ULTRASONIC MAXIMUM APERTURE SAFf IMAGING

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INTRODUCTION

The focused transducer combined with C-scan imaging is currently the workhorse of ultrasonic nondestructive evaluation (NDE) [1]. Its strength lies in its simplicity and high quality images. There is room for improvement, however. First, the lateral resolution of C-scan images is inversely proportional the diameter of the transducer. At a given operating frequency, the diameter of a transducer cannot be made arbitrarily large due to the accompanying increase in capacitance. Another limitation is that the depth of field of a focused transducer is proportional to its beam width. So the depth of field is relatively short for high resolution images requiring the use of multiple transducers which focus at different depths. Finally, the transducer has difficulty achieving consistent focus when inspecting parts with contoured surfaces. With the advent of computed imaging [2], many of the limitations of the focused transducer can be circumvented by sophisticated image reconstruction algorithms implemented on high-speed computers. One such image reconstruction algorithm is the Synthetic Aperture Focusing Technique (SAFT) [3]. The idea behind SAFT is to synthesize an aperture by coherently combining data from a set of transducer positions to form an image point. In a typical SAFT implementation, the raw data is obtained by digitizing the RF-waveforms from a scanned transducer focused on the surface of the part (see Fig. 1a). Subsequently, the A-scans are coherently combined to form focused images of the part's interior.

In this paper, we extend conventional SAFT with planar apertures to apertures which conform with the shape of the part. The ability to perform SAFT over contoured apertures is important for two reasons. First, parts of interest come in all shapes and sizes, so this development greatly extends the applicability of SAFT to parts found in the aerospace industry. Second, SAFT images formed from contoured apertures have the potential to show increased signal-to-noise ratio (SNR) over a focused C-scan image of the same part. Instead of using lenses for physical transducers to focus through a particular surface curvature (which works well only for parts with constant curvature), we are able to collect data over the surface of a part with varying curvature and make that the effective aperture of our synthesized transducer. Ideally, the output SNR should improve with increasing aperture size. However, for the planar or concave aperture, increasing the aperture size is achieved by broadening the transmitted beam pattern which limits SNR. Thus, SAFT will perform best on convex apertures where interior points of the part can be interrogated ultrasonically from multiple directions without having to broaden the transmitted beam pattern.
SAFT implementations to date have generally assumed a planar sound entry surface [4]. Contoured SAFT has been limited to simpler geometries such as cylinders and spheres. These SAFT algorithms have been implemented in two ways. The first is a wave-theoretic implementation based on the back-propagation of wave-fronts in the frequency domain. The second is a delay-and-sum implementation in the time-domain. Since the maximum aperture SAFT algorithm is based on the time-domain method, we will limit our discussion to that here. A discussion of the frequency domain method can be found in [4].

Figure 1a illustrates a typical data acquisition setup for planar SAFT. A single transducer is scanned over the surface of the part which contains an acoustic reflector at \((x_0, y_0, z_0)\) with reflectivity \(r(x_0, y_0, z_0)\). At each spatial position indexed by \(i\), a pulse \(p(t)\) is transmitted. The backscattered signal is given by

\[
  u_i(t) = r_i(x_0, y_0, z_0) p \left( t - \frac{2p_i(x_0, y_0, z_0)}{c} \right) + n(t), \tag{1}
\]

where \(p_i(x_0, y_0, z_0)\) is the distance between the transducer focus and the reflector, \(c\) is the speed of sound in the material, and \(n(t)\) is the noise term. The resulting data set consists of a set of waveforms denoted \(\{u_i(t) : i \in \mathcal{I}\}\) where \(\mathcal{I}\) is the set of all points at which data were collected. Several waveforms \(\{u_i(t) : i \in \mathcal{I}\}\) will have energy reflected from each potential location, \((x, y, z)\), of an acoustic scatterer within the material. Here \(\mathcal{I}\) denotes the set of scan positions which contain energy from a given location and is referred to as the aperture of the transducer. The delay-and-sum SAFT method simply accumulates the amplitude for a given scattering location over its aperture, \(\mathcal{I}\), using

\[
  r(x, y, z) = \sum_{i \in \mathcal{I}} w_i u_i \left( t + \frac{2p_i(x, y, z)}{c} \right), \tag{2}
\]

where \(w_i\) is a weighting factor.

The coherent summation in (2) increases the signal-to-noise ratio (SNR) of the SAFT image over the raw RF-data by summing the signal in-phase while summing the noise out-of-phase. In general, the increase in SNR realized by applying the SAFT algorithm to a given RF-data set is directly related to the aperture size. The resulting resolution in the processed image is also controlled by the size of the aperture. This relationship is expressed by the Raleigh resolution criterion [5].
\[
\delta = 1.22\lambda \left( \frac{Z}{d} \right) \tag{3}
\]

where \( \delta \) is the resolution cell size, \( \lambda \) is the wavelength of the transducer, \( Z \) is the depth of the scatterer, and \( d \) is the aperture diameter. Thus, the larger the aperture of the transducer, the higher the resolution in the resulting image.

