Reference wavelets used for deconvolution of ultrasonic time-of-flight diffraction (ToFD) signals

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Abstract

One major disadvantage of ultrasonic time-of-flight diffraction (ToFD) technique is the weakness of echoes which are diffracted from crack tips. This shortcoming, to some extent, can be overcome by application of proper signal processing techniques. Deconvolution techniques have shown to be quite effective for this purpose. A deconvolution process needs to use a reference wavelet in order to extract the required information from the signal. Accordingly, one of the major challenges in using deconvolution techniques is the choice of the reference wavelet. This paper discusses some of the problems encountered in the selection of the reference wavelet and proposes methods to overcome these problems. The angle-dependent deconvolution technique is one of these methods in which the reference wavelet used for processing each part of the signal is different from wavelets used for other parts. The principles of this method are described and its effectiveness is demonstrated by both simulation and experiment.

Keywords: ultrasonic testing, time-of-flight diffraction (ToFD) technique, deconvolution, wavelet

Introduction

Ultrasonic testing (NDT) is an effective nondestructive method for evaluating the quality of materials and manufactured components. In an ultrasonic test, the signal received by the transducer contains considerable information about the specimen properties including the location and/or size of cracks and defects. Either amplitude or time-of-flight of the pulse is used for evaluating the crack size and/or location. Since the amplitude of the received signal could be affected by many parameters such as roughness, transparency, and orientation of a defect, it is more appropriate to use the time-of-flight diffraction (ToFD) technique to ensure higher accuracy in measurements.

The basic principle of ToFD is illustrated in figure (1). When an ultrasonic wave is incident on a crack-like defect, besides specular reflection of the wave from the crack, part of the wave is also diffracted at the tips of the crack. The diffracted energy spreads over a wide angle and can be picked up from almost anywhere along the surface of the specimen. ToFD is a very powerful ultrasonic technique which could be used for both detection and sizing of defects. Accurate sizing is accomplished by determining the location of the tips of the flaw by measurement of time-of-arrival of echoes bouncing off the flaw tips [1]. Since the emitted wave from an ultrasonic transducer diverges with respect to the central axis of the probe, in many ToFD tests, the whole thickness of the specimen can be inspected in one single shot. A crack tip diffracted echo can be easily identified as it lies between the lateral and backwall echoes.

Although crack tip diffracted echoes are useful for detection of flaws, the captured signals are sometimes hard to interpret due to the impulse response of the measurement system and electronic noise [2]. Moreover, overlapping echoes from closely spaced reflectors may further complicate the interpretation of results.

One major disadvantage of time-of-flight diffraction (ToFD) technique is the relative weakness of the crack tip diffracted echoes. This shortcoming, to some extent, can be improved by application of proper signal processing techniques. Deconvolution techniques have shown to be quite effective for

this purpose. To apply a deconvolution process to an ultrasonic signal, first a wavelet must be chosen as the reference signal. Since for a ToFD signal, the frequency spectrum of each echo can be different from other echoes, so it is very important to choose the proper wavelet for deconvolving the signal.

This paper discussed the problems encountered in the selection of the reference wavelet and proposes methods for overcoming these problems. Angle dependent deconvolution is introduced as good approach for avoiding the aforementioned problems. The principles of this method are described and its effectiveness is demonstrated by applying it to both simulated and experimental ultrasonic signals.
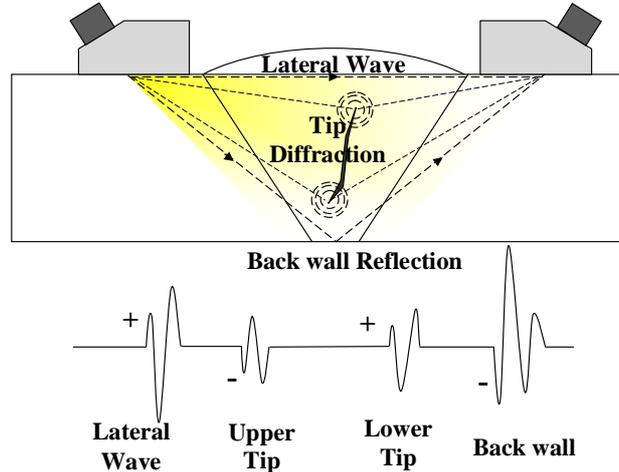

