NDE for Bulk Defects in Ceramics

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Abstract
A 50 MHz C-scan imaging system is used to find defects in ceramics. The imaging system consists of a microcomputer-controlled scanner for data acquisition and signal conditioning. Synthetic aperture imaging at 50 MHz is carried out to obtain 3-D images of flaws. Image reconstruction is accomplished digitally on a minicomputer. A square synthetic aperture is used to image flaws in flat disk samples and a cylindrical synthetic aperture is used in the cylindrical rod case. We have developed the theory to predict the imaging performance of the two aperture geometries. The respective point spread functions are simulated and agree well with theoretical results. Special attention is given to reconstructing images of specular reflectors. Computer simulations based on theoretical flaw models have been carried out.

Keywords
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Abstract

A 50 MHz C-scan imaging system is used to find defects in ceramics. The imaging system consists of a microcomputer-controlled scanner for data acquisition and signal conditioning. Synthetic aperture imaging at 50 MHz is carried out to obtain 3-D images of flaws. Image reconstruction is accomplished digitally on a minicomputer. A square synthetic aperture is used to image flaws in flat disc samples and a cylindrical synthetic aperture is used in the cylindrical rod case. We have developed the theory to predict the imaging performance of the two aperture geometries. The respective point spread functions are simulated and agree well with theoretical results. Special attention is given to reconstructing images of specular reflectors. Computer simulations based on theoretical flaw models have been carried out.

Introduction

First, a sample is immersed in a water bath and scanned in C-scan reflection mode to locate the transverse positions and depths of the flaw sites. Then a sampled aperture is synthesized over a relatively small volume of interest around the flaw, as depicted in Figs. 1a and 1b. This operation limits the number of reconstruction points required to a reasonable value. In our imaging system, a single 50 MHz focused transducer, operated in pulse-echo mode, is used. The focal point of the incident beam is located at the water/silicon nitride interface to approximate a point source and also, because of the large velocity mismatch at the interface, to create a wide angle transmitted beam insonifying the interior of the sample. For the flat disc geometry, pulse-echo data is collected over a square 8 x 8 element aperture with a sampling point spacing of two wavelengths. For the cylindrical case, an open-ended sampled cylindrical aperture is used. It consists of a stack of sixteen rings, two wavelengths apart, each ring having 32 evenly-distributed sampling points. Image reconstruction is accomplished by back-projecting the pulse-echo data on a minicomputer. The back projection procedure is illustrated in Figs. 2a and 2b.

We have carried out theoretical analyses and computer simulations to gauge the performance of the two aperture geometries. Much effort was devoted to establishing the respective point spread functions (PSF), the conventional way of specifying the resolving power of an imaging system. Inherent in the PSF concept is the assumption that a finite size reflector is regarded as a collection of point scatterers; thus, every point in the aperture responds to every point in the reflector. This assumption is invalid for strong specular reflectors, as is the case in imaging finite size flaws inside silicon nitride samples. This fact is illustrated in Fig. 3 where we have a two-dimensional fully enclosed aperture imaging a finite size circular defect. Based on the geometric optics argument, a sampling point on the aperture tends to respond only to a point on the defect boundary directly facing it. In reconstructing the image point by back-projection, because of the finite width of the transmitted pulse (typically a few rf cycles), a limited number of sampling points in the vicinity of the actually-excited aperture element will contribute constructively. Outside of this neighborhood, the contributions due to the other sampling points are either negative or random. Hence, 100% coherent summing at an image point is not possible, giving rise to undesirably high sidelobe levels. We concluded that the connection between the PSF and the "resolution" of specular reflector images is not clear.

Figure 1. Imaging flaws inside silicon nitride samples using synthetic aperture techniques: (a) flat disc samples; and (b) cylindrical rod samples.
Figure 2. Image reconstruction by back-projection.

For the first time, computer simulated reconstructions based on theoretically-calculated backscattered waveforms for spherical void, iron, and silicon inclusions have been conducted. A typical backscattered waveform from a spherical flaw consists of a front-face echo which demarcates the boundary of the defect, and trailing echoes which are a combination of back-face echoes and mode-converted waves. Different kinds of flaws have distinct backscattered signals. Synthetic focus reconstruction results in an image which shows the defect boundary and the associated "ring" artifact corresponding to later echoes, which is characteristic of the nature of the flaw, as shown in Figs. 4a, 4b, and 4c. However, a significant drawback to these results is that the sidelobe levels are very high. This is a fundamental difficulty with reconstructing images of specular reflectors using the back-projection scheme we have described.

