VISUALIZATION OF SURFACE-BREAKING FLAWS BY SHADOW IMAGING

D. K. Peterson, S. D. Bennett, and G. S. Kino

Edward L. Ginzton Laboratory
Stanford University
Stanford, California 94305

INTRODUCTION

It is becoming fairly routine to detect flaws in structures by ultrasonic methods. However, the characterization of flaws, once they are found, is much more difficult. We will present a method called "shadow imaging" for the visualization of surface-breaking crack-like flaws using ultrasonic imaging. Shadow images provide an easily interpretable record of the crack depth profile, and also an indication of the degree of crack closure.

The shadow imaging method uses a unique acoustic imaging system developed at Stanford University over the past six years. This system has been described in much more detail in other papers.[1,2] Only a brief description is attempted here.

The imaging system uses a 32-element linear array of acoustic transducers to transmit and receive acoustic energy. The image is formed by synthetic-aperture reconstruction of the thirty-two individual acoustic echo traces. The echo data acquisition and synthetic-aperture image reconstruction is performed in special-purpose imaging hardware to allow real-time presentation of images (forty new image frames per second). The images are displayed on a television video screen in standard B-scan format, i.e. with increasing range away from the array represented in the horizontal dimension of the display, and displacement parallel to the array represented in the vertical dimension of the display. The resolution of the acoustic imaging system is about one wavelength. At the

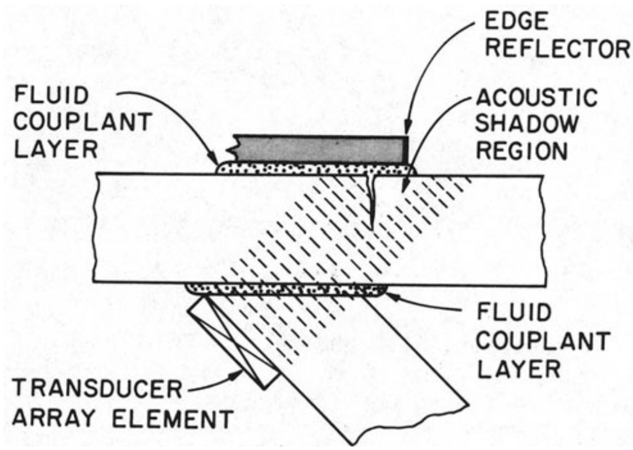

Fig. 1. Arrangement of transducer array, sample, and top plate used in the shadow imaging method. The surface-breaking crack casts an acoustic shadow on the edge reflector.

typical working frequency of three megahertz, the resolution cell is about 1 mm range x 1 mm lateral .

ACOUSTIC SHADOW IMAGING

The shadow imaging technique exploits the fact that behind a crack is cast an acoustic shadow, as shown in Fig. 1. A 32-element shear wave array is bonded to one face of a 45° aluminum wedge.[3] The sample is placed on the opposing face of the wedge and a thin plate is placed in contact with the top surface of the sample so that it lies directly in the path of the shear wave beam. The front edge of the plate serves as an edge reflector which reflects incident waves directly back to their source (an edge reflector is the two-dimensional analog of a corner reflector).

The same arrangement of sample, crack, and top plate is shown in a top view in Fig. 2a. When no flaw is present (cross section shown in Fig. 2b), the path from the transducer array to the edge of the top plate is unobstructed. A strong edge-reflected echo is sent back to the array. When a flaw _is_ present (cross section shown in Fig. 2c), the flaw casts an acoustic shadow over a portion of the edge of the top plate so that no echo returns from that portion.

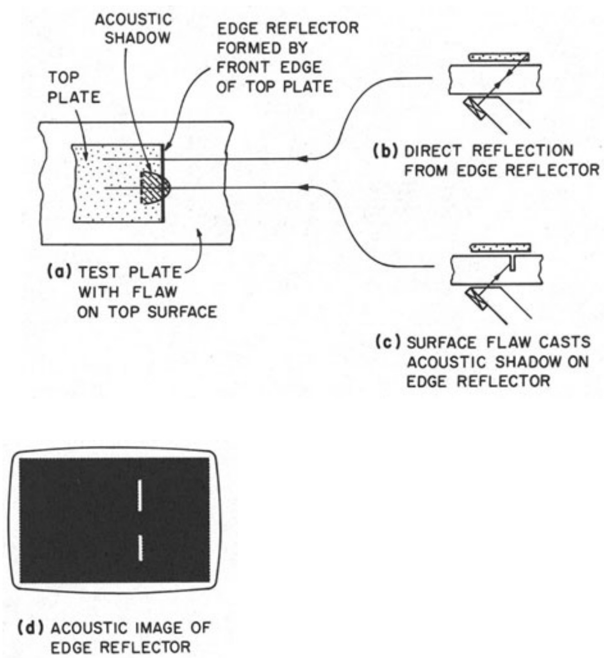

Fig. 2. The shadow imaging technique. (a) A top view of the top plate and the sample (with a surface flaw in it). (b) A cross-section through a portion of (a) where there is no flaw present. (c) A cross-section through a portion of (a) where there is a flaw present. (d) The acoustic image of (a) as seen on the display screen of the real-time imaging system. The bright vertical image of the edge reflector is broken in the middle where the flaw casts a shadow across it.

