ACOUSTIC EMISSION LINEAR PULSE HOLOGRAPHY

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ABSTRACT

This paper describes Acoustic Emission Linear Pulse Holography which combines the advantages of linear imaging and acoustic emission into a single NDE inspection system. This unique system produces a chronological linear holographic image of a flaw by utilizing the acoustic energy emitted during crack growth.

Conventional linear holographic imaging uses an ultrasonic transducer to transmit energy into the volume being imaged. When the crack or defect reflects that energy, the crack acts as a new source of acoustic waves. To formulate an image of that source, a receiving transducer is scanned over the volume of interest and the phase of the received signals is measured at successive points on the scan.

The innovation proposed in this paper is the utilization of the crack generated acoustic emission as the acoustic source and generation of a line image of the crack as it grows.

A thirty-two point sampling array is used to construct phase-only linear holograms of simulated acoustic emission sources on large metal plates. The phases are calculated using the pulse time-of-flight (TOF) times from the reference transducer to the array of receivers. Computer reconstruction of the image is accomplished using a one-dimensional FFT algorithm (i.e., backward wave).

Experimental results are shown which graphically illustrate the unique acoustic emission images of a single point and a linear crack in a 100 mm x 1220 mm x 1220 mm aluminum plate.
INTRODUCTION

This paper describes a unique technique for imaging fatigue, IGSCC cracks, etc. as they propagate with time using their emitted acoustic energy (i.e., acoustic emission) as the source. The short bursts of acoustic energy generated by stress, etc. propagate through the medium to the discrete element receive array. A reference timing transducer positioned between the array and the inspection zone initiates the time-of-flight (TOF) measurements. The received signals are sampled at different positions across the array and time-of-flight (TOF) data are measured at each position. The aperture data (i.e., series of TOF measurements) are then transferred to a small PDP 11/03 computer for reconstruction of the linear holographic image. Computer reconstruction of the images are accomplished using a one-dimensional FFT algorithm. Images are displayed on the computer terminal graphic console.

All image data are stored on digital tape cartridges to allow generation of a chronological history of crack growth with respect to the material depth, etc.

TECHNICAL DESCRIPTION

Concept and Hardware Implementation

The concept behind AE Linear Pulse Holography is illustrated in Figure 1. As a crack grows, each small segment of the crack front emits acoustic waves. Figure 1 illustrates emissions coming from the crack; hence, one can consider the crack front to be a group of sources, \( S_1 \ldots S_N \). When, for example, the source segment \( S_1 \) emits, the acoustic wave is detected at each sensor in the array. The relative phase of the pulse at each sensor is determined. As each source emits, the cumulative phase information is combined into a phase image or hologram of the sources. The hologram is then reconstructed into an image where each source segment, \( S_i \), has a counterpart image, \( I_i \), in the total reconstructed image.

Hence, over a period of time as the crack grows, an image is constructed of the crack. This provides information on the length of the crack and its growth rate.

A block diagram of a data acquisition system to implement this concept is shown in Figure 2 and operates on the following principles. The AE burst from the crack propagates and is detected by an array of \( n \) transducers. Each transducer has a separate processing channel consisting of a receiver, clock, etc. The channel outputs are converted into TOF data and transferred to a computer for reconstruction.
The data are defined by Equation (1) which relates the TOF in terms of the propagation velocity and the crack emission position to array element distance

\[
TOF = \frac{1}{V_P} [r_i - (Z_0 - d_o)] ,
\]

where \( r_i = \sqrt{Z_0^2 + X_i^2} \) and \( V_P \) = propagation velocity.

Figure 3 is a typical TOF profile. Holography is based upon the measurement of phase rather than pulse transmit time. Therefore, the TOF information is synthetically converted into phase by the following relationship:

\[
\phi = \omega t ,
\]

where \( \omega \) = radian frequency. The phase components, as required for digital reconstruction, with their selected synthetic frequency are defined by the two simple equations:

\[
f_r(x) = K \cos \omega \left( \frac{1}{V_P} [\left(X_i^2 + Z_0^2\right)^{1/2} - (Z_0 - d_o)] \right)
\]

and
Fig. 2. Block diagram of a data acquisition and display system that implements the principles of acoustic emission linear pulse holography.
Fig. 3. Plot of typical time-of-flight profile across a linear aperture.

\[ f_i(s) = K \sin \omega \left( \frac{1}{\Delta} \left( \frac{x_i^2 + z_o^2}{2} - (z_o - d_o) \right) \right). \]  

A plot of Equations (3) and (4), shown in Figure 4, yields curves equivalent to a Fresnel zone pattern or point object hologram. Thus, it appears that by proper signal processing of the acoustic emission TOF data, it can be converted to holographic format and the linear image reconstructed as shown in Figure 5.