We have developed a new image reconstruction algorithm called "selective back-projection," which to some extent circumvents the difficulties inherent in the conventional back-projection method. In conventional back-projection, the amplitude of an image point is evaluated by summing contributions from all the sampling points in the aperture indiscriminately. This indiscriminate summation in the case of specular reflectors is inconsistent with the fact that an object point on the defect boundary is apparently "visible" to only a localized group of sampling points in the aperture. Thus, the obvious strategy is to only sum over sampling points that contribute constructively, and deliberately leave out sampling points that do not matter. There is also the necessity to distinguish between random and meaningful contributions, which is discussed in detail below. Based on computer simulation results, there is a dramatic improvement in the images generated by selective back-projection over those by conventional back-projection.

Figure 3. Imaging specular reflector by synthetic focus technique.

Hardware Description

The functional blocks of the three-dimensional synthetic focus imaging system are shown in Fig. 5. The scanning mechanism consists of a precision X-Y stage with ±7 μm positional accuracy and a rotator mount accurate to within 1/100 of a degree. A single 50 MHz transducer operated in pulse-echo mode is scanned over the sample of interest to create a synthetic aperture. The pulse-echo data is time-expanded by use of a sampling oscilloscope to facilitate data collection. The scanning and data acquisition operations are coordinated by a microcomputer system which also serves as an off-line data storage unit. Image reconstruction is performed on a minicomputer system in which all the processing algorithms reside. The two computer systems are linked so that data files can readily be retrieved for processing.

Theory of Operation

Point Spread Function

(1) Square Aperture System. This particular geometry does not lend itself to a complete
analytic description because it is basically a wide aperture system and does not admit the paraxial approximation. However, one would not expect the PSF to deviate significantly from the analytical paraxial result.

\[
H(x,y) = \frac{\sin \left( \frac{2\pi D}{\lambda z} (x - x_0) \right) \sin \left( \frac{2\pi D}{\lambda z} (y - y_0) \right)}{\sin \left( \frac{2\pi x}{\lambda z} (x - x_0) \right) \sin \left( \frac{2\pi y}{\lambda z} (y - y_0) \right)}
\]

where \( D \) is the width of the square aperture, \( \lambda \) is the element spacing in \( x \) and \( y \), and \((x_0, y_0, z)\) is the location of the point target. The 4 dB lateral single point definition is therefore

\[
d_x = d_y = \frac{\lambda z}{20}
\]

Note that the resolution is twice as good as a receiver array focused on a point insonified by a separate source, because in a synthetic aperture system the signal path is twice the distance from an array element to an object point.

Range resolution is primarily determined by the pulse width. The typical impulse response of the transducer used in the imaging system approximates a Gaussian envelope \( rf \) pulse four and a half cycles long.

Since the aperture is undersampled by a factor of 4, grating lobes are expected to occur where

\[
\Delta x = n(N - 1) \frac{\lambda z}{20}
\]

and

\[
\Delta y = m(N - 1) \frac{\lambda z}{20}
\]

\( n, m = 1, 2, 3, \ldots \), where \( N \times N \) is the number of elements in the sampled square aperture. However, because short pulses are used, there is no longer coherent summing at locations far removed from the point target. Thus, the grating lobe levels are reduced by approximately \( M/N \), where \( M \) is the number of \( rf \) cycles in the pulse.
(2) Cylindrical Aperture System. Again, we do not attempt to derive the exact expression for the PSF of the system. Rather, we divide the difficult overall problem into two much simpler, mathematically tractable, albeit non-exact, parts. Through this exercise, we can estimate the resolution of the system. The validity of the approximation can easily be checked by computer simulation. We will consider the resolution in the z direction and that in the (r, θ) plane separately.

(a) Definition in z. The resolution of the z direction is assumed to be dependent only on the extent of the aperture in z. Further, we apply the paraxial approximation to obtain the definition in z.

\[ H(z) = \frac{2D_z}{AR} \left( \frac{z - z_0}{R} \right) \]

where \( D_z \) is the width of the aperture in z, \( z_0 \) is the element spacing in z, and \( R \) is the distance of the point target from the aperture. The 4 dB single-point definition in z is therefore

\[ d_z = \frac{R \lambda}{2D_z} \]  

(6)

Also, since the system is undersampled in z by a factor of 4, grating lobes are present. However, the use of short pulses suppresses the grating lobe levels. The aberration in the grating lobes due to the non-paraxial nature of the focusing at the grating lobe locations also serves to reduce their amplitudes.

