

SIGNAL PROCESSING FOR UNDERCLAD CRACK SIZING

R. Shankar, S. S. Lane, T. J. Paradiso
Tetra Tech, 1911 Ft. Myer Drive, Arlington, VA 22209

J. R. Quinn
EPRI, 3412 Hillview Ave., Palo Alto, CA 94303

Underclad cracks in the beltline welds of some pressurized water reactors have been implicated by analysis as a potential safety issue. This issue is known as Pressurized Thermal Shock (PTS) in which a complex sequence of events can, in a very limited number of vessels, cause a small underclad crack (6 mm minimum calculated depth) grow to an unacceptable size. A cost effective countermeasure to the PTS issue is the development of a highly reliable inspection technique for underclad cracks.

Although the reliability levels required to effect the PTS issue are high, a successful demonstration has been achieved. The question remains as to the sizing of cracks and their proper classification. This paper addresses these items.

Pressurized water reactor vessels are made of a base ferritic material with a stainless steel weld clad layer of about 6 mm thickness deposited on the inner surface. Several processes have been used at various times and locations on the vessels to deposit the clad. Three commonly used techniques are illustrated in Figure 1. The underclad cracks start at the clad/base metal interface and proceed down into the base material. They are usually perpendicular to the surface and oriented either parallel or perpendicular to the clad lay direction.

The clad surface finish, clad metal grain structure and clad/base metal interface irregularities govern the propagation of ultrasound into the underclad region. These features may introduce inaccuracies into sizing information.

A number of test blocks containing a variety of known sizes and orientations of mechanical fatigue cracks and notches in the top surface of the base metal had been previously constructed. These blocks were overlaid with clad by various representative processes and at a number of thicknesses and surface finishes. Several of these specimens were used to develop sizing algorithms while others were used for evaluation purposes. It may be of some interest to note that flaw signal to noise ratios varied between 13 and 20 db in the base metal and 8 to 17 db in the clad.

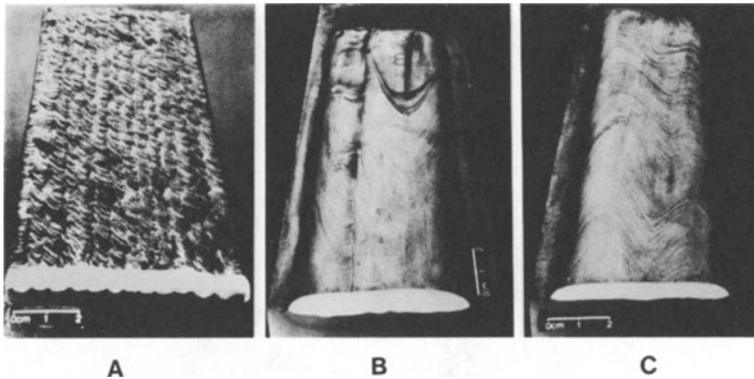


Fig. 1. Cladding types commonly used in PWR vessels: A) manual, shielding metal arc; B) automatic, 3 wire, submerged arc; C) automatic, strip electrode, submerged arc.

Data were collected with a minicomputer (LSI 11-02), a transient recorder (Biomation 8100) and anti-aliasing filter arranged as shown in Figure 2. The transducer was a 60 degree dual element longitudinal unit of 2.0 MHz peak frequency. RF waveforms were recorded on scan lines perpendicular to the crack plane at intervals of 0.25 mm between data collection points. B-scan displays were generated from these data. Representative displays appear in Figure 3.