There is also an echo (not shown in Fig. 2) due to the reflection from the root of the crack, but this arrives slightly earlier than the edge reflection from the top plate (i.e., the root of the crack is slightly nearer to the array than is the edge of the top plate). Since the imaging system has excellent resolution in the range dimension, a simple electronic gate is able to select only those echoes originating from the edge of the top plate and to reject all other echoes.

The imaging system also has excellent resolution along the lateral dimension (parallel to the edge of the top plate). Therefore, the shadowed portions of the edge reflector are well differentiated from the unshadowed portions. Figure 2d shows the acoustic image of the edge reflector. The gap in the image is caused by the shadow cast by the surface flaw on the middle portion of the edge reflector (as shown in Fig. 2a).

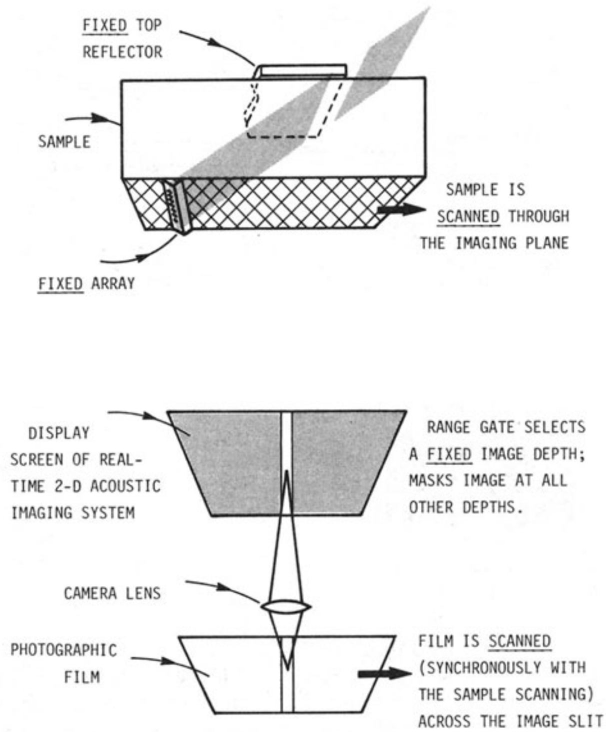

Fig. 3. Generation of a "shadow image". At the top of the figure is shown the movable sample sandwiched between the fixed top plate and transducer array. At the bottom of the figure is shown a perspective view of the imaging system display screen and recording film as they would be seen from above and behind. The shadow image is generated by painting a bright slit (as shown in Fig. 2d) across the recording film as the sample is scanned through the acoustic beam.

So far, we have discussed the method for imaging just a one-dimensional slice of the acoustic shadow region (the position of the slice being determined by the intersection of the edge reflector with the shadow). To map out the entire two-dimensional extent of the acoustic shadow, the flawed sample is scanned through the beam path (determined by the fixed transducer array and edge reflector). As the sample is scanned, a synchronously-scanned photographic film records the variations in the acoustic shadow cast on the stationary edge reflector. Figure 3 shows this operation in a schematic view. At the top of the figure is the arrangement of the

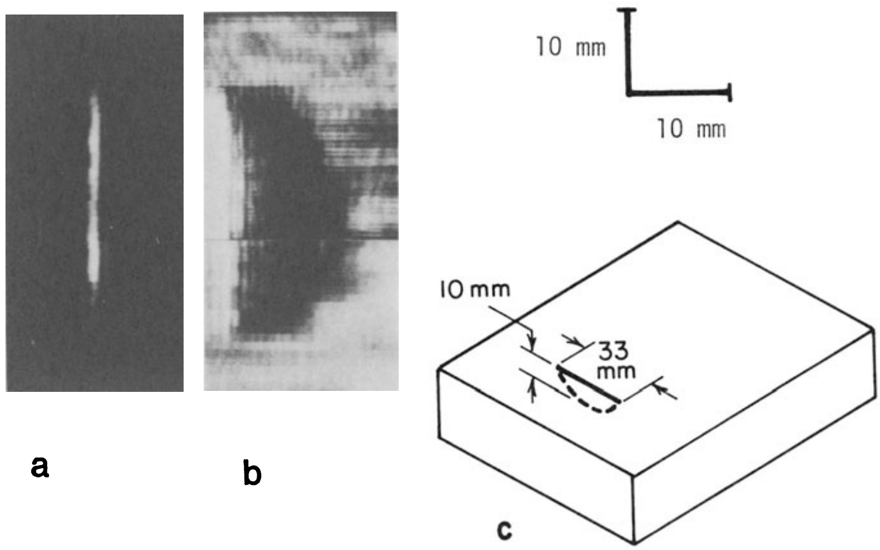

Fig. 4. Images of saw cut sample. (a) A standard pulse/echo image of the saw cut. (b) A shadow image of the saw cut showing a well-defined shadow region behind the cut. (c) The saw cut sample.

