APPLICATION OF ACOUSTIC WAVEFIELD IMAGING TO NON-CONTACT ULTRASONIC INSPECTION OF BONDED COMPONENTS

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\textbf{ABSTRACT.} Through transmission ultrasonic (TTU) methods are widely used for inspection of critical aerospace structural components because of their simplicity and the high sensitivity of TTU methods to bonding and delamination type defects. TTU inspection requires access to both sides of a component, which is generally not a problem before components are installed in final assemblies. However, limited access to the back side of a component on final assemblies usually precludes using TTU methods. Pulse echo (PE) methods are often used when only single side access is available, but PE ultrasonic methods have a limited penetration range from the outer surface, and do not have the sensitivity of TTU, particularly when surfaces are non-parallel. Thus, structural assemblies are often disassembled when a thorough TTU inspection is required. The work presented here addresses the need for a field deployable ultrasonic inspection method which has the sensitivity of TTU methods, is non-contact, i.e., couplant is not required, and does not require access to the back side of the part. These goals are accomplished by attaching a sparse array of ultrasonic transducers to the back side of a component or embedding them within the component. These transducers are excited to generate ultrasonic waves which propagate through the structure, and the resultant acoustic wavefields are imaged using a non-contact, air-coupled transducer. This ultrasonic wavefield imaging method is referred to as Acoustic Wavefield Imaging (AWI). Results are presented for a bonded aluminum plate specimen demonstrating that recorded wavefield images clearly show bonding flaws at internal interfaces.

\textbf{Keywords:} ultrasonic imaging, wavefield visualization, air-coupled ultrasound, guided waves

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\textbf{INTRODUCTION}

It is well known that ultrasonic guided waves may be generated in structures using attached or embedded piezoelectric transducers. Further, the use of ultrasonic guided waves has been proposed for inspecting large areas of a structure and this has been the subject of extensive research within the nondestructive evaluation (NDE) community [1,2,3]. Once developed, ultrasonics-based structural health monitoring (SHM) methods will have a profound effect on the field of NDE. As SHM systems are implemented and
their data become available, the role of NDE must be re-evaluated. There will most likely be a time period where SHM and NDE as we currently know it coexist in order to validate newly deployed SHM systems. Even after SHM systems have been verified, NDE methods will still be utilized to corroborate positive findings before an expensive structure is retired or undergoes costly repairs. Here we present a method which may be used to integrate SHM and NDE, both in the early stages of SHM system implementation and as SHM systems mature.

Ultrasonic methods are widely used for inspection of critical aerospace structural components when they are manufactured; however, the in situ use of ultrasonic sensors for SHM is still in its infancy. One approach is based upon a sparse array of permanently mounted ultrasonic transducers. The premise is that ultrasonic bulk, guided or diffuse waves can be generated and received between the various transducers to diagnose the health of the structure [4]. Once potential structural damage is detected, the next step is to determine the location and the extent of the damage [5]. The work reported here utilizes a newly developed method referred to as Acoustic Wavefield Imaging (AWI) [6]. This method integrates the attached transducers with conventional ultrasonic scanning methods to produce images of the propagating acoustic wavefield generated by permanently attached transducers. As is demonstrated here for a bonded aluminum plate, the resulting images approach the sensitivity obtained by conventional through transmission ultrasonic imaging.

Through transmission ultrasonic (TTU) methods are the standard techniques used for inspection of parts during the manufacturing process because of their effectiveness in detecting bonding and delamination type defects and their insensitivity to transducer normality. The requirement of accessing both sides of the part is usually not a concern before components are built up into final assemblies. However, access to both sides of components can be a severe problem for field inspections where extensive disassembly may be required. Pulse echo methods may be an alternative, but the inspection sensitivity may be compromised due to limited penetration range from one side, the sensitivity to incident angle, and difficulties in inspection non-parallel surfaces. Disassembly of built-up structures is often necessary to meet inspection requirements, although such disassembly can be expensive, time-consuming, and potentially introduce damage.

The AWI method presented in this paper may be an alternative to extensive structural disassembly when such detailed ultrasonic inspections are required. It is based upon using a sparse array of permanently mounted piezoelectric transducers to generate acoustic waves which propagate through the structure. An external air-coupled transducer acts as receiver and is scanned over the surface of the specimen. Ultrasonic waveforms are recorded from each location of the pixel grid for the AWI image.