Figure 1- A typical ToFD set-up and the corresponding ToFD signal

Signal processing

In ultrasonic testing, the impulse response of the test specimen can be assumed to be a discrete sum of delta functions [3],

$$x(t) = \sum_j x_j \delta(t - t_j) \tag{1}$$

where x_j designates the amplitude of each echo. In practice, this impulse response is convolved with the impulse response of the measurement system, $h(t)$ which incorporates the effects of the transducer(s), ultrasonic instrument, coupling fluid, cables, and travel paths in the test material. Therefore, a measured ultrasonic signal, $y(t)$ can be modeled as the convolution of the measurement system impulse response, $h(t)$, with the test specimen impulse response, $x(t)$, plus noise, $n(t)$, that is,

$$y(t) = x(t) * h(t) + n(t) \tag{2}$$

where $*$ is the linear convolution operator.

Extraction of $x(t)$ from the measured signal, $y(t)$, improves the appearance and the time resolution of the signal by elimination of the adverse effects of the measurement system and noise. Several signal processing methods such as split-spectrum processing [4], Wigner-Ville Transformation [5], deconvolution methods [6], noise reduction by wavelets [7] etc. have already been examined for the enhancement of ultrasonic testing signals.

It has also been shown that the application of Wiener filtering followed by autoregressive spectral extrapolation can significantly improves the time resolution and signal-to-noise ratio of ultrasonic testing signals [6]. While the original technique is relatively prone to selection of processing parameters, a modified version of this method has shown to be quite robust and well suited for real applications [3].

The common practice in applying the Wiener filter to ultrasonic testing signals is to use one of the echoes of the received signal, for example the backwall echo, as the reference wavelet. Choosing the proper reference signal is very important in the deconvolution process. In all previous studies which

use this method, a certain reference wavelet is chosen for processing the ultrasonic testing signal. This could be the backwall echo or echo obtained from a known reflector. In ToFD technique, the probe has a wide beam spread and flaw echoes can be received from different parts of the beam. Since echoes arriving from different parts of the beam have different frequency spectra, use of one single reference signal for deconvolution is not suitable any more [8, 9].

Wave field of a circular flat transducer

Before considering the frequency spectra of the signals that could be obtained in ToFD tests, it is necessary to discuss the pressure field of a vibrating piston source. Tang [10] studied the radiation emitted by a circular flat transducer into an elastic half space to show the dependence of the frequency spectrum of each point of the wave field relative to its position. He used the Johnson's Green Function for numerical calculation of the integral for an arbitrary point in the far field of a solid medium.
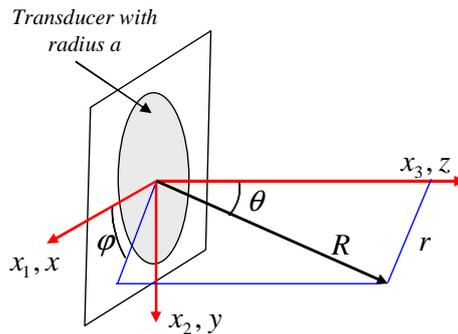

Figure 2- Representation of a circular transducer

Figure (2) shows an example of the configuration and coordinate system used in these calculations. In a circular transducer, the ultrasonic beam is radiated symmetrically, therefore the dependency on φ can be neglected and the wave field can be assumed to be a function of R and θ. For a uniformly excited transducer, the radial displacement is expressed as [9],

$$u_R = \frac{a^2 \sigma_{zz}}{4\pi\mu} \frac{\exp(-ik_\alpha R)}{R} [\frac{2J_1(k_\alpha a \sin\theta)}{k_\alpha a \sin\theta}]$$

$$\times \frac{(\beta/\alpha)^2 \cos\theta[1-2(\beta/\alpha)^2 \sin^2\theta]}{[1-2(\beta/\alpha)^2 \sin^2\theta]^2 + 4(\beta/\alpha)^3 \sin^2\theta \cos\theta[1-(\beta/\alpha)^2 \sin^2\theta]^{1/2}}$$

(3)

where α is pressure wave velocity, β is the shear wave velocity, k_α is the compression wave number and σ_{zz} is the stress at the surface of the transducer. Since σ_{zz} is unknown, the displacement is normalized with respect to its value at $\theta = 0$.

