

## EMAT/SYNTHETIC APERTURE APPROACH TO THICK-WELD INSPECTION\*

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### INTRODUCTION

Rapid advances in automated welding and increased demands for reliable weld-quality inspection tools have created a need for new ultrasonic inspection systems. In particular, new systems capable of operation at elevated temperatures and rapid scan rates are in demand in fully and semi-automated welding applications to complement radiographic and conventional ultrasonic inspection techniques. In such applications, radiography is fundamentally limited because of its inability to detect and dimension most sharp flaws, and possible health hazards. On the other hand, conventional ultrasonic techniques are limited because they tend to be difficult to automate, require fluid couplants, and are often operator-dependent.

This paper summarizes an extensive report<sup>1</sup> on a new weld inspection system currently under development at the National Bureau of Standards for the U.S. Navy and indicates the direction of new studies using this system. The core of this system is the electromagnetic-acoustic transducer (EMAT). There are several reasons for this choice. Since they operate by electromagnetic induction, EMATs are noncontact devices; they do not require any acoustic couplant and will work on unprepared surfaces (e.g., rusty, painted). They can generate any polarization desired. In this instance, shear horizontal (SH) waves were chosen because their use leads to a simplified scattering model.<sup>2</sup> Although the SH waves may undergo mode conversion, the EMATs are relatively insensitive to other polarizations which might otherwise clutter the signal. Our transducers were specifically designed to operate at a relatively low frequency of about 500 kHz. The resulting long wavelength made it possible to determine flaw depth from signal amplitude or power rather than more elaborate methods such as time-of-flight.

Another element of this approach has been the implementation of a synthetic aperture approach to signal analysis. This improves the signal-to-noise ratio and mathematically focuses the ultrasonic beam for inspection of thick weldments.

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## EQUIPMENT

Although EMATs have become available on a limited commercial scale, we constructed all the transducers used in this work, choosing a periodic-permanent-magnet approach.<sup>3</sup> The unit cell consists of a pair of Sm-Co magnets positioned over a flat wire coil connected to an rf power source. In practice, adding a number of these cells together by increasing the number of magnet pairs and enlarging the coil makes it possible to increase the acoustic energy injected into the specimen and to shape the radiation pattern.

An intrinsic limitation of EMATs is their low efficiency. Therefore, careful attention to the associated electronics is necessary. The power amplifier used here generates about 800 watts; since the duty cycle is only 0.01%, there is no heating problem with the transducer coil. Due to small signal size, the receiver amplifiers were very carefully designed to achieve a low noise figure. Particular attention was paid to impedance matching between EMATs and amplifiers. Because of the transformers used for this, a transmit-receive switch is necessary for single transducer, pulse-echo operation. To date, we have been unsuccessful in designing an adequate switch, and have chosen instead to use separate transmitter and receiver transducers (pitch-catch).

The synthetic aperture method, using several positions of a single pair of transducers, requires the collection of numerous data sets from precise positions. For this reason, the transducers were mounted in a gimbaled housing to maintain proper orientation on the specimen surface. A two-axis positioner moved this assembly under computer control.

Figure 1 outlines the EMAT connections with their associated electronics. Besides controlling the positioner, the minicomputer collects and analyzes data. The current setup has proven to be reliable and rugged in a laboratory environment.

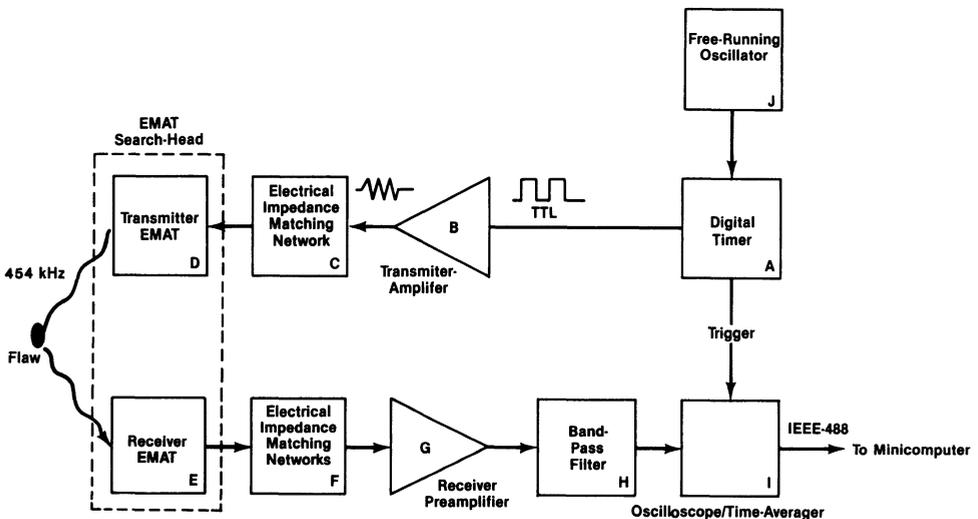


Fig. 1 Block-diagram of the electronics section.