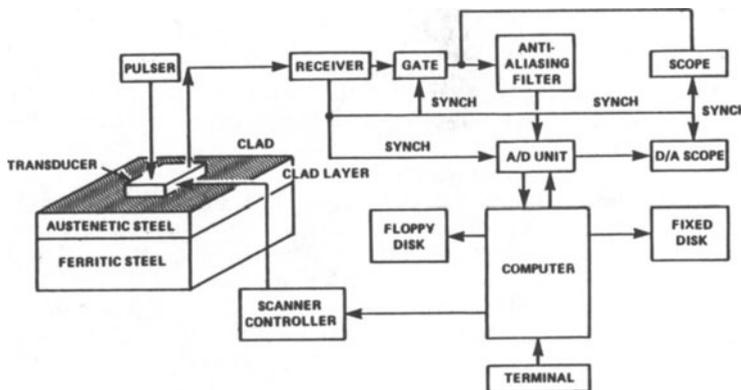


Fig. 2. Schematic of experimental set-up

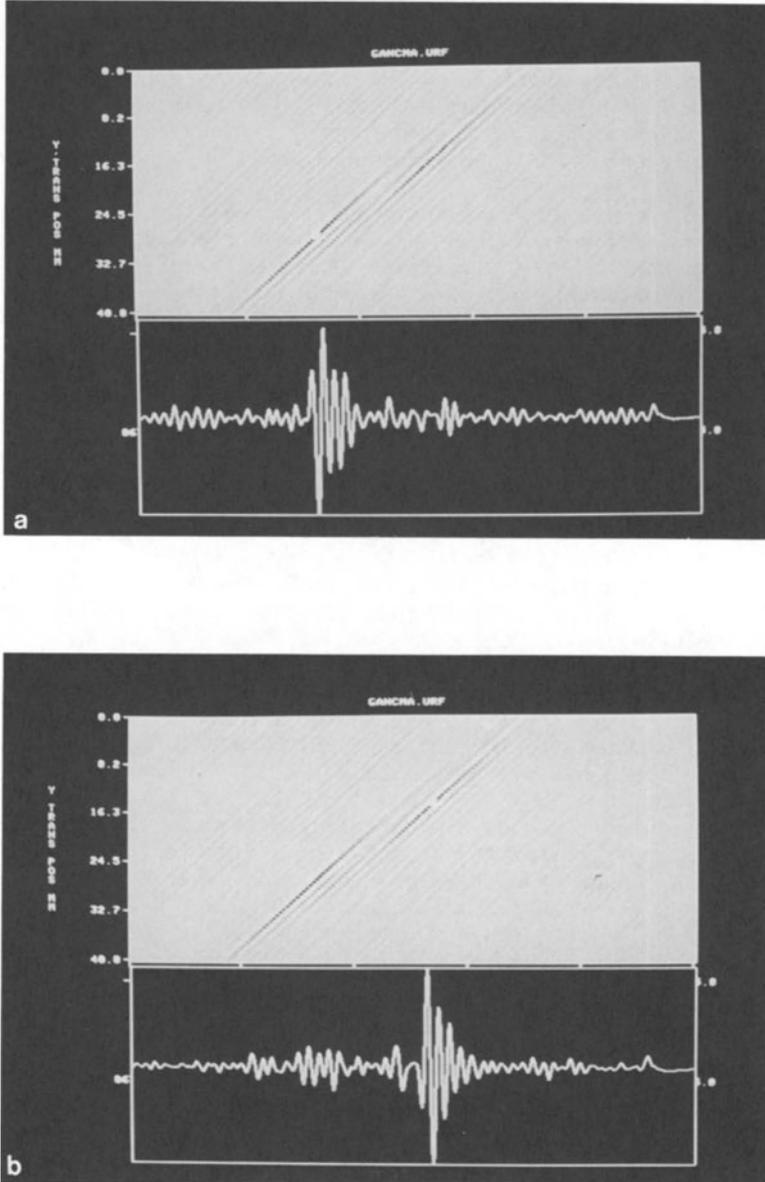


Fig. 3. Typical B-scan images with individual A-scans selected at indicated cursor positions

- a. Upper tip
- b. Lower tip

In the figure, the upper and lower crack tip diffraction signals are illustrated. The traces are A-scans corresponding to the cursor position. Note that these data indicate a possible phase reversal between the upper and lower tip (1). This feature is of importance in correctly identifying and sizing cracks.

Crack sizing is accomplished by geometric techniques in which the velocity (v) and angle of propagation (θ) of the ultrasound diffracted by the tip give the depth by the expression $vt \cos(\theta)$. The difficulties arise in that θ is not well known due to the surface and interface irregularities and that the velocity changes slightly between the clad and base material with accompanying refraction phenomena. The latter refraction problem will not be treated here.

Three techniques were developed: the calibration curve, phase velocity and epicentral. The calibration curve technique is based on the assumption that the peak amplitude of the diffracted signal is always at the same beam angle. A plot of arrival time of peak amplitude versus depth of known reflectors is thus a straight line with slope $v \cos(\theta)$. The clad surface irregularities cause this assumption to be questionable.