The potential benefits of SAFT are realized by using as large an aperture as possible. In the planar case, this is done by broadening the beam of the physical transducer (the distance, \( d \), in Fig. 1a) to collect the data and summing the data over that larger aperture. In highly scattering media such as titanium, broadening the beam decreases the SNR in the raw RF-data. In many cases, the increase in SNR realized from the SAFT processing over this larger aperture is offset by the decrease in SNR in the RF-data. This makes it extremely difficult for planar SAFT to offer any large improvement over focused transducer C-scan images. A second limitation of planar SAFT concerns the planar geometry itself. A large class of NDE problems, such as those found in the aircraft engine industry, involve the inspection of contoured surfaces such as billets, disk forgings, blades, and panels. To be of practical use in this industry, an imaging algorithm must be able to handle these contoured surfaces.

MAXIMUM APERTURE SAFT IMAGING ALGORITHM

A method to overcome the limitations of planar SAFT is to collect data over the largest physical area (maximum aperture) possible for each imaging location as shown in Fig. 1b. In this case, the SAFT aperture is increased while the beam width of the physical transducer remains the same. This preserves the SNR of the raw RF-data and increases the SNR in the resulting SAFT image. The result is the potential for a real increase in inspection sensitivity when compared to conventional imaging techniques. In addition, such an approach would be able to image parts with contoured surfaces.

The maximum aperture SAFT algorithm is an extension of the planar delay-and-sum SAFT algorithm. In this development, we assume that a single surface-focused transducer with axis oriented normal to the entry surface is used to collect the data. The raw data are assumed to be a collection of sampled waveforms, \( \{u_i(t) : i \in \mathbb{I}\} \), each having \( T \) samples, collected at \( t_j \) seconds per sample, and starting at a distance \( d_{gs} \) below the entry surface. Furthermore, for each \( u_i(t) \), the location of the point of focus \( (x_i, y_i, z_i) \) and a unit transducer orientation vector \( (X_i, Y_i, Z_i) \) are known with respect to a global coordinate system. We desire to reconstruct \( M \) points, \( \{ z_j \} _{j=0,1,\ldots,M-1} \), at locations \( (x_j, y_j, z_j) \) in the interior of the part being imaged.

The maximum aperture SAFT algorithm requires some knowledge of the physical transducer's beam and pulse shape. The transducer's beam shape is necessary to determine the set of data points, \( A_j \), which contained reflected energy from each reconstruction point \( r_j \). In this case some simplifying assumptions are made about the transducer beam behavior. We assume the beam simply sweeps out a cone-shaped volume of material. This volume is defined by the half-angle \( \theta \) and starting and ending radii

\[
\rho_1 = d_{gs} \tag{3a}
\]

\[
\rho_2 = d_{gs} + \frac{T_s (T - 1) c}{2} \tag{3b}
\]

respectively. The vertex of the cone is at the point of focus for the transducer. The algorithm also requires a digitized version of the transmitted pulse, \( p(t) \). It is assumed the \( p(t) \) is collected at a sampling rate of \( t_s \) and is non-zero over \( P \) samples.
The first step in the algorithm is to determine for each reconstruction point \( r_j \) which waveforms \( u_j(t) \) are in its aperture, \( \mathcal{A} \). This decision has been broken down into a two part process. First, the distance between \( r_j \) and \( (x_j, y_j, z_j) \), \( \rho_{ij} \), is calculated for all \( i \in \mathcal{D} \) using

\[
\rho_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}
\]  

(4)

and compared to \( \rho_l \) and \( \rho_h \). The points which satisfy

\[
\rho_l \leq \rho_{ij} \leq \rho_h
\]  

(5)

are separated into a set \( \{u_j(t) : i \in \mathcal{D}_j' \} \). Then a second step is performed for all \( i \in \mathcal{D}_j' \) where the cosine of the angle between \( r_j \) and the axis of the transducer is calculated using the inner product

\[
\cos \theta_{ij} = \frac{(x_j - x_i)x_i + (y_j - y_i)y_i + (z_j - z_i)z_i}{\rho_{ij}}
\]  

(6)

and compared to the cosine of \( \theta \). The points which satisfy

\[
\cos \theta_{ij} \geq \cos \theta
\]  

(7)

are in the aperture and separated into a set \( \{u_j(t) : i \in \mathcal{A}_j \} \). Next, the time index \( t_{ij} \) which corresponds to the distance \( r_{ij} \) is computed with

\[
t_{ij} = \frac{2(\rho_{ij} - d_{gs})}{ct_s}
\]  

(8)

for all \( i \in \mathcal{A}_j \). Finally, the value of the image point \( r_j \) is calculated by first summing the return pulse over all the points in the aperture

\[
r_j(t) = \sum_{i \in \mathcal{A}_j} w_i u_i(t_{ij} + t) \quad t = 0, \ldots, P - 1
\]  

(9)

where \( w_i \) is a weighting factor related to the transducer's beam pattern. Finally, \( r_j(t) \) is matched filtered [6] with the transmitted pulse to get the image point \( r_j \)

\[
r_j = \sum_{i=0}^{P-1} r_j(t)p(t).
\]  

(10)

After all \( M \) reconstruction points are finished, they can be ordered into a volumetric image for display or further analysis.