movable sample sandwiched between the stationary array and top plate. At the bottom of the figure is shown a perspective view (as one would see when looking from above and behind the display screen of the real-time imaging system) of how the full two-dimensional shadow image is recorded on film. As the sample is scanned through the acoustic beam, the film is scanned synchronously. When the scan is complete, the developed photographic film contains a so-called "shadow image," depicting the acoustic shadows cast by surface cracks.[4]

Figure 4 shows a "half-penny" shaped saw cut in an aluminum block. The saw cut has a radius of curvature of 19 mm and penetrates the sample to a maximum depth of 10 mm . Figure 4a shows an image of this flaw using the standard method of pulse/echo acoustic imaging. The depth profile of the flaw can be inferred only indirectly from the intensity of the acoustic image (the deeper the flaw, the greater is the reflected wave amplitude).

A shadow image of the same flaw is shown in Fig. 4b. In this image the location and depth profile of the flaw are vividly outlined by the extent of the shadow region. The contrast between the shadowed and unshadowed regions is quite good, allowing quantitative determination of the flaw depth

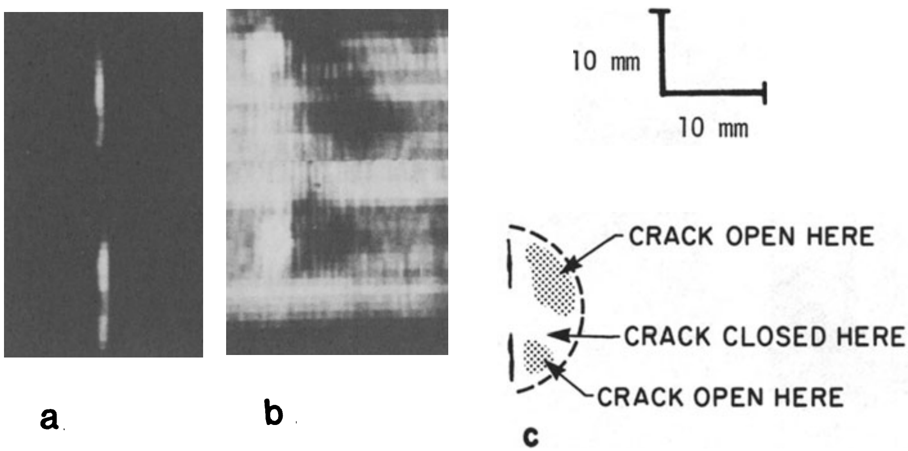

Fig. 5. Images of a fatigue crack in steel. (a) A standard pulse/echo image of the crack. (b) A shadow image of the crack showing shadows near the edges of the crack, but no shadow behind the middle portion. (c) The interpretation of the shadow image in (b).

profile using the 10 mm reference bars at the top right of the figure.

The next flaw to be discussed is a surface-breaking fatigue crack in steel (nuclear grade A533). The standard pulse/echo acoustic image of this flaw (Fig. 5a) shows an unexpected gap in the middle portion. This might be due to either or both of the following reasons: (1) the face of the crack may be bent away from the normal to the sample surface in the central portion so that the edge reflection from this portion is directed away from the array, or (2) the crack faces may be closed here so that acoustic energy goes through the crack rather than being reflected. The shadow image in Fig. 5b definitely favors the second explanation, for we see that in the middle portion of the shadow image there is indeed no shadow. This indicates that acoustic energy has traveled through the crack, was reflected from the top plate, and traveled back through the crack to return to the array. If the first hypothesis above had been correct (i.e., the crack face bent away from the normal), then an acoustic shadow would still be present and the shadow image would be uniformly black behind the entire length of the crack. Figure 5c shows the interpretation of these results. Note that the information from the shadow image is indispensable in explaining the strange appearance of the standard acoustic image in Fig. 5a.

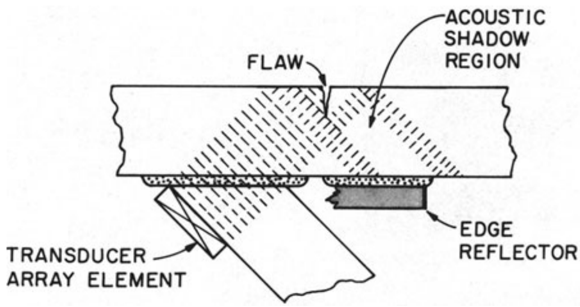

Fig. 6. Arrangement of array, sample, and edge reflector used in the "far-side-only" variant of the shadow imaging method. This method allows crack depth profiling when access to only the far side of the sample is available.

