ULTRASONIC WELD DEFECT SIZING USING THE SYNTHETIC APERTURE FOCUSING TECHNIQUE

Stuart Kramer
NDE Centre
Ontario Hydro Research Division
800 Kipling Avenue
Toronto, Ontario
Canada M8Z 5S4

INTRODUCTION

The synthetic aperture focusing technique (SAFT) has been shown to increase lateral resolution of appropriately acquired B-scan images [1,2,3,4]. The requirements of very accurate transducer position information and a well understood divergent ultrasonic beam can make it difficult to incorporate the technique into conventional inspections or to use it on previously acquired data. By using a reference reflector and an echo locus matching procedure it is possible to ease the latter requirement so that data acquired using conventional focused or flat transducers can be enhanced using the SAFT process.

THE BASIC SAFT PROCESS

The synthetic aperture focusing technique is, in its common implementation, a simple process of shifting and summing adjacent waveforms based on a knowledge of the system geometry [1]. The basic process requires a broad ultrasonic beam in the test material such that reflections will be received from a point reflector for a number of transducer positions (Figure 1). The longer path to and from the reflector for a laterally offset position (position b in Fig. 1) results in a delayed arrival of the echo. Thus, the family of received echoes forms the locus of a hyperbola, the curvature of which is directly related to the defect depth. If we are considering a potential reflector at a particular depth, we will expect to see a hyperbola of reflections with its apex directly above the reflector. By shifting the waveforms adjacent to the apex by an amount calculated from the geometry (i.e. by the shape of the expected hyperbola) all the echoes will line up if there was indeed a reflector at the expected position. If there was no reflector at the position in question, any echoes will not line up when shifted in this manner. Adding the shifted echoes will produce a coherent summation with a large amplitude resulting from constructive interference when the echoes are aligned, and a small amplitude when not aligned. Replacing each waveform in the acquired data set with the corresponding coherent summation results in a more highly resolved image (Figure 2).
Fig. 1. Family of echoes acquired as a transducer (focused at the water/metal interface) is scanned across a point reflector.

Fig. 2. Coherent summation for positions a and b for the data set shown in Fig. 1.

This shifting and coherent summation of entire waveforms effectively focuses the data at one particular depth and can be performed directly in the time domain or implemented with a simple linear phase-shift filter performed on the two dimensional angular spectrum of plane waves of the data set [3].

Extending the concept somewhat further, if we regard every point in the received data set as the potential apex of a hyperbola of reflections we can coherently sum the values along each hyperbola and
effectively focus at all depths at once. The improvement in overall resolution comes at the cost of an increased computational burden and a distortion of the resultant pulse shape.

Accurate calculation of transit time hyperbolae is crucial to the correct functioning of SAFT algorithms. For the simple case of normal beam incidence, the difference in transit time for lateral positions is given by

$$\Delta t = \frac{2}{c} \sqrt{x^2 + d^2 - d}$$

(1)

where $c$ is the longitudinal stress wave velocity in the material, $x$ is the lateral position and $d$ is the depth in the material. Detailed descriptions of SAFT algorithms have been given elsewhere [3,4].

MANWAY WELD APPLICATION

One current application of the SAFT technique is the accurate sizing and monitoring of known defects in a nuclear generating station boiler manway weld. Limited access and an unusual part geometry have made conventional inspection techniques difficult and only partially successful. The fundamental problem has been the difficulty in achieving an adequately focused ultrasonic beam at the required material depth (90 mm in steel through a curved interface). Custom designed dual-lensed contact transducers have been used with some success but the resolution achieved is still inadequate.

Testing on laboratory samples which duplicate the manway geometry indicate the potential for improved resolution using SAFT. The test specimen (Figure 3) has three 1.6 mm holes drilled laterally through the weld which joins the boiler head to the manway.

![Fig. 3. Test specimen of a section of a boiler manway used for SAFT testing.](image-url)
Pre-SAFT and post-SAFT unrectified grey scale B-scan images are shown in Figure 4 where the horizontal dimension is 38.4 mm and the vertical dimension is 100 mm. The SAFT process has increased the resolution of the three holes and the edges of the boiler/manway joint. Figure 5 shows the same images after the magnitude of the analytic signal has been calculated to produce a rectified signal without loss of temporal (depth) resolution and a 6dB threshold has been applied.

The -6dB threshold sizes of the reflections (calculated from the magnitude of the analytic signal) are shown in Figure 6, indicating the superiority of the SAFT technique in this situation. Of course, since the beam spread in each case exceeds the actual size of the holes, this does not allow sizing per se, but can establish an upper limit on reflector size, which is sufficient for most monitoring situations. Comparison of pre-SAFT and post-SAFT results should not be used as an indication of the value of the technique since the pre-SAFT results are intentionally unfocused and can be expected to be of little value for defect sizing. A more realistic performance measure is achieved by comparison with the best results that can be achieved with conventional techniques using appropriately focused transducers.

Fig. 4a. Unrectified grey scale images of the data set acquired using the manway test block of figure 3: raw data set.
ECHO LOCUS MATCHING FOR EQUIPHASE POSITION CALCULATION

As the previous section makes apparent, one problem with SAFT is that a transducer is required which is, by the conventional wisdom, inappropriate for the task. This arises because the SAFT algorithms require an equiphase position, a phase reference point to which the echoes can be compared when calculating appropriate time shifts. This is normally done in one of three ways (Figure 7): a) by focusing the transducer to a point (or line) at the water/specimen interface, b) by using a small transducer for which phase variations across the face are negligible, or c) by calculating a virtual equiphase position based upon the expected refraction at the interface [4].

Fig. 4b. Unrectified grey scale images of the data set acquired using the manway test block of figure 3: after SAFT processing.
Fig. 5. 6dB threshold format applied to the magnitude of the analytic signal of the data from Figure 4.
Fig. 6. 6dB drop width measurement for the three holes shown in Fig. 3 calculated from the raw data, SAFTed data, and using a custom dual-lensed focused contact transducer.

Fig. 7. Methods used to obtain an equiphase position: a) focusing at the water/metal interface, b) constant phase approximation using a small contact transducer, c) calculation based on refraction at interface, d) calculation of a virtual equiphase point using best fit locus matching.
Our approach has been to gauge the equiphase position from signals received using a reference reflector. A best fit hyperbola is then calculated using equation (1) to match the received hyperbolic locus of echoes using the phase reference position as a variable parameter. The fit can be determined visually or using a numerical least squares criterion. The resulting equiphase position can then be used to allow SAFT processing of data sets acquired with that transducer on a similar geometry. The technique can be used with focused or flat transducers to enhance the resolution of previously acquired conventional inspection data.

SUMMARY

The synthetic aperture focusing technique has been used to enhance the lateral resolution of weld defect images. A method has been described which allows conventional transducers and techniques to be used for the acquisition of synthetically focused data sets.

REFERENCES