRACT

A method is presented for extracting the acoustic velocities and attenuation parameters of an immersed specimen as well as the precise probe location and orientation. The method only needs one set of data from a single location if the couplant velocity is known. The method is shown to be effective at both normal and oblique angles, with a single test case orientated at 13 degrees given. Both longitudinal and shear properties are determined for the copper specimen examined.

1. INTRODUCTION

Ultrasonic inspection using phased arrays in an immersed oblique configuration is common across numerous industries for weld inspection. Maximising the scanning resolution of this configuration relies on accurate specification of material properties for all mediums encountered. A basic example of this is determining the array location from signal responses extracted from ultrasonic data and specification of the water velocity. Inaccuracies in the resulting array location arise due to uncertainty in the water velocity and parameters such as instrument delay. The overall effect on the inspection is defocusing and mislocation of defect indications. In addition to identification of the probe location (standoff and orientation angle), water velocity and instrument delay, for accurate reconstruction within an isotropic specimen it is also necessary to have knowledge of the specimen's thickness and velocities (longitudinal and shear). These seven parameters are used to define the immersed experimental setup. Additionally, the specimen's attenuation parameters are desirable to aid understanding the detection capabilities of the inspection and are required for some imaging algorithms.

In established literature, there are various techniques for the estimation of ultrasonic velocity within a material, with these typically developed for a single transducer configuration and not updated to account for technological advances. Numerous pulse-echo approaches exist, typically requiring a normal incidence transducer configuration, perhaps in contact with the specimen material. More recent literature on assessing material or geometric properties has focused on extracting information when the signal is a superposition of multiple reflections. Ultrasonic spectroscopy has also been utilised [1] to measure the thickness, density and attenuation within thin layered specimens. This required both an oblique and normal incidence inspection.

In this work, a novel method to extract knowledge on the experimental configuration is presented. This method utilises the capabilities of a phased-array system to maximise the accuracy of the setup variables, whilst possessing minimal data requirements and robustness across a range of inspection regimens.

2. METHODOLOGY

The inspection configuration considered here is shown in figure 1. In the figure, six parameters employed to quantitatively describe the experimental setup are presented. The seventh, namely the instrument delay t_d, refers to the delay inherent within the transmit and receive instrumentation. It is assumed that the delay itself is uniform for all elements in the array. In figure 1, the fluid velocity, typically water, is denoted by v_w.

The probe location can be defined by its normal distance or standoff Z_s relative to a particular reference point on the array and its orientation angles. In the case of the 1D linear phased array utilised in this work, only a single orientation angle θ is required, together with the specification that the out-of-plane angle (along the Y-axis) is zero. Although only a 1D array is employed here, the method could be extended to 2D arrays, which would require measurement of the additional angle. The reference point used throughout is the centre of the element closest to the specimen. In this work, the specimen is assumed to be an isotropic block of uniform thickness d, with longitudinal and shear velocities denoted by v_L and v_s respectively.

To demonstrate the abilities of the method even in the presence of high grain noise, a copper sample is examined. The probe consisted of a 5MHz linear 1D phased array with 128 elements and pitch of 0.3mm. The thickness of the sample, $d = 26.1$mm, is measured prior to ultrasonic determination of the other variables.

The data collection procedure known as full matrix capture (FMC) [2] is utilised. For a phased-array with n elements, a single FMC consists of n^2 A-scans; with all possible combinations of transmitter and receiver elements from the phased array captured. Post data collection, the raw FMC dataset is filtered and Hilbert transformed in the frequency domain using a Gaussian window function centred at the phased array centre frequency and -40dB half-bandwidth of 90% relative to the centre frequency.

It should be emphasised that only a single FMC dataset is required for determination of the setup variables, although the

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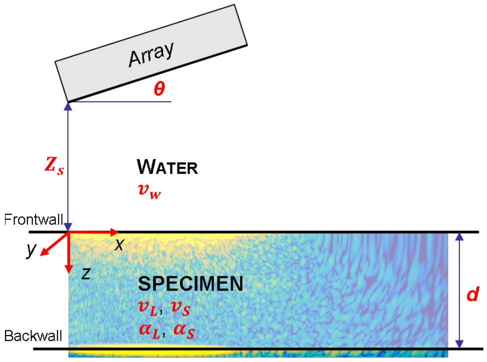


FIGURE 1: IMMERSED OBLIQUE INSPECTION SETUP

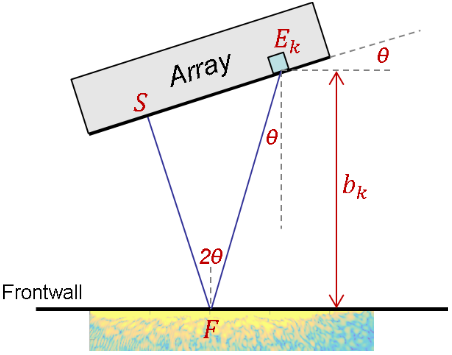


FIGURE 2: PATH FOR SECOND FRONTWALL

water velocity determination accuracy can be improved through use of a second FMC dataset as outlined presently. The variables are determined in a specific order, with the accuracy of each dependent upon the measurement accuracy of the preceding ones.