In the phase velocity method, the change in peak arrival time with transducer position is found from the echo dynamic curve and related to beam angle. This is done by the relationship that the phase velocity is equal to the propagation velocity divided by the $\sin(\theta)$. The phase velocity is obtained by fitting a straight line to the echo dynamic curve. The slope of this line is the phase velocity.

Velocity in the clad was taken as 5.8 km/sec. and a value of 5.5 was used in the base metal. The upper tip depth calculations used the former value exclusively.

In the epicentral, the echo dynamic curve is fit by least squares methods with an analytic expression and the slope is calculated. This allows for a more exact measurement of θ than by the straight line as used in the phase velocity method.

These three techniques were tried on two test blocks. The root mean square (RMS) errors for the techniques on eighteen flaws were 2.0 mm, 1.3 mm, and 1.3 mm respectively. In a subsequent blind test on a third evaluation block containing fourteen flaws under difficult clad, the RMS error for the calibration curve technique was 2.9 mm and for the phase velocity and epicentral techniques were 3.7 mm.

This apparent degradation of crack sizing accuracy on the more difficult clad presented a concern for application of the technique to actual reactor vessels. A means of separating accurate sizing data from that of poorer quality was clearly needed.

Two measures of data quality were developed, spectral analysis and deconvolution. The former technique utilized the Fourier transform of the tip diffraction echo dynamic curve (Figure 3). A window about the actual tip signal defined the portion of the data in each A-scan that was to be transformed. The magnitude and phase components of the resulting complex frequency spectrum are then displayed separately. These images are displayed in Figure 4a and b for a crack that was accurately sized.

Similar plots for a crack which was poorly sized are displayed in Figure 5a and b. By comparison, the magnitude display for "good" quality data appears to have a higher degree of mirror symmetry than for the "poor" quality data. In addition, the phase reversal between the upper and lower tip is clearly evident in the phase display in 4b and much less

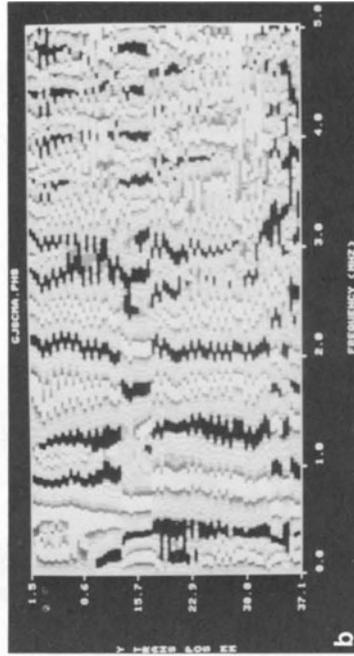
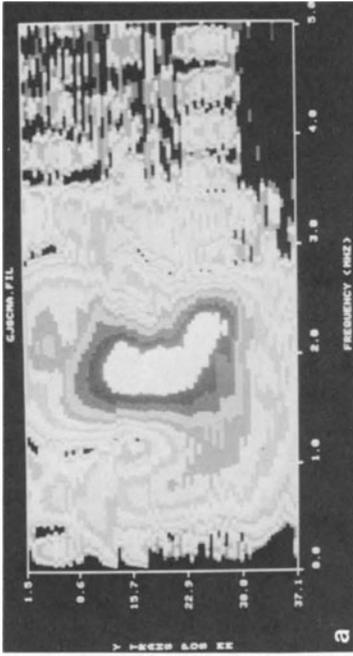


Fig. 4. Fourier B-scan images of a "well" sized crack

- a. Magnitude
- b. Phase

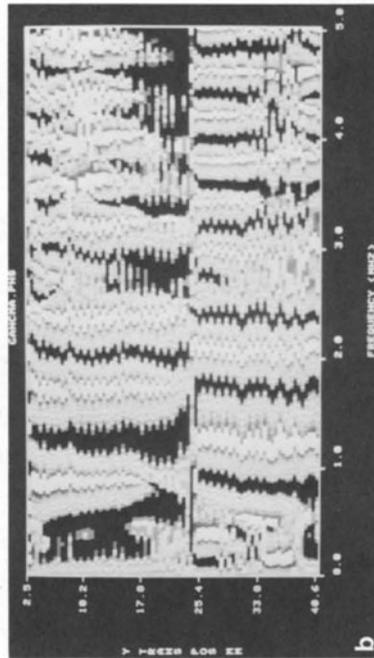
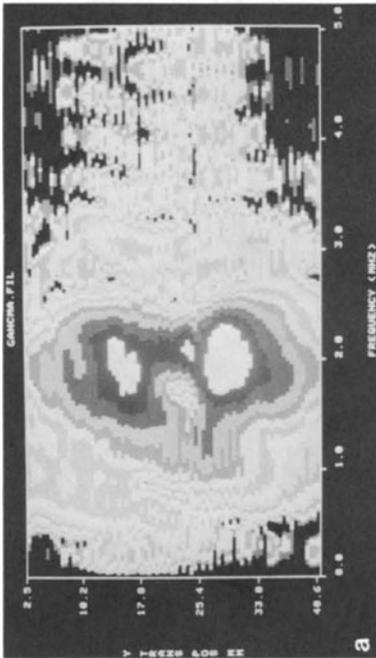


