A REAL-TIME SAFT SYSTEM APPLIED TO THE ULTRASONIC INSPECTION OF NUCLEAR REACTOR COMPONENTS(a)

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INTRODUCTION

In 1982 Pacific Northwest Laboratory began activity under the sponsorship of the U.S. Nuclear Regulatory Commission to implement SAFT technology in a field usable system. The University of Michigan had previously laid the groundwork by performing extensive research related to the development of the SAFT algorithm in the area of ultrasonics and the investigation of ways to improve the computation time [1,2]. The task given PNL was to deploy the results of this research effort by developing an instrument that would perform in-service inspection of nuclear reactor components using the SAFT-UT algorithm.

Initially at PNL, a study was performed to review the status of SAFT as it applied to ultrasonic testing. This established a firm understanding of the SAFT algorithm and investigated a number of parameters related to SAFT, such as expected resolution and system bandwidth effects. The results of this review may be found in a document by Busse, et al. [3].

A number of items needed to be addressed in order to accomplish the deployment task. The physical realities of developing a field system, such as portability and environmental concerns, were important. A pipe scanner needed to be developed to perform the precision scanning necessary for SAFT-UT data collection. The algorithm itself needed to be accelerated to produce a real-time three-dimensional SAFT-UT system. And finally, graphics software must be developed to display the resultant image in a clear and interpretable manner.

The hardware components employed in the SAFT-UT field system are commercially available whenever possible. The purpose for this was to improve the final system reliability and facilitate technology transfer to the commercial realm. Also it allowed internal PNL engineering resources to be focused on developing the SAFT field system algorithm and related software rather than developing unique hardware.

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A significant amount of work has been focused on acceleration of the computationally intensive coherent summation SAFT algorithm. This has been accomplished through advanced signal processing techniques and development of a Real-Time SAFT Processor peripheral device. These efforts have been described in a separate paper [4] and will not be dealt with in depth here. It is essential for the successful deployment of SAFT in a commercial environment to achieve rapid imaging. This allows the operator to make timely judgments with respect to specimen integrity, thus reducing the costs involved with reactor inservice inspection.

This paper will focus on describing configurations developed for the implementation of SAFT-UT on thin-wall materials such as piping. Of primary importance is detection and sizing of vertically oriented defects, such as intergranular stress corrosion cracks (IGSCC), in the primary cooling system of light water reactors.

SAFT-UT IMAGE RECONSTRUCTION

"Synthetic aperture focusing" refers to a process in which the focal properties of a large-aperture focused transducer are generated from an orderly series of measurements over a large area using a small aperture transducer. The processing required to focus this collection of data has been called beam-forming, coherent summation, or synthetic aperture processing.

Inherently, SAFT has an advantage over physical focusing techniques in that it provides a full-volume focused characterization of the inspected area, where traditional physical focusing techniques provide focused data only at the depth of focus of the lens. For the typical data collection scheme used with SAFT-UT, a focused transducer is positioned with the focal point located at the surface of the part to be inspected. This configuration is used to produce a broad, divergent ultrasonic beam in the object under test. As the transducer is scanned over the surface of the object, a series of A-scan lines (rf waveforms) are recorded for each position of the transducer. Each reflector produces a collection of echoes in the A-scan records. If the reflector is an elementary single point reflector, then the collection of echoes will form a hyperbolic surface. The shape of the hyperboloid is determined by the depth of the reflector within the test object and the velocity of sound in the material under test. This relationship between echo location in the series of A-scans and the actual location of the reflectors within the test object makes it possible to reconstruct a processed image from the acquired signals.

If the scanning and surface geometries are well known, it is possible to accurately predict the shape of the locus of echoes for each point within the test object. The process of coherent summation involves shifting the A-scans by a predicted time delay and summing the shifted A-scans. This process may also be viewed as performing a spatial-temporal matched filter operation for each point within the volume to be imaged. Each element is then averaged by the number of points that were summed to produce the final processed value. If the particular location correlates with a locus of A-scan echoes, then all of the values summed will be in phase and produce a high-amplitude result. If the location does not correlate with a locus of predicted echoes, then destructive interference will take place and the spatial average will result in a low amplitude.
The principles of the elementary single-transducer SAFT-UT pulse-echo configuration are essential to comprehend in order to accurately interpret results of the SAFT-UT process and to understand the more complex multiple-transducer configurations. SAFT-UT pulse-echo is a single-transducer source-receiver scanning configuration (i.e., the same transducer that generates the sound field in the object space also receives the return echo).

In thin materials, where reflections from the back surface need to be considered, multiple sound paths may contribute to the reconstructed image. In the SAFT-UT pulse-echo configuration there are two of these candidate propagation paths that are dominant when observing generally vertical oriented defects. These are illustrated in Figure 1. The part as shown has a thickness of T with an elementary point reflector at depth D from the scanned surface. The transducer scanned has its focus located at the surface, and in general has a non-zero incident angle.