(b) Definition in the (r, θ) Plane. The PSF in the constant z plane is assumed to depend only on angular (θ) distribution of the aperture. The PSF of a continuous cylindrical aperture at the constant z focal plane is given by

\[ H_r(\theta) = \frac{2\pi}{a} J_0(2kp) \]  

(7)

The Rayleigh definition \( d_R \) is therefore given by

\[ d_R = \frac{0.6 \lambda}{\pi} = 0.2 \lambda \]  

(8)

Hence, in principle, a remarkable resolution of 0.2 λ can be attained. The reasons for this surprisingly good theoretical definition are two-fold. Firstly, a cylindrical system instead of a spherical one is being considered. Therefore, the first zero of the \( J_0 \) rather than the \( J_1 \) Bessel function dictates the Rayleigh definition. This gives an improvement by a factor of 1.6, but with higher sidelobe levels, and thus a relatively poorer two-point definition. Secondly, because in a synthetic aperture system any ray suffers twice the phase shift that it would in a single lens system, there is a factor of 2 improvement in definition.

IMAGING SPECULAR REFLECTORS

Consider, for instance, a spherical defect of radius \( b \), at the center of an array of radius \( a \), \( a \gg b \). Suppose we are trying to obtain an image of a point \( P \) on the defect boundary, a distance \( R \) from the synthetic aperture array, as shown in Fig. 6. When a transducer is opposite the point \( P \) at the point A on the aperture, the response is maximum. Similarly, when the transducer is moved to point \( B \), a point \( Q \) on the radial line passing through \( B \) and the center \( Q \) of the circle have maximum response. If the system is focused on the point \( P \), the signal arriving at \( B \) from \( Q \) has the wrong time delay. The error in time delay is

\[ \Delta T = \frac{2(BP - BQ)}{v} \]  

(9)

where \( v \) is the velocity in the medium. Let angle \( POQ \) be \( \theta \). Since \( a \) or \( R \gg b \), it can be shown that

\[ \Delta T = \frac{4a}{v} \sin^2 \frac{\theta}{2} \]  

(10)

If we regard the sampling points as essentially continuous, the total contribution to the received signal is

\[ \phi = \int_{0}^{2\pi} \exp \left[ \frac{4a}{v} \sin^2 \frac{\theta}{2} \right] d\theta \]  

(11)

where we have ignored the amplitude variation due to the change in signal path length. For \( \theta \) small, Eq. (11) becomes a Fresnel integral. It can be shown that the main contribution to this integral is approximately from the region where

\[ \frac{4ka \sin \frac{\theta}{2}}{2} < \frac{\pi}{2} \]  

(12)

where \( k = \omega/v \). This corresponds to contributions having the same sign. The elements making the main contribution to the image point \( P \) are within the angular range

\[ 0 < \frac{\sin \theta}{2} < \frac{\pi}{2\sqrt{2ka}} \]  

(13)

Points outside this range may give in-phase or out-of-phase contributions.

As an example, in silicon nitride, at a frequency of 50 MHz, \( \lambda = 220 \mu \text{m} \). A flaw 600 μm in diameter corresponds to \( kb = 8.6 \). Thus, the angular range 2θ over which all the contributions to received signals are positive, is approximately 50°. For 32 elements evenly distributed around the aperture, this result implies that only five of them give cumulative contributions to the image of the point \( P \), and
the remaining elements essentially contribute randomly.

Figure 6. Finite size circular specular reflector using a circular aperture.

SELECTIVE BACK-PROJECTION

Figure 7 diagrams the entire synthetic focus procedure. Without loss of generality, a two-dimensional circular aperture is chosen as a specific example. The aperture synthesis step is mathematically a mapping from the object field \( f(x,y) \) into the data field, which is a set of time series. For the purpose of illustration, the time series are ordered in the form of a matrix with each row corresponding to the complete pulse-echo data record at a sampling point. The columns are the progressive time entries of the pulse-echo data records. The synthetic focus step is simply the evaluation of the amplitude of each pixel in the image plane with the aid of a focus map generated independently based on geometric considerations. The focus map maps out a meandering path in the image plane along which the contribution from each sampling point should be picked up for a particular image pixel.

![Select focus matrix](image)

**SELECTIVE BACKPROJECTION ALGORITHM**

1. **DISCARD ISOLATED VALUES**
2. **ONLY SUM OVER PACKET OF ANGLES WITH THE SAME SIGN AND MAXIMUM CONTRIBUTION**

Figure 7. Selective back-projection algorithm.