Fig. 5. Fourier B-scan images of a "poorly" sized crack

- a. Magnitude
- b. Phase

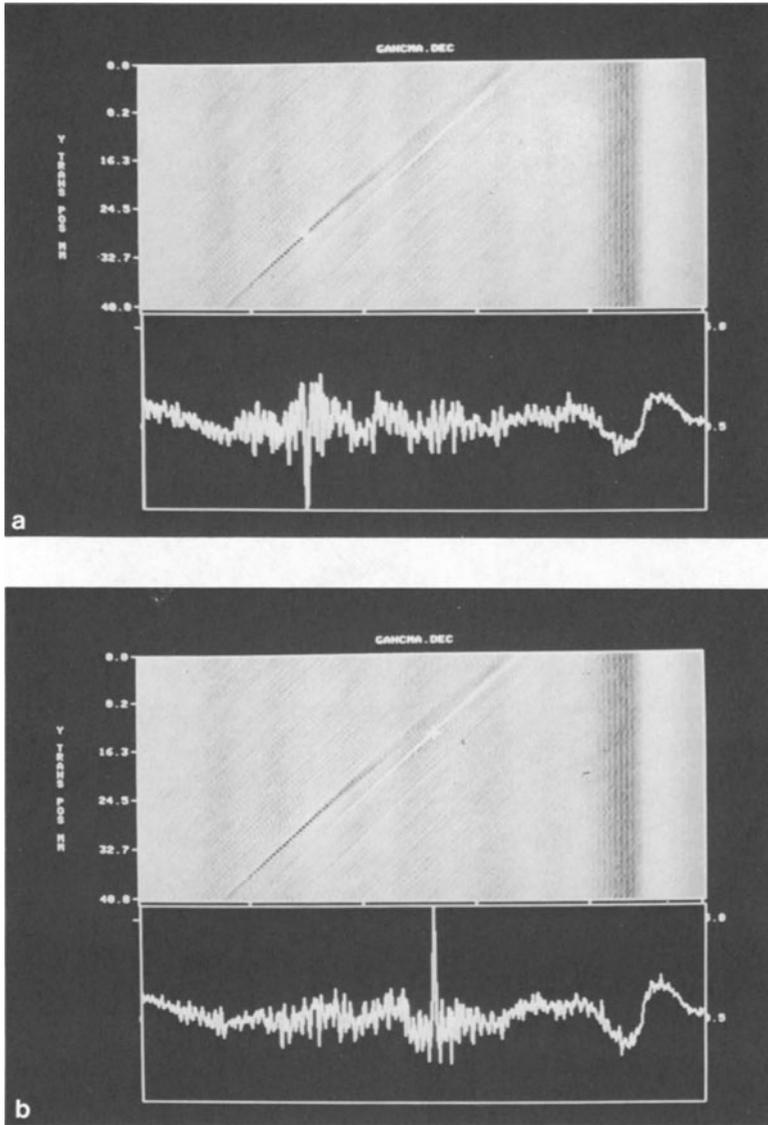


Fig. 6. B-scan images as in 3 after deconvolution

- a. Upper tip
- b. Lower tip

so in 5b. These features are the qualitative discriminants used to separate data on the basis of quality that were derived by spectral analysis.