The first path to be considered is the direct path (P₁-P₁) from the beam entry point to the reflector and back to the entry point, without intersecting the far surface. Analysis shows that data received along this path will be deterministic and represent accurately and uniquely lateral position and depth information [5]. This path represents the sometimes elusive 'tip' signal commonly referred to when imaging vertical-oriented defects such as IGSCC.

The second path (P₂-P₃-P₁) is the propagation path from the entry point to the far surface to the object and back to the transducer. This sound path length may be represented by Eq. 1.

\[
P = (D^2+x^2)^{1/2} + [(2T-D)^2+x^2]^{1/2}
\]

Figure 2 shows the family of curves generated when solving Eq. 1, while discretely varying depth D. A definite ambiguity is apparent when observing this diagram. Very little unique object depth information is available from reconstruction of this sound path, and as a result the time-of-flight of the reflected signal will be in general independent of the object depth. From this elementary analysis, it appears that this bounce path would be difficult to incorporate into a SAFT imaging system since the expected propagation data is weakly indicative of the reflector depth. This fact is unfortunate, since this path is commonly encountered in normal ultrasonic data gathered with angle-beam illumination. This is especially true for verti-

Fig. 1. Single transducer, SAFT-UT, pulse-echo configuration.
Fig. 2. Length of sound path vs. transducer lateral position for SAFT-UT pulse-echo path P_1-P_2-P_3
cally oriented planar defects. This phenomenon is the cause for the high amplitude 'corner trap' signal that is encountered when scanning this class of defects. It aids in the detection of these defects, but hinders accurately sizing the vertical extent of a given reflector.

Figure 3 shows a SAFT-UT image of a machined vertical sawcut in a stainless steel coupon. The data was collected in the SAFT-UT pulse-echo configuration. The notch, which simulates a vertical defect, was 0.6 inches in length and 0.3 inches deep into the material, and the coupon thickness was 0.585 inches. The image displays the B-scan side view and B-scan end view of the volume inspected. A tip signal has been imaged successfully in this example and the very strong corner reflection is apparent. As predicted, then, it would be difficult to size this defect in the vertical direction if the tip signal was not present. Also an operator may judge that this image represents a single continuous defect because of the duality nature of the indications, or he may judge that two independent reflectors on the same vertical plane are present in the material. Not enough information is available in the data to distinguish between these two cases.

Fig. 3. SAFT-UT pulse-echo image of a semi-circular sawcut (0.6 x 0.3 inches) showing both the B-scan side view on left and B-scan end view on right.
For vertically oriented defects in materials with a finite thickness, the strength of the pulse-echo configuration lies in detection of these defects. The corner-trap echo is typically very strong and is present even in very attenuative materials.

TANDEM SAFT CONFIGURATION (TSAFT)

Tandem SAFT or TSAFT has been implemented to provide a method for characterizing and sizing these vertical defects in materials with a finite thickness. The TSAFT configuration capitalizes on the forward scatter from the object rather than the direct back scatter as in the pulse-echo case. It consists fundamentally of a fixed transmitter that is placed in line with, or in tandem with, a scanned receiving transducer. The transmitter is placed such that the divergent sound beam illuminates the primary object area. The scanned receiver is then translated to receive direct energy reflected from the defect area. As in the pulse-echo configuration, after each pass of the receiver transducer, the transport mechanism is incremented so that a rectilinear pattern is obtained (e.g., around the circumference of a pipe).

In the interest of brevity we will consider here only the most common sound path used in the tandem SAFT configuration. A more complete description of TSAFT multiple sound paths may be investigated by reviewing a previous paper by S.R. Doctor [6]. In the configuration we will consider here, the energy from the illuminating transducer reflects from the far surface prior to striking the object area, and the receiver in turn captures the energy directly reflected from the object. The total path length for a given point reflector, then, may be represented by Eq. 2.

$$P = \left[ X_T^2 + (N+T)^2 \right]^{1/2} + \left[ X_R^2 + (T-D)^2 \right]^{1/2} \quad (2)$$

where $X_T$ and $X_R$ are the lateral position of the transmitter and receiver relative to the object plane, $T$ is the thickness of the material, $D$ is the distance of the object point from the near surface, and $N$ is the number of reflections the transmit ray undergoes prior to striking the object point.

A graph may be generated using Eq. 2 that will assist in predicting results when implementing this configuration. Figure 4 shows the family of curves that resulted from performing this exercise. These curves represent the total path length with respect to the receiver lateral position for various object depths ($D$). It was assumed that the echo from the point reflector was received in the central angle of the receiver. It can be predicted from this graph that the object depth, $D$, will map to a unique position in the image space and that the redundancy experienced in the pulse-echo configuration will not be present here.