**Array Element Spacing and Synthetic Frequency Criteria**

The choice or selection of the maximum synthetic frequency and array element spacing is not completely arbitrary, but depends on three important parameters: pulse bandwidth, propagation velocity, and source-to-hologram distance.

With pulse systems, the timing accuracy (i.e., detection jitter) is a function of the pulse bandwidth (B) or rise time T. Typically, the resultant time jitter in AE pulse detection systems is usually about one-hundredth of the rise time (i.e., 0.01T). Naturally sophisticated correlation techniques can reduce this error, but we will assume this value in our array element spacing analysis. The propagation velocity multiplied by the detection jitter is the associated position error in the TOF measurements. Thus, these two parameters will be involved in the expression for the
Fig. 4. Plot of the Fresnel zone phase pattern corresponding to the time data in Fig. 3.

Fig. 5. A linear, holographic reconstruction of the image based on Fresnel zone patterns of Fig. 4.
minimum selectable element spacing. The remaining parameter, source-to-array distance, determines the time delay or phase between array elements. The greater the distance, the less time delay between elements and if the point source is at infinity, a plane wave exists across the array (i.e., no time variation). So we would expect this parameter to be in the final expression of array element spacing and frequency selection.

Figure 6 shows the pulse receiving array geometry used in the analysis where the source-to-array distance, assuming paraxial approximation, is

\[ r_n \approx Z_0 + \frac{(nd)^2}{2Z_0} \]

where \( n = 1, 2, \ldots \) and \( d \) = array element spacing.

The minimum detectable time difference between elements is assumed to be 0.01 \( T \), and the following equation defines the relationship mathematically

\[ \text{Up}(0.01T) = \frac{1}{2} \frac{d^2}{Z_0} \]

where \( T \) is the pulse rise time = 0.35/B, and B is the pulse bandwidth.

The array spacing \( d \) is easily determined by equation (6)

\[ d \geq 0.08 \left( \frac{Z_0 \text{Up}}{B} \right)^{1/2} \]

The relationship between the array receiver spacing and \( f \) can be derived by the sampling theory, where the highest spatial frequency must be sampled at least two times per cycle. This can be expressed by the following equation

\[ d = \lambda/2 \]

Fig. 6. Diagram of the pulse-receiving array geometry used to determine the maximum synthetic frequency.
and the selectable frequencies are

\[ f \leq 6.25 \left( \frac{U_p B}{Z_o} \right)^{1/2}. \]  

(9)

A typical example using AE data from a 10 cm thick steel plate would yield

\[ Z_o = 30.48 \text{ cm} \]
\[ U_p = 3.17 \text{ mm/\mu sec}, \]
\[ B = 0.8 \text{ MHz}. \]  

(10)

Using equations (7) and (8), the calculated array spacing \((d)\) is 2.7 mm, and the maximum selectable frequency \((f)\) is 570 kHz.

Thus, a system timing jitter of 0.01\(\tau\) and the two parameters \((U_p, Z_o)\) uniquely define the receiver spacing and the maximum equivalent holographic continuous wave frequency.

**Lateral and Depth Resolution**

The lateral resolution can now be calculated using the Rayleigh criterion for incoherent radiation

\[ \Delta X = \frac{\lambda Z_o}{L}, \]  

(11)

where \(L = (m-1)d\) is the array length, \(\lambda\) = the wavelength, \(Z_o\) = object-to-array distance and \(m\) = number of array elements. Equation (11) can be expressed in terms of the array parameters \(m\) and \(Z_o\)

\[ \Delta X = \frac{2Z_o}{(m-1)}, \]  

(12)

where \(d = \lambda/2\).

Using the AE data (10) and the calculated values of \(d\) and \(f\), the lateral resolution using equation (12) for a 32 element array is 2 cm. The depth resolution can be obtained by TOF triangulation method using the timing jitter or can be calculated using the depth of focus criterion

\[ \Delta r \approx \lambda \left( \frac{Z_o}{L} \right)^2 = \frac{2}{d} \left( \frac{Z_o}{m-1} \right)^2, \]  

(13)

where \(Z_o/L\) is the F number.