Divergence of the emitted beams at different frequencies in a polar coordinate system is shown in figure (3) where with the increase of frequency, the angle at which the first cancellation point occur decreases. In other words, higher frequencies diverge less than lower ones. The cancellation points are caused by destructive interference of waves originating from different points on the transducer surface [9]. Each emitted ray from the transducer includes a spectrum of frequencies, therefore, rays which travel at different angles with respect to the central axis of the transducer have different frequency spectra and consequently echoes reflecting back from these rays have different shapes.
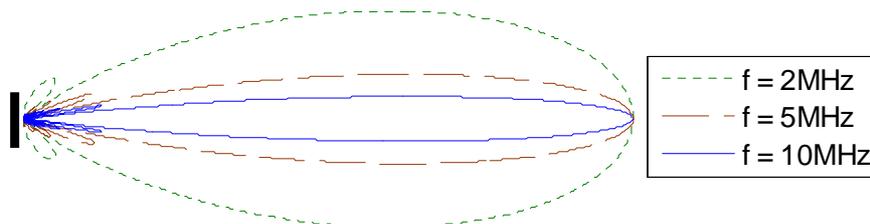
Figure 3- Wave distribution from a flat transducer is a function of frequency

To explain this phenomenon, we can assume an aluminum half cylinder shown in figure (4). A transmitting ultrasonic transducer is placed at the center of half cylinder, and an identical receiving transducer can swipe the outer surface of cylinder along the periphery of the half cylinder. By assuming a Gaussian impulse response for the measurement system, the captured signal at different angles will be as shown in figure (5).
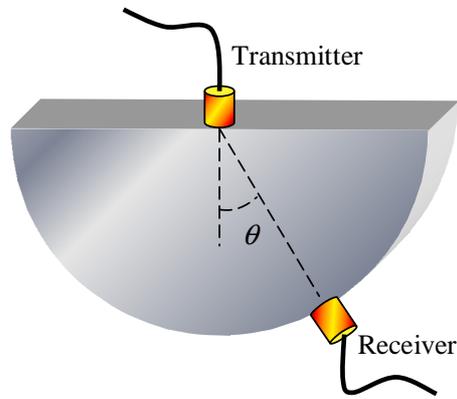

Figure 4- Configuration of setup for collecting signals at different angles
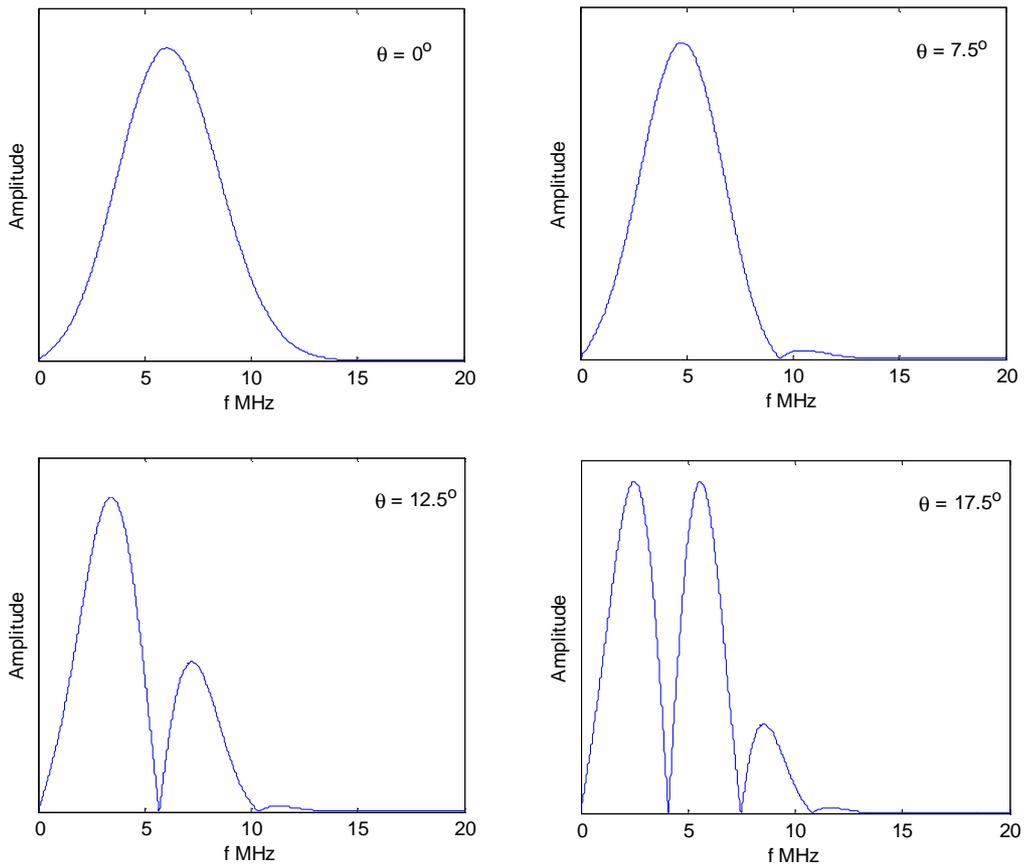