As explained before, conventional back-projection indiscriminately sums up all the contributions. The selective back-projection scheme sums up only the subset of contributions from adjacent elements that are of the same sign and give maximum total magnitude. The basis for this strategy is shown in Fig. 3. Although point A on the defect boundary is only physically "visible" to array element 1 in the reconstruction process, the sidelobe due to point B, which physically only excites array element 2, can influence the amplitude at A because of the use of a finite width transmitted pulse. If the sidelobe contribution from B, or equivalently the back-projected contribution from array element 2, is in phase with the main lobe contribution from array element 1, then the main level is boosted. For a smooth specular reflector, constructive contributions should only come from a connected neighborhood of the aperture. Since the data is automatically searched to find the packet of numbers which gives maximum contribution, one does not have to make any a priori assumptions about the orientation and radius of curvature of the surface of the specular reflector.

It is important to point out that even though the main lobe of an image point is boosted by sidelobe contributions from neighboring points, the improvement in overall amplitude is meager because only a small number of array elements are involved. A sidelobe from an image point tends to leave streaks in the image. These streaks come from lone contributions in the selective summing step. Therefore, to reduce the undesirably high sidelobe levels, lone contributions are discarded, and the corresponding pixel amplitudes are set to zero. In other words, one can set up a criterion that an object point has to be "seen" by at least \( M \) array elements to discriminate against unwanted sidelobes.

RECONSTRUCTION OF SPECULAR REFLECTORS

Because the selective back-projection algorithm can easily be implemented on a two-dimensional system without excessive computation time, we have, for purposes of illustration, reconstructed images of a void and of silicon and iron inclusions for a two-dimensional system on the computer. 32 evenly-distributed array elements are used. To simulate the pulse-echo data, theoretically derived backscattered waveforms for voids, silicon, and iron inclusions are employed. The calculation is based on the work on Ying and Truell on scattering from spherical objects. The pulse-echo data for each array element is generated based on geometric optics considerations. The signal path is assumed to be along the line segment between the array element and the point on the defect boundary directly opposite the element, as shown in Fig. 3. Selective back-projection is then applied to reconstruct the image of the various single defects. The amplitude of each image point is evaluated by inspecting the contributions from all 32 array elements. Only the packet of contribution which gives maximum magnitude is kept. The number of entries in the packet (corresponding to the number of array elements involved) is checked, and if it is more than two, the amplitude of the image point is set to equal the packet sum. Otherwise, the image point value is forced to zero. Note that not all the array elements in the packet contribute equally. The element nearest to the normal of the defect surface at the image point will contribute the most. The neighboring contributions will fall off.
approximately cosinusoidally. Thus, the selective back-projection algorithm, when used to image specular reflectors with dimensions greater than one wavelength, is equivalent to a limited angular aperture imaging system with cosinusoidal apodization.

Figures 8a and 8b show the images of a void 600 µm in diameter obtained by conventional and selective back-projection methods respectively. There is decidedly great improvement in the clarity of the defect boundary in Fig. 8b. The defect boundary amplitude is boosted by 3-4 dB compared to that obtained by conventional back-projection, and the far-out sidelobe is almost completely annihilated by the selective back-projection process.

Similar improvement can readily be observed in Figs. 9 and 10 for the cases of silicon and iron inclusions.

Even greater improvement in the image quality can be achieved when selective back-projection is combined with nonlinear processing. This is clearly evident in Fig. 8c for the case of a void.

Figure 8. Images of a circular void defect processed by different schemes: (a) conventional back-projection; (b) selective back-projection; and (c) selective back-projection and nonlinear processing.
CONCLUSION

We have developed the theories to characterize the imaging performance of square and cylindrical synthetic apertures. Most of the theoretical predictions are confirmed by computer simulation results. We have established that the three-dimensional synthetic focus technique is capable of extremely good single point resolution in all three directions. The result on the PSF for the cylindrical aperture configuration is of particular importance because of its generality. The theoretical analysis was carried out without making any assumption about the position of the image point relative to the aperture. This result may also apply to tomographic systems because of similarity in aperture geometry. In addition, we have analyzed the effect of sampling the aperture. Sampling introduces grating lobes whose positions are nearer to the main lobe than in a rectilinear system, but whose amplitudes are far weaker. Short pulse operation tends to reduce the grating lobe levels.

Specular reflectors present special difficulties for synthetic aperture imaging. Computer simulations show that the conventional back-projection technique is seriously inadequate in reconstructing images of specular reflectors because of the resulting high sidelobe levels. A selective back-projection technique has shown great promise in enhancing the images by suppressing sidelobe amplitudes.

We hope to obtain experimental results on our three-dimensional imaging system in the near future to substantiate the simulation results.

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