Usually, this resolution is very poor compared to the TOF resolution unless the F number is less than one. In certain AE applications, the F number can be substantially less than one and the depth resolution as defined by equation (13) is very useful.
AE Source Location and Optimum Focus Algorithm

The AE source location algorithm predicts the position of the emission source within the medium by sequential image reconstruction at preselectable depth intervals. The predicted depth or range is then determined by where the optimum focus occurs. Figure 7 illustrates this concept of optimum or best focus using an isometric display of the reconstructed source amplitude or intensity function. Each line represents a discrete depth increment of 0.635 cm starting at 3.7 cm from the array. The distribution peaks at where best focus occurs as shown in Figure 7 and the predicted depth is at 14.48 cm or about the middle of the distribution.

This unique isometric focus/depth graphic display program can be used effectively in determining the AE source position within the test medium.

EXPERIMENTAL VERIFICATION

Experimental Hardware System

In order to verify the concept of AE Linear Pulse Holography, some means of making time-of-flight measurements was needed. Since the equipment to make 16 simultaneous TOF measurements was not available, we modified existing equipment to make a single time measurement between the reference sensor and one array sensor. The

![Fig. 7. Sequential isometric images of point source data showing the concept of optimum focusing.](image-url)
array sensor was initially placed at one end of the linear aperture and a measurement made. Then the sensor was moved to the next position and another measurement made. In this way, we gradually accumulated the required TOF information. The system shown in Figure 2 would acquire measurements from all sensors from a single acoustic emission event.

The acoustic source in the first experiment was a piezoelectric transducer driven by a voltage pulse. This ensured that the same source waveform was emitted for each measurement at the array locations. With simultaneous, multi-channel recording, one image point is obtained for each AE event. Since we had to build up data one location at a time, a reproducible source function ensured that this temporary technique was representative of the ultimate hardware system performance.

Experimental Results

The first experiments consisted of verifying the various basic linear image parameters using a simulated acoustic emission source positioned on a flat aluminum plate 30 to 60 cm from the array.

Figure 8 illustrates the digital image reconstruction sequence of the AE source positioned on the plate surface 30 cm from the 32 point array. The minimum array element spacing is 0.27 cm using the given image parameters: \( u_p = 0.317 \text{ cm/sec}, z_0 = 30 \text{ cm}, B = 0.8 \text{ MHz} \). The actual sampling (0.635 cm) for this experiment was determined by the dimensions of the AE receive elements. The selected synthetic reconstruction frequency using one wavelength sampling between elements was approximately 0.5 MHz. Figures 8b and 8c are the quadrature components and the reconstructed image respectively.

The 3 dB amplitude width (Figure 8c) which defines the source holographic lateral image resolution is 6 mm. The theoretical predicted resolution using equation (10) is approximately 8 mm, which compares very nicely with the experimental results.

Figure 9 illustrates graphically the chronological image sequence of a simulated crack growing from the bottom to the upper surface. The time series of isometric amplitude plots and their corresponding point images integrate into a single composite crack image defining the physical length in terms of its AE emissions.

The sequence starts with the AE source positioned at the bottom face \((y = T)\) of the 10 cm thick aluminum block simulating the crack initiation point. The corresponding linear image is a single point (see Figure 9d end view). As the crack propagates upward, the AE emissions occur at different positions, \(3/4T, 1/2T, \text{ etc. until they stop at } 1/4T\). The integrated sequential image uniquely defines the dynamic crack growth length.
Fig. 8. Experimental data obtained using piezoelectric transducers as both the point source and receiver. Part A is the time-of-flight profile, B shows the Fresnel zone pattern, and C shows the reconstructed image.
Fig. 9. Illustration of a chronological image sequence of a simulated crack growing from the back to the upper surface of a plate.
Figure 10 illustrates an image of a crack tip when the crack length was 2 cm. The position of the tip is indicated with an arrow on the figure. This type of image allows for precise location of the "active" portion of a growing crack at any instant in time. Integration of many such images during the course of stress cycling would provide a record of total crack growth. Hence, the concept has been shown to be feasible when applied to actual crack acoustic emission.

CONCLUSIONS

We have demonstrated the unique concept of imaging cracks as they propagate using their self-generated acoustic emission energy. The experimental results graphically illustrate the technique using a one-dimensional FFT computer algorithm (i.e., linear backward wave) for AE image reconstruction.

The image reconstruction time is essentially in real time, thus providing sequential snapshots of dynamic crack growth.

An AE imaging system using a small computer and discrete element array will provide a powerful crack surveillance tool for various nuclear and non-nuclear applications (i.e., pipe welds, pressure vessel welds, etc.).

Fig. 10. Linear reconstruction image of data taken on the aluminum test specimen. The arrow identifies the actual location of the crack tip. The peak in the image intensity gives the measured or image location obtained by AE holographic techniques.
REFERENCES


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