Figure 5- Comparing Frequency spectrum of different angles of aluminum half cylinder of figure (4)

Considering the wide beam spread of ToFD transducers, echoes which return from different angles have different frequency contents and consequently different shapes. Therefore, it would not be appropriate to use a fixed reference signal for deconvolving echoes which appear in different parts of

the ToFD signal. The following experiment was set up to show the change of the frequency spectra at different parts of the ultrasonic beam (Figure 6). In this experiment, an angle-beam probe is used as the transmitter. A normal-beam probe receives the ultrasonic signal on the side wall of the specimen. The transducers are identical with central frequencies of 10 MHz and diameters of 0.25 in.
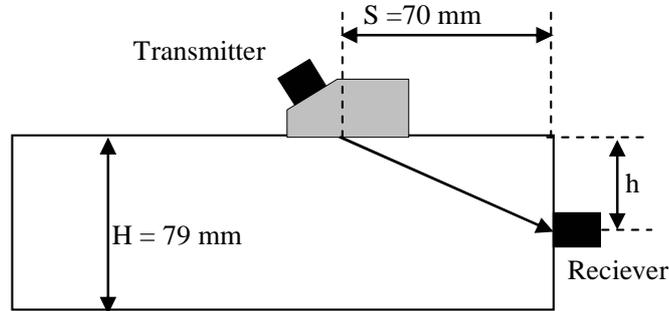

Figure 6- Experimental set-up for measuring the variation of beam shape

The frequency spectra of the signals received at different depths are shown in figure (7).
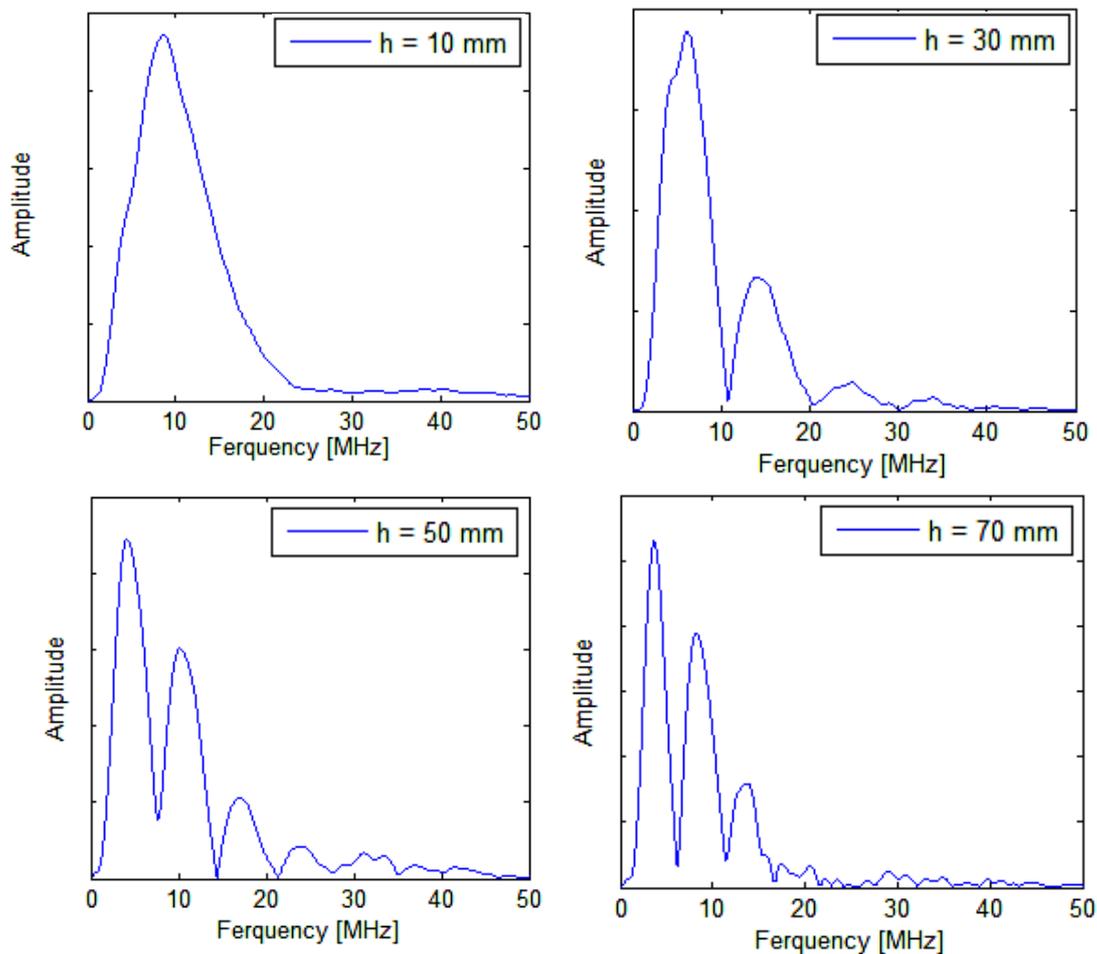