To summarize, the shadow imaging technique produces easily interpretable images of surface-breaking cracks with the additional advantage of discriminating between the conditions of crack closure and crack non-normality to the surface.

Finally, we mention a possible extension to the shadow imaging technique which would greatly extend its practical usefulness. If the thin top plate is placed in contact with the bottom surface of the sample rather than the top surface, as shown in Fig. 6, then we require no access to the flawed face of the sample -- it is possible to examine surface flaws from the far side of the sample. An image of the "half-penny" saw cut using this "far-side-only" technique is shown in Fig. 7. The shadow image is now a full circle, instead of a semicircle as in Fig. 4. This is because, as the sample is scanned through the beam in Fig. 6, it breaks the beam path once as it obstructs the upcoming beam and again when it obstructs the down going beam. The result is that shadow images made in this manner have mirror symmetry about their vertical midlines. The shadow image still shows the correct location of the flaw, but underestimates the depth of the flaw (i.e., the shadow is smaller than expected). This is due to the finite size of the edge reflector.[5]

CONCLUSIONS

We have presented a technique, called shadow imaging, for visualizing the depth profiles of surface-breaking cracks by acoustic imaging. The imaging system used in these experiments is a real-time synthetic-aperture acoustic imaging system which uses a 32-element linear array of transducers working at approximately three megahertz.

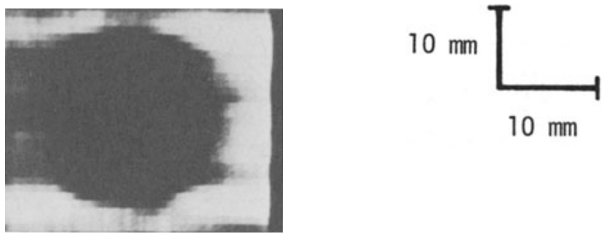

Fig. 7. Shadow image of the half-penny crack in Fig. 4c using the far-side-only variant of shadow imaging. Because the flaw breaks the beam path on both the upcoming and downgoing paths, the shadow is a full disc instead of the semi-disc in Fig. 4b.

The shadow imaging technique uses the acoustic shadow cast by a crack on the adjacent surface of the sample. A top plate is put in direct contact with the top of the sample. When no flaw is present, the acoustic image of the front edge of the top plate is a bright vertical bar. If a flaw is present, however, it casts an acoustic shadow on the edge reflector so that the acoustic image has a gap (or gaps) in it. The so-called "shadow image" of the flaw is made by recording the extent of these gaps on a photographic film as the sample is scanned past the edge reflector.

It was shown that this shadow imaging method may be modified so that it allows depth profiling of cracks from the far side of a sample. This would be of great importance in applications such as pipes and vessels, where nondestructive evaluation of these parts could be carried out while they are in service.

ACKNOWLEDGMENTS

We wish to thank the Electric Power Research Institute (EPRI) and Combustion Engineering, Inc. of Chattanooga, Tennessee for supplying the steel fatigue crack sample. This work was supported by the Air Force Office of Scientific Research (AFOSR) under Contract No. F49620-79-C-0217.

REFERENCES AND FOOTNOTES

1. D. K. Peterson, S. D. Bennett, and G. S. Kino, "Real-Time NDE of Flaws Using a Digital Acoustic Imaging System," Materials Eval. 40 (12), 1256-1262 (November 1982).

2. S. Bennett, D. K. Peterson, D. Corl, and G. S. Kino, "A Real-Time Synthetic-Aperture Digital Acoustic Imaging System," Acoustical Imaging, Vol. 10, P. Alais and A. F. Metherell, Ed., Plenum Press, New York, 669 (1982).

3. R. L. Baer and G. S. Kino, "A Shear Wave Transducer Array for Real-Time Imaging," Review of Progress in Quantitative NDE 2, Plenum Press, New York, (1983).

4. The reference to a scanning photographic film is used for pedagogical reasons. Actually, the image slit is translated across the display screen by modifying the TV synch signals. The important feature in both descriptions is that the image of the edge reflector moves across the film to create a shadow image.

5. The top plate used in Figs. 1-5 is 1 mm thick. The edge reflector used in Figs. 6 and 7 is about 7 mm thick. The larger edge reflector affords a larger echo signal. It is also possible to boost the signal-to-noise ratio by replacing the edge reflector with an acoustic transmitter so that the acoustic beam travels only once through the sample, rather than the round-trip paths shown in the figures.