Figure 5 is the tandem SAFT image of the identical sawcut described earlier with the pulse-echo case. Notice that, as predicted, the full extent of the surface of the vertical object is represented. Using TSAFT in this example provides the information to the interpreter so that a judgement may be made concerning the vertical extent of the defect. The image is independent of the tip diffracted signal. Also it is plain to the observer that there is a single vertical defect and not two co-planar defects.
Fig. 4. Length of sound path vs. receiver lateral position for TSAFT configuration.

Fig. 5. SAFT-UT tandem image of a semi-circular sawcut (0.6 x 0.3 inches). Both the B-scan side view and B-scan end view are shown.

MODIFIED TANDEM SAFT CONFIGURATION (TSAFT-2)

When considering inspection of certain materials, defects may exist at any depth in the specimen— from small cracks located at the far surface, to deep cracks or fabrication defects that will reflect energy near the scanned surface. A full vertical object plane needs to be uniformly illuminated in this type of specimen in order to accurately determine the nature and size
of the defects. Analysis of the tandem SAFT configuration reveals that illumination throughout a vertical object plane is in general not fully uniform. This is due to the fact that the transmitter is stationary and, due to laws of diffraction [7], will exhibit a non-uniform intensity distribution throughout the illumination aperture. This is easily seen by observing Fig. 6(a). Given two points in the object plane, \( P_1 \) and \( P_2 \), the rays striking these points from the transmitter arrive at unequal angles \( \phi_1 \) and \( \phi_2 \). It can be shown that the amplitude of the signal received by the scanned transducer, along independent paths, is not equal simply because the wave transmittance at the transducer-specimen interface is angle dependent. This phenomenon leads to undersizing when the object of interest extends beyond about half the beam-width (insonification angle).

An alternative tandem technique (TSAFT-2) was implemented to alleviate the illumination deficiency of the TSAFT configuration. This second configuration may be seen in Fig. 6(b). To maintain a constant illumination throughout a given object plane, the transmit transducer is scanned in the opposite direction as the receiver. For each object plane in this case, \( \phi_1 \) and \( \phi_2 \) are equal, thus ensuring that the total center ray path length is constant, from the transmitter to receiver. This concept has proven to be valuable when imaging the full vertical-object plane, and in particular it has enhanced the imaging of near-surface defects.

Figure 7 shows a comparison view of two SAFT-UT scans of the same object. Two opposing vertical sawcuts (semi-circular) were placed in a 1.0-inch-thick aluminum coupon. They were inserted such that there was a 0.050-inch separation at the center of the part. These objects were scanned implementing 5.0-MHz contact transducers in the 45-degree shear-mode configuration. The upper image shows the B-scan side view and B-scan end view of results obtained from the TSAFT configuration (fixed transmitter). It can be easily seen that the lower machined defect is imaged, while the upper

![Fig. 6a. SAFT-UT tandem (TSAFT) configuration.](image)

![Fig. 6b. SAFT-UT Tandem-2 (TSAFT-2) configuration.](image)
structure is not. This is primarily due to the aperture-limiting effect of the insufficient illumination. The lower image of Fig. 7 shows the corresponding results of the TSAFT-2 configuration. Notice that very good illumination resulted from simultaneously scanning the transmitter with the receiver. Also it may be observed that the image shows uniform reconstruction amplitude throughout the thickness of the specimen.

It may be expected that improved near-surface imaging should result from this technique. And this is the case. Figure 8 shows the B-scan side view and B-scan end view of an image of fabrication defects in the weld region of a carbon steel block. The block was 1.5-inches thick. The image shown is a result of a TSAFT-2 scan using 5.0-MHz contact transducers in a 45-degree shear-mode orientation. Of particular interest in this image is
the imaged defect located near the scanned surface. It is located approximately 0.2 inches from the near surface and is approximately 0.8 inches in length. This defect may easily have been overlooked in a volumetric inspection utilizing other configurations. The advantage of TSAFT-2 is the uniform illumination of the complete vertical object plane.

SUMMARY

SAFT-UT has evolved in recent years to become a viable real-time acoustical imaging method. A variety of configurations have been developed to accommodate various geometrical requirements and provide full-volume focusing capability. The single transducer, pulse-echo configuration provides a straightforward configuration for imaging volumetric defects, and for reliably detecting strong 'corner-trap' signals from vertical defects. The tandem SAFT configurations provide a means for sizing vertical defects and the TSAFT-2 technique, in particular, performs well for imaging the full vertical object plane. These results, along with the development of real-time processing, have moved SAFT-UT from a laboratory-imaging method to a field usable inspection technique.

REFERENCES