Figure 7- Frequency spectra of received echoes at different depths

As illustrated in figure (7), echoes received at different depths have different frequency spectra. However, ToFD signals can be modeled as nonstationary or time-varying signals. So it is necessary to provide a suitable signal processing method to improve the time resolution of each echo. The

angle-dependent deconvolution technique is one of these methods in which the reference wavelet used for each part of the signal is chosen to be different from wavelets used for other parts.

Angle dependent deconvolution

To carry out a deconvolution process, first a reference wavelet should be chosen. For ToFD signals, this reference signal could be the lateral wave or backwall echo. However, since these two echoes have completely different frequency spectra and consequently different shapes, using each echo as the reference wavelet lead to a different result. Apparently, each echo would be a more suitable reference wavelet for flaws which lie in the vicinity of the location where the reference wavelet is coming from.

To account for difference in the shape and frequency content of the echoes, one can use different reference wavelets for processing echoes which come from different parts of the specimen. For this purpose, we need to have a library of reference signals to be used for various parts of the returned signal. Using this library, each echo in the ToFD A-scan signal can be deconvolved by an angle-dependent deconvolution process.

To apply the angle-dependent deconvolution process, the ToFD signal is divided into a number of windows and each window is deconvolved by its corresponding reference wavelet. The processed windows are then put together by applying an inverse Fourier transform in time domain.