## SIGNAL PROCESSING

Averaging of several (usually 8 to 32) signal traces helps considerably to reduce electronic noise. In the present instrumental setup, the digital oscilloscope used for display did this automatically. The majority of our processing efforts went toward implementing a method of synthetic aperture analysis. This helped reduce incoherent noise and signals from locations other than the focus, but the main purpose was to help in localizing a flaw through the depth of the material under examination.

The synthetic aperture approach is a method of combining data from multiple transducers (e.g., real-time medical imaging systems) or from a single transducer moved to several locations (as done in this work). We have discussed this in some detail earlier.<sup>4,5</sup> In summary, with a knowledge of the location of the transducers with respect to the weld and the sound velocity, this method shifts the phase of the signal from each location to produce a focus of ultrasonic energy. Because the signal waveforms are digitized at fixed time intervals, quantization errors can arise when the signals are phase-shifted in the time domain since the required shifts are not, in general, integral multiples of the digitizing period. To avoid such problems, we perform phase shifting in the frequency domain by rotating each of the vectors formed by the real-imaginary pairs of Fourier coefficients by an amount  $\omega\Delta t$  (Fig. 2). Here  $\omega = n(2\pi f_0)$ , where  $n$  is the harmonic number of the Fourier coefficients and  $f_0$  is the inverse of the signal measurement period, and  $\Delta t$  is the change in path length from the reference point divided by the sound velocity. A different focal spot means a different path length and a change in  $\Delta t$ . There is then a simple geometric relationship between original and shifted coefficients.<sup>5</sup> The shifted coefficients are summed and then reverse transformed to produce the focused signal. While in the frequency domain, it is, of course, possible to calculate both power distribution and integrated power for additional signal information. Figure 3 is a block diagram of the overall process. By way of example, Fig. 4 presents a series of easily discernible signals from a large slot in the surface of a 25-mm-thick plate. The transducers were moved 2.1 mm further away from the slot between each data set and so the peak signal moved to a later position (the right dashed line traces this process). The synthetic aperture process shifted these signals to coincide in phase (left vertical dashed line) and produced the bottom trace.

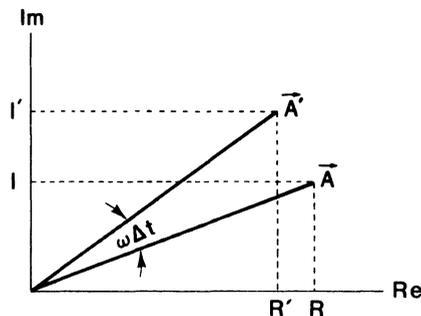


Fig. 2 Phase shift of Fourier coefficients in the real-imaginary plane.

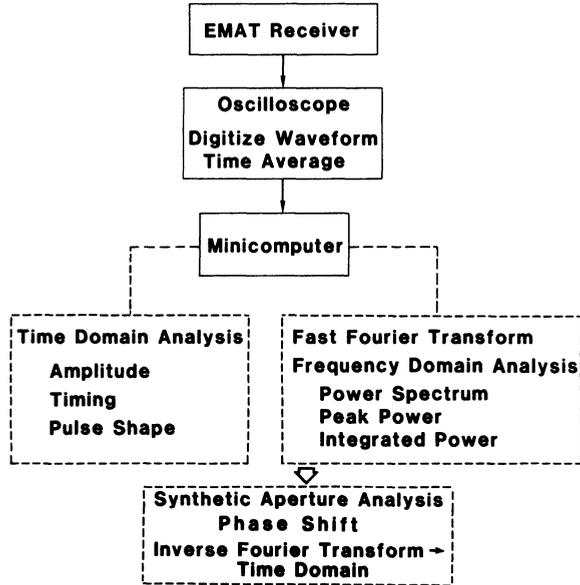


Fig. 3 Sketch of the signal processing procedure.

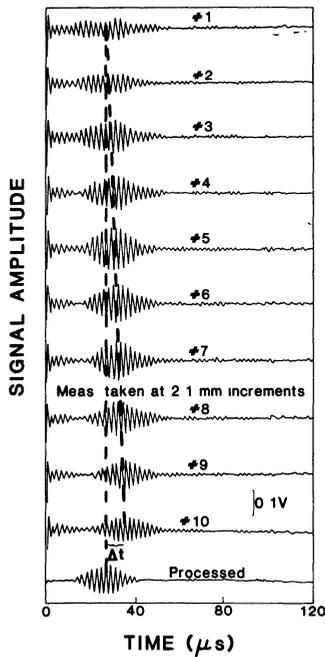


Fig. 4 Example of synthetic-aperture processing. Data collected at 10 locations is phase shifted to produce a "focused" signal.

At 500 kHz the ultrasonic wavelength in steel is about 7 mm. This limits the system spatial resolution, but in 25- or 50-mm thick plates it should be possible to estimate flaw position through the depth to at least top, middle, or bottom third. On thinner material (12-16 mm) the ultrasonic energy fills the plate and propagates in a plate mode<sup>6</sup> so no focusing is possible.