**EXPERIMENTAL RESULTS**

Experimental data were taken on 50.8 mm diameter, Ti6-4 barstock samples as shown in Fig. 2. These samples were prepared by using wire EDM to slice the samples in half axially, subsequently four holes were drilled in the cut faces, and 0.4 mm, 0.8 mm and 1.6 mm ruby spheres were inserted into the holes. Then, the samples were welded and hot-isostatically pressed to bond the halves back together. Finally, the samples were turned round. In the finished cylindrical samples, the spheres are located 6.35 mm, 12.7 mm, 19.05 mm, and 25.4 mm radially beneath the surface and 12.7 mm apart axially. A number of samples were made so each size sphere appeared at each depth.
Both waveform and C-scan data were acquired for each sphere using a 7.5 MHz, 12.7 mm diameter, 63.5 mm focal length transducer. The RF-data were collected using a 63.5 mm waterpath which focused the sound on the surface of the part. A 0.254 mm index was used in both the axial and the circumferential directions, and the data was digitized at a rate of 50 MHz. For comparison purposes, C-scan data were also collected for each target using the same transducer. In this case, a 38.1 mm waterpath was used to create a focal zone within the cylinder from approximately 6.35 mm below the surface to centerline. A gate which ran from 9.5 mm below the entry surface to 2.4 mm beyond centerline was used to collect images with 0.254 mm pixels. Good results were obtained for the 1.6 mm and 0.8 mm targets but not the 0.4 mm targets. The results from the 0.8 mm spheres will be discussed in detail below.

Typical B-scans in the area of the 0.8 mm spheres located 12.7, 19.05 and 25.4 mm below the surface are shown in Fig. 3 with time shown horizontally and circumferential position vertically. Figure 5 shows the results of the C-scan inspection of the same spheres. Here circumferential and axial positions are shown horizontally and vertically, respectively. Notice how the signal in the RF-data varies and the SNR in the C-scan images increases as the spheres move away from the centerline of the cylinder. Maximum aperture SAFT images were formed for each of these targets using 0.37 mm voxels. The results are shown in Fig. 5 which displays a slice perpendicular to the axis of the cylinder through the maximum voxel in the image and a profile down the axis of the cylinder through that same voxel. Notice how the quality of the reconstructed image decreases as the sphere position moves away from the centerline. This occurs because the aperture transitions from a full $2\pi$ radians at the center of the sample to a short arc at the edge of the sample. In effect, the aperture becomes more planar as the target approaches the edge of the sample.

![Photo and schematic of titanium samples](image)

Figure 2. Photograph and schematic of titanium samples used to demonstrated maximum aperture SAFT algorithm.
Figure 3. Typical B-scan data from acquired with a 7.5 MHz transducer on 0.8 mm targets.

Figure 4. C-scan data for 0.8 mm targets acquired with a 7.5 MHz transducer focused subsurface in the samples.
Figure 5. Maximum aperture SAFT images and axial amplitude profiles for 0.8 mm targets acquired with a 7.5 MHz transducer.
Table 1. A comparison of SNR between maximum aperture and C-scan images for 0.8 mm targets.

<table>
<thead>
<tr>
<th>Target Depth</th>
<th>C-Scan Image SNR</th>
<th>SAFT Image SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.4 mm</td>
<td>&lt;1</td>
<td>40</td>
</tr>
<tr>
<td>19.05 mm</td>
<td>1</td>
<td>4.6</td>
</tr>
<tr>
<td>12.7 mm</td>
<td>4.2</td>
<td>3.7</td>
</tr>
</tbody>
</table>

A quantitative comparison between the C-scan and maximum aperture images for each target is performed based on SNR. Here SNR is defined as

$$\text{SNR} = \frac{P_s - \mu_n}{P_n - \mu_n}$$  \hspace{1cm} (11)

where \(P_s\) is the maximum value of the signal, \(P_n\) is the maximum value of the noise and \(\mu_n\) is the mean value of the noise. The results of this quantitative comparison can be found in Table 1. The greatest increase in SNR occurred for the target at centerline. Here, the target was undetectable in the C-scan image but had a SNR of 40 in the SAFT image. The SNR was also dramatically improved for the target 6.35 mm from centerline, but the increase was an order of magnitude less than the centerline target. As the targets moved further away from centerline to 12.7 mm, the C-scan image outperformed the SAFT image.

CONCLUSION

We have extended the capability of ultrasonic SAFT imaging from planar parts with contoured surfaces. This extension utilizes the largest possible or maximum aperture permitted by part geometry and physical transducer selection for image formation. Experimental results were presented for 0.8 mm ruby spheres imbedded in pieces of Ti6-4 barstock. The maximum aperture images for these targets showed a distinct advantage over conventional C-scan imaging toward the center of the samples. As the distance of the targets from the centerline increased, however, conventional C-scan images provided better results. There were also 0.4 mm spheres located in the test pieces which we were not able to image. With more accurate modeling of the transducer beam, the algorithm should be able to produce high quality images at a greater distance from centerline and show improved detection for the smaller spheres.

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REFERENCES