Results

a) Simulated signal

In the signal shown in figure (8a), we consider two echoes each having a different shape. In figure (8b) and 8(c), the signal shown in figure (8a) is processed with reference wavelets which resemble the first and second echo, respectively. We observe that, when the first echo is used in the deconvolution process, figure (8b), the resolution of this echo has noticeably improved. The same applies to figure (8c), where the resolution of the second echo has become much better than the first echo. Therefore, it can be concluded that for improving the quality of the whole signal, one needs to use more than one reference wavelet. In real situations, it means that in the calibration process, we have to measure echoes form a number of reflectors lying at different depths of the calibration block. Each of these reference wavelets should then be used for processing a certain section of the signal.
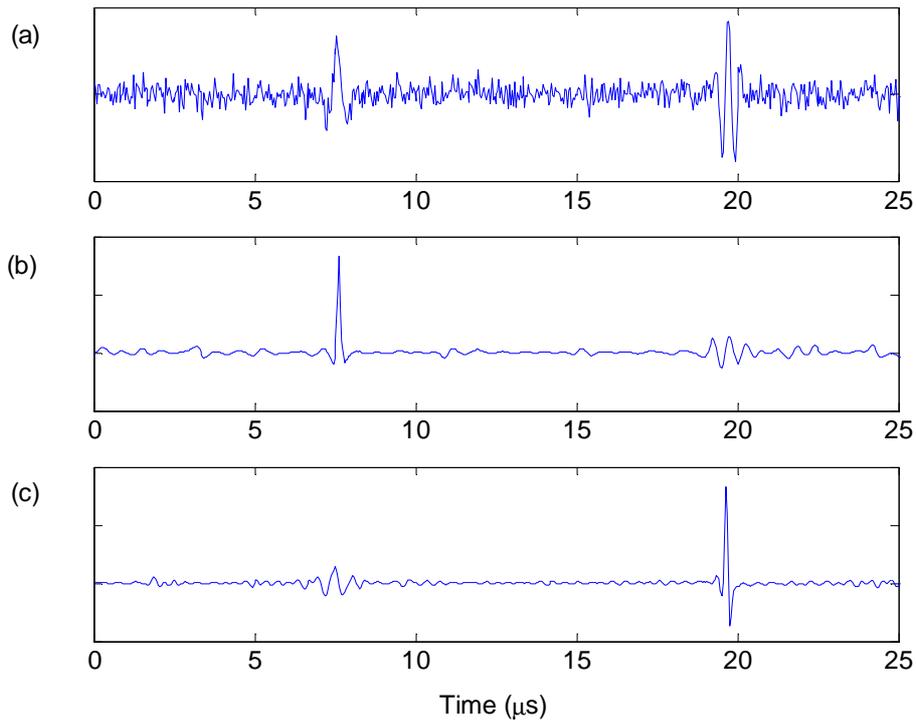
Figure 8- (a) Ultrasonic testing signal with two echoes with different pulse shapes, (b) signal processed by choosing the first echo as reference, (c) signal processed by choosing the second echo as reference.

b) Experiment

To demonstrate the effect of the choice of the reference wavelet an experimentally measured ToFD signal is processed by the deconvolution technique in this section. The ToFD signal is chosen from a taken from a single V-groove plate weld of 12 mm thickness. A centerline crack is implanted in the weld as shown in the B-scan image of the weld as shown in figure (9). Two identical longitudinal angle-beam probes with center frequencies of 8 MHz and diameters of 3 mm were used in a configuration similar to that shown in figure (1). The raw ToFD signal collected from the crack is shown in figure (10a). In figure (10b), the raw signal is processed by using the lateral echo as the reference wavelet and in figure (10c), the backwall echo is used for this purpose. The raw signal was then divided into two different sections. The first section was deconvolved by the lateral echo and the second section was deconvolved by the backwall echo. These two processed sections were then combined together by applying an inverse Fourier transform in the time domain as shown in figure (10d). This procedure has improved the time resolution and signal-to-noise ratio of the ToFD signal quite noticeably. If required, the number of windows can be increased to cover a wider range of wavelet references.
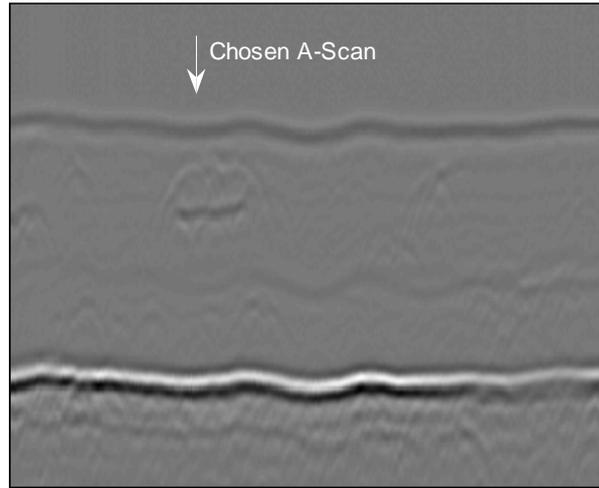
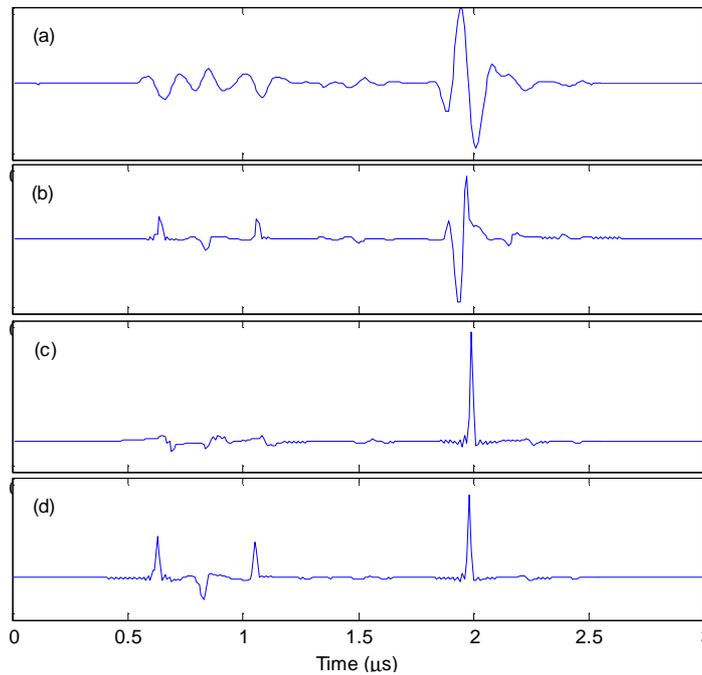**Figure 9- ToFD B-scan of a single V-groove plate weld**