2.1 Water Velocity

Water velocity is the only parameter which requires data from more than a single array position if it is to be determined from the ultrasonic data. To achieve this, data obtained from two array locations with an accurately known difference in stand-off, Δz, is required. The time differences for the k^{th} element, Δt_k, between the pulse-echo frontwall signal responses within each FMC dataset are converted into a mean velocity measurement $v_w = \frac{1}{n}\sum_{k=1}^{n} 2\Delta z/\Delta t_k$

2.2 Instrument Delay and Probe Location

The instrument delay is determined through use of a simple analytical model of the pulse-echo ray path associated with the second reverberation of signals in the couplant between the array and the frontwall. In this model, the ray is emitted from the transmitting element, E_k, is reflected off the specimen frontwall, F, and back towards the array surface, S, before being reflected again and reversing to retrace its path back to the (now) receiving element (figure 2). With the assumption that the strongest response corresponds to the ray impacting the array surface at S at normal incidence, the travel time, $t_k^{(2)}$, can be determined for the k^{th} element's vertical displacement, b_k, using

$$t_k^{(2)} = 2b_k \frac{1+\cos(2\theta)}{v_w \cos(\theta)} + t_d \tag{1}$$

The experimental signal response corresponding to the first frontwall for the k^{th} element, t_k^{EXP}, consists of the true travel time, $t_k^{(1)}$, and the instrument delay, or $t_k^{(1)} = t_k^{EXP} - t_d$. The frontwall travel time, $t_k^{(1)}$, is then used to determine the probe location from the pulse-echo data by

$$\frac{1}{2}v_w(t_k^{EXP} - t_d) = Z_s + \sin^{-1}(\theta)h_k \tag{2}$$

where h_k denotes the elemental coordinates within the array. By specifying t_d, the Z_s and θ parameters are then determined via linear regression. These are then used to compute b_k, giving $t_k^{(2)}$ and the corresponding amplitudes from the A-scans. These element amplitudes are then averaged. Across the parameter space, the true t_d is one which corresponds to the maximum (absolute) mean amplitude.

2.3 Specimen Velocities

The specimen's longitudinal and shear velocities are determined using ultrasonic imaging. The total focusing method (TFM) imaging algorithm [3] utilises image-wide focusing in both transmission and reception using the linear delay-and-sum beamforming approach. The multi-view TFM method [4] utilises multiple ray paths and modes to generate the multiple views of the same region of interest via indirect beamforming. The TFM image for a given view is generated using the summation of the time-delayed data

$$I(\mathbf{r}) = \sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}\tilde{f}_{ij}(\tau_{ij}(\mathbf{r})) \tag{3}$$

where $\mathbf{r}$ represents the image pixel location, τ_{ij} is the time delay associated with the view, $\tilde{f}_{ij}$ the filtered, Hilbert-transformed FMC data with i denoting transmitter element, j the receiver element and a_{ij} represents an optional apodisation term, although no apodisation is applied in this work ($\mathbf{a} = 1$).

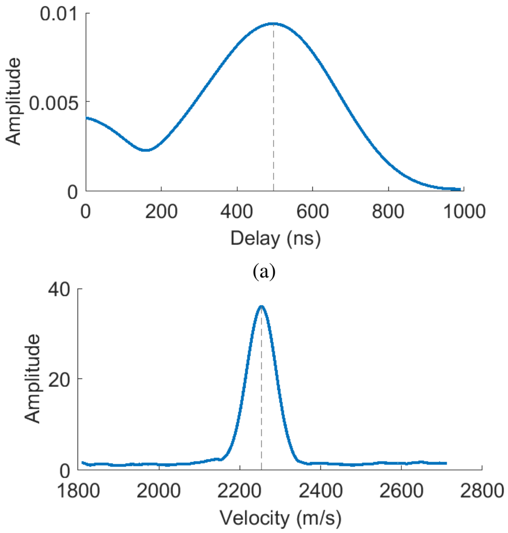
To calculate the v_L velocity, the direct L-L view (where the longitudinal mode is considered within the specimen, see [4] for further information on TFM view terminology) is used. The region of interest is a single line of pixels corresponding to the backwall depth, $z = d$. The image extent is limited to immediately below the array. Sweeping through the v_L parameter space, the true solution maximises the peak amplitude response within the single line of pixels identified above. Once determined, the v_T velocity is sought in the same manner, this time using the L-T view. The L-T view is preferred over that of the T-T view, as in that view, the corresponding signal is typically significantly weaker with a similar arrival time to that of a multiple skip L mode.