#### FLAW SIZING

For fitness-for-service evaluation, it is important not only to detect, but also to size planar flaws within a region of concern. To evaluate this system's sensitivity limits and sizing capabilities, we prepared a calibration specimen containing EDM slots normal to the surface of an HY-80 steel plate 25 mm thick. These slots varied both in length and through-thickness depth.

Measurements of signal amplitude as a function of these two flaw dimensions<sup>5</sup> indicate a sensitivity of about 0.5 mm and a linear response region extending to about 2.5 mm, or  $\lambda/3$ .<sup>6</sup> This flaw depth is consistent with the fitness-for-service criteria for pipeline girth welds,<sup>7</sup> and was the basis for selecting this operating frequency. For flaws deeper than this, the signal saturates and further sizing is not possible. The acoustic beam has a finite width and so both the flaw length and depth couple to the signal amplitude. With the EMAT design used here, the minimum length for accurate depth sizing is about 25 mm. A caution may be in order here, however. These measurements were on a plate with no surface irregularities. With the presence of weld reinforcement, weld root, etc., the noise floor will probably be higher, decreasing sensitivity.

#### FUTURE STUDIES

Artificial flaws have been emphasized in most of this work, but we are now preparing flawed welds for measurement and subsequent destructive examination. An initial test of the welding facility produced a small butt-welded steel plate, 50 mm thick. The length of the plate was too small to allow our usual transducer configuration with both transmitter and receiver axes normal to the weld. It was possible, however, to make some simple measurements with the transducers inclined at 45° to the weld. The preliminary measurements (Fig. 5) indicate good sensitivity and suggest considerable variation of flaw depth in this intentionally-flawed weld. This has not yet been confirmed by metallography.

Emphasis thus far has been largely on signal amplitude as a flaw-size indicator. There are, however, many other parameters of potential value. Included among these are power spectral density and total integrated power (available from the Fourier transform, as noted above), signal shape (from moments), phase, etc. Experiments are currently in progress to assess the usefulness of such parameters in flaw-sizing applications.

Other studies have involved thinner (16 mm) plates and, to date, have concentrated on the backscattered or "reflected" signal from a flaw. Complementary to this signal is the energy transmitted through

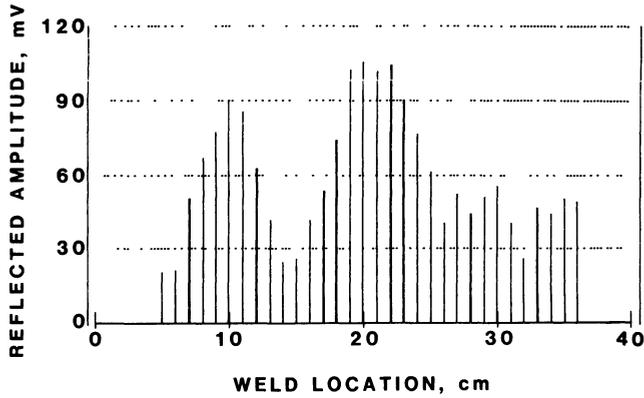


Fig. 5 Preliminary scan of 50-mm thick weldment indicating considerable structure in the intentional flaw.

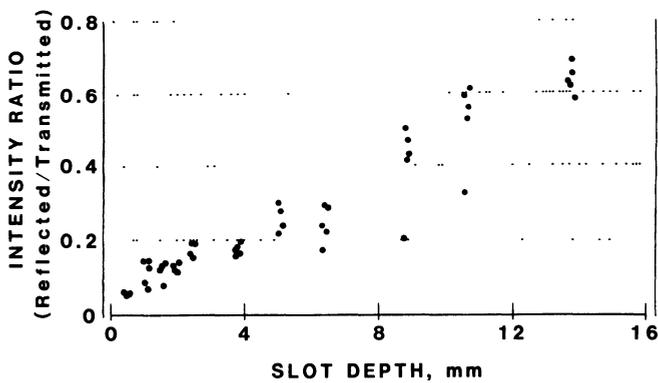


Fig. 6 Measurements on 16-mm thick plates with saw cuts indicate a considerable extension of flaw-depth sizing by using receivers on both sides of the flaw.

the weld. Recent measurements included a receiver EMAT on both sides of thin, surface saw-cuts. Plotting the ratio of reflected intensity to transmitted intensity against slot depth (Fig. 6) yielded a fairly linear response (at least monotonic) through the entire range of flaw sizes, instead of reaching saturation at about  $\lambda/3$ .<sup>2</sup> The series of five independent measurements on each standard gives a good indication of the repeatability of the data. We intend to pursue this approach with flawed weld specimens. Should the technique prove reliable, it may point to the possibility of inspecting individual weld passes as they are laid down.

## CONCLUSION

This work has demonstrated the feasibility of constructing a low frequency, SH-wave EMAT system for the detection and sizing of planar flaws in a thick, welded steel plate. Computer control and digital processing techniques for signal improvement point to the possibility of developing an automated inspection capability for finding flaws of larger-than-critical size as determined by fitness-for-service criteria.<sup>7</sup> Current measurements on flawed welds will further test these results and assess the system's sensitivity to nonplanar flaws such as slag and porosity.

## ACKNOWLEDGMENTS

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