Time (μs)

Figure 9- a) Raw ToFD signal, (b) deconvolution with lateral wave as reference wavelet, (c) deconvolution with backwall echo as reference wavelet, and (d) angle-dependent deconvolution

Conclusion

A signal processing technique which incorporates a combination of Wiener filtering and autoregressive spectral extrapolation has shown to be quite effective in improving the time resolution and signal-to-noise ratio of ultrasonic signals. Application of the deconvolution process is based on the choice of a reference wavelet. In some applications, including ultrasonic time-of-flight diffraction (ToFD) technique, due to the varying nature of the echoes that arrive from different directions of the beam, use of one single reference wavelet would not produce acceptable results. Therefore, it is necessary to use different wavelets for deconvolving different parts of the signal. The angle dependent deconvolution method which is proposed in this paper can overcome this problem. In this method, the signal is broken into a number of windows and each window is processed separately. Signals in the processed windows are then put together by applying an inverse Fourier transform in the time domain. Using both simulated and experimental ToFD signals, the effectiveness of the proposed method in improving the ultrasonic signals was demonstrated.

8

References

[1] J. P. Charlesworth, J. A. G Temple, "Engineering Applications of Ultrasonic Time-of-Flight Diffraction", Great Yarmouth: Galliard, 1989.

[2] J. Chen, Y. Shi, S. Shi, "Noise analysis of digital ultrasonic nondestructive evaluation system", International Journal of Pressure Vessels and Piping, 76, pp. 619–630, 1999.

[3] F. Honarvar, H. Sheikhzadeh, M. Moles, A.N. Sinclair, "Improving the Time-Resolution and Signal-to-Noise Ratio of Ultrasonic NDE Signals", Ultrasonics, 41, pp. 755-763, 2004.

[4] V. L. Newhouse, N. M. Bilgutay, J. Saniie, and E. S. Furgason, " Flaw-to-Grain Echo Enhancement by Split-Spectrum Processing", Ultrasonics, 59, 1982

[5] M.A.R. Hernandez, "Ultrasonic non-destructive evaluation with spatial combination of Wigner-Ville Transformation", NDT & E International, 36, pp. 441-445, 2003.

[6] S.K. Sin, C.H. Chen, "A Comparison of Deconvolution Techniques for the Ultrasonic Nondestructive Evaluation of Materials", IEEE Trans., 1(1), pp. 3-10, 1992.

[7] S. S. Peng, Q.P. Wen, "Wavelet Based Noise Suppression Technique and its Application to Ultrasonic Flaw Detection", Ultrasonics, 44, pp. 188-193, 2006.

[8] L. W. Schemerr, "Fundamentals of Ultrasonic Nondestructive Evaluation", Plenum Press, pp. 3-13, 1998.

[9] F. Farzbod, "Enhancement of Ultrasonic B-scan Images", M.A.Sc. Thesis, University of Toronto, 2003.

[10] X.M. Tang, M.N. Toksoz, C.H. Cheng, "Radiation patterns of compressional and shear transducers at the surface of an elastic half-space", JASA, Vol. 95, pp. 71-76, 1994.