2.4 Specimen Attenuation Parameters

Attenuation is modelled using equation 4, where A_o denotes the initial signal amplitude, h the travelled distance (in metres) and α is the attenuation coefficient in Nepers/m. The attenuation coefficient is frequency and mode dependent, with α_L and α_T referring to the longitudinal and shear coefficients.

$$A = A_o e^{-\alpha h} \tag{4}$$

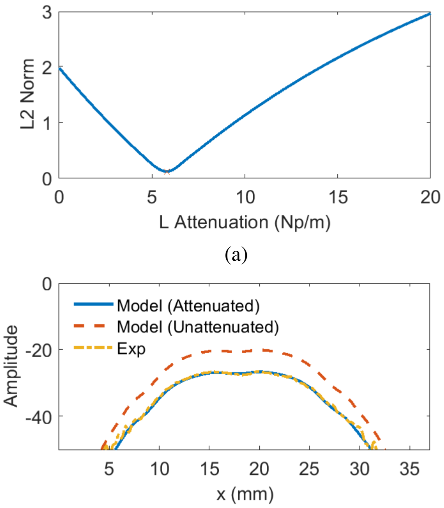
Determining the α_L coefficient is undertaken by examining the backwall amplitudes imaged within the L-L and L-LLL views



(a)

(b)

FIGURE 3: PARAMETER SPACE INVESTIGATION OF A) INSTRUMENT DELAY AND B) SHEAR VELOCITY



(a)

(b)

FIGURE 4: EXPERIMENTAL AND MODELLED DATA A) L_2NORM OF ERROR FOR L-LLL VIEW B) L-T TFM BACKWALL CROSS-SECTION

for the image extent used previously. In the latter view, the return path (LLL) is pixel $\rightarrow$ frontwall $\rightarrow$ backwall $\rightarrow$ frontwall $\rightarrow$ probe making a significantly longer travel path within the specimen compared to the L-L view. To isolate the impact of attenuation, and hence calculate α_L, a forward model [5] which accounts for beam spread and directivity is employed. The value of α_L is defined as the one which minimises the overall difference between the attenuated model and experimental image pixel intensities. This process is repeated with the backwall from the L-T view to get the α_T coefficient.

3. RESULTS

A single FMC dataset, with a sampling frequency of 25MHz was utilised to determine the instrument delay. To improve resolution, Lanczos interpolation was used during time signal extraction. Figure 3a shows the modulus of the averaged amplitudes as a function of t_d, with a maximum when $t_d = 496$ ns which is taken as the correct value. Prior setup using two FMC datasets separated by $\Delta z = 20$ mm had obtained a water velocity of 1473.3m/s. The probe standoff was 50.00 mm and angle of 13.12 degrees.

Figure 3b shows the peak image intensity in the L-T view as a function of the shear velocity v_T. From the figure, the maximum peak intensity corresponds to $v_T = 2252.8$ m/s within a clear, unambigious signal. Although not shown, the same is true for the v_L parameter, with the maximum peak intensity in the L-L view obtained at $v_L = 4685.0$ m/s. The accuracy of both velocity parameters is primarily based upon the accuracy of the thickness, d.

The L_2Norm was utilised to assess the discrepancies between the attenuated model and the experimental image intensities as shown in figure 4a for the L-LLL view, with the minimum at $\alpha_L = 5.8$ Np/m. Similarly, the L-T image intensities give $\alpha_T = 34.3$ Np/m. Figure 4b demonstrates how well the attenuated model is agreeing with the experimental intensities across the backwall.

4. CONCLUSION

The method outlined is capable of determining ultrasonically the experimental setup and the acoustic velocity and attenuation parameters of a specimen, with a high degree of accuracy. This can be achieved using only a single FMC dataset and no requirement for a specific orientation making it eminently suitable for the immersed oblique setup typical for weld inspection.

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REFERENCES

[1] A. I. Lavrentyev and S. I. Rokhlin. Determination of elastic moduli, density, attenuation, and thickness of a layer using ultrasonic spectroscopy at two angles. *Journal of the Acoustical Society of America*, 102:3467–3477, 1997.

[2] C. Holmes, B. W. Drinkwater, and P. D. Wilcox. Post-processing of the full matrix of ultrasonic transmit-receive array data for non-destructive evaluation. *NDT & E International*, 38(8):701–711, 2005.

[3] J. Zhang, B. W. Drinkwater, P. D. Wilcox, and A. J. Hunter. Defect detection using ultrasonic arrays: The multi-mode total focusing method. *NDT & E International*, 43(2):123 – 133, 2010.

[4] R. L. T. Bevan, J. Zhang, N. Budyn, A. J. Croxford, and P. D. Wilcox. Experimental quantification of noise in linear ultrasonic imaging. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, in press.

[5] N Budyn, R. L. T. Bevan, J. Zhang, A. J. Croxford, and P. D. Wilcox. A model for multi-view ultrasonic array inspection of small two-dimensional defects. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, in press.