The location of the tip diffraction signal extrema is made less accurate by bandwidth limitations of the measurement. A positional inaccuracy of one cycle at 2.0 MHz could introduce an error of 1.5 mm. Deconvolution of signal waveforms may be an appropriate procedure to avoid these inaccuracies, by effectively increasing the bandwidth of the signal in analysis. The technique used is basically a Wiener filter as described in reference 2. The deconvolved B-scans are displayed for an accurately sized crack in Figure 6. The A-scan traces are sharp, approximately of equal signal to noise ratio for the two tips and opposite in phase. Data from poorly sized cracks were not found to display clean, phase reversed peaks of nearly equal signal to noise ratio.

These two criteria were applied to the data taken on the third test block, the evaluation block. Six flaws were judged to have satisfactory spectra displays and/or deconvolved traces. The error for this group was 1.7 mm while the others, the unsatisfactory group, the error was 3.6 mm. This should be compared to the previously quoted RMS error of 2.9 mm.

The difference between the two groups is not clear. As a first hypothesis, the unsatisfactory group may represent tip signals which were distorted or interfered with by variations in the clad material.

The techniques developed in this work provide a means of sizing underclad cracks and quality control methods for assessing the accuracy of the data. Additionally, the phase reversal characteristic in the data is a strong indication of the nature of the signal source. That is, cracks are clearly separable from two isolated inclusions on the basis of observed phase reversal. These methods have been implemented on a computer and appear to provide an accurate, rapid method to discriminate and size underclad cracks.

REFERENCES

1. J. A. G. Temple, "Time of Flight Inspection: Theory". Paper presented at the Specialist Meeting on Defect Detection and Sizing. Ispra, Italy, May 3-6, 1983.
2. A. C. Kak and K. A. Dines, "Signal Processing of Broadband Pulsed Ultrasound", IEEE Trans. on Bio. Eng., Vol. BME-25, No. 4, pp 321, July 1978.

DISCUSSION

From the Floor: These results, are they mainly on the hand-clad samples?

J.R. Quinn: That's where we ran into trouble with our tip diffracted measurements, was on the hand-clad materials.

From the Floor: Were these all the hand-clad materials?

J.R. Quinn: The latter results. The initial results where we drove the error down to 1.5 millimeters was on three-wire cladding. But when we went to the thick manual clad, our error went up to 2.9 millimeters and we decided we had to somehow sort the good data from the bad data, and that's what motivated the use of the deconvolution techniques.

From the Floor: Then it was not ground?

J.R. Quinn: It was ground to a certain extent because all reactor vessels at the shop have to be ground in order to provide for die penetrant testing.

From the Floor: One should forget the hand-cladding? Your experience is that after having ground this material, you can forget it was hand-clad?

J.R. Quinn: No, that's not true, because the grinding is done by hand and it's highly irregular. There's still a log of long wavelength, low-frequency oscillation in the surface that still cause you a lot of problems.

From the Floor: Another question. Were these real underclad cracks or were these artificial defects?

J.R. Quinn: Most of them were mechanical fatigue cracks that were fatigued in bar samples that were then welded into ferric plates on top of which the clad was applied. There were also a number of machined EDM notches and sawcuts. We observed no difference between the technique as it was applied to mechanical fatigue cracks, EDM notches and sawcuts.

From the Floor: Were these low-cycle fatigue cracks?

J.R. Quinn: I think it was high-cycle fatigue.

From the Floor: I think that's the difference. One must expect in reality a low-cycle fatigue. We have recently done a very similar trial on machine-clad and hand-clad samples. I do not report here all these results, but I can assure you when I say that the results are quite similar. There's a difference in high-cycle fatigue and low-cycle fatigue.

J.R. Quinn: Oh, yes, there is.

From the Floor: And low-cycle fatigue is what one has to expect.

J.R. Quinn: Yes. I'm not sure that the difference in the interaction of the acoustic waves from the high-cycle fatigue crack versus a low-cycle fatigue crack is in fact the dominant issue here. I think it's the surface clad preparation that's the dominant issue.

From the Floor: It is not the routine method in this country to do this type of testing?

J.R. Quinn: It's not routine but we are trying to implement it in the field.

From the Floor: I see. Thank you.

G.J. Gruber (Southwest Research Institute): When you showed us those deconvolved tip diffracted waves, the lower and the upper extremities, there must have been times when you could see both pulses on the screen simultaneously?

J.R. Quinn: Yes.

G.J. Cruber: And the separation, of course, is constant. If you lift off the separations, you might get a little bit more accurate results in spite of some rough manual cladding things. If you use the beams focusing sideways, like a particle beam.

J.R. Quinn: I'm sure that may be possible.