Stored RF waveforms are processed and displayed as consecutive time slices, as shown in Figure 1. Propagating waves are visible as a concentric wavefield emerging from the embedded source transducer. Interactions with discontinuities in the structure are visible as scattered waves. Time slice images of RF waveforms, waveform envelopes, and accumulated energy waveforms are all useful presentation methods to show the interaction of propagating waves with the structure. The images shown in Figure 1 are examples of these presentations and show the image detail that is possible using the AWI method [6]. RF waveforms for these images shown in Figure 1 were from an immersion scan of a simple plate specimen with artificial flaws and serve to illustrate the nature of the images. Subsequent images are based upon data obtained with a scanned air-coupled transducer.
MEASUREMENTS

A bonded aluminum plate specimen was used for this study, which was constructed by epoxy bonding two 1.5 mm thick aluminum plates. The upper plate measured 31.5 mm x 61 mm and the lower 31.5 mm x 31.5 mm. Intentional disbonds were introduced by applying an uneven epoxy layer before joining the plates. Figure 2 shows a C-scan image of this specimen that was performed with an ultrasonic reflector plate method using a 100 mm focal length, 10 MHz immersion transducer. Disbond regions appear as dark areas on the right side of the specimen. Four 2.25 MHz PZT disc type piezoelectric transducers, 12.5 mm diameter, were permanently attached to the back side of the specimen and these

![C-scan Image](image_url)

**FIGURE 2.** Through transmission C-scan of bonded aluminum plate specimen (31.5 mm x 61 mm). Single sheet thickness, 1.5 mm, on left side and double sheet thickness on right side. Multiple bonding defects in the epoxy bond layer are visible as dark regions on the right side of the image. Four 2.25 MHz transducers are permanently mounted to the back side of the specimen.
are visible as dark spots on the C-scan image. The upper right transducer, T2, is only partially visible on the C-scan image because it happens to be mounted directly under the position of a large disbond. The specimen was attached to a mounting frame which is visible as a darker region around the edges of the image, and rivets used to attach the plate to the frame are also visible.

The wave source for subsequent AWI images was one of the permanently attached 2.25 MHz transducers, which was pulsed with a 900 volt broadband spike pulser (Panametrics model 5058 pulser/receiver). RF waveforms were recorded using an air-coupled 400 KHz, 50 mm focal length transducer (QMI #AS400ARi), which was scanned above the plate with a pixel resolution of 1.27 mm. This receive transducer has an internal low noise preamplifier, the output of which was connected to the receiver input of the pulser/receiver. Output signals from the pulser/receiver were digitized at 10 MHz with 8 bits of resolution, and were stored as 2000 point waveforms (200 µs) at each of 280 x 480 pixel locations. These waveform sets were collected in approximately 20 minutes using an automated scanning system (Panametrics LSC). This is a significant improvement in acquisition time over previous work using a scanning laser vibrometer system to capture surface displacements for forming wavefield images [7].

RESULTS

Results are first shown for pulsing transducer T1, which is mounted on the upper left quadrant of the specimen. The AWI images shown in Figure 3 were produced using this

![Figure 3](image)

**FIGURE 3.** Selected AWI images at various propagation times; (a) 20 µs, (b) 35 µs, (c) 50 µs, (d) 65 µs, (e) 80 µs, and (f) 90 µs.
transducer as the transmitter. Several snapshots of waves emerging from this transducer are shown in Figure 3 for propagation times ranging from 20 to 90 µs. The time scale is referenced to zero at the first observable wave disturbance from the source. Wave interactions with both the boundaries of the plate and impedance discontinuities in the specimen are clearly visible on these AWI images. After 90 µs the waves have reflected from several boundaries and the lead edge of the wave disturbance has just reached the right edge of the specimen. A vertical band of scattered energy is visible near the center of the images after 50 µs. This scattering is caused by impedance and bonding discontinuities associated with the transition between the single and double thickness plate sections.

The AWI images are a useful tool for visualizing and understanding complicated wavefields. The images of Figure 3 show several concentric wavefronts propagating outward from the source transducer. Some of these wavefronts are the result of multiple oscillations, i.e., ringing of the source transducer, and others are due to the excitation of multiple propagation modes in the plate because a broadband pulse was used to pulse the transducer. The AWI images provide snapshots of the wavefield at various propagation times from transmit, and it is straightforward to determine phase velocities and visualize effects of dispersion on these images.

Figure 4 shows the lead disturbance from the first major wave group as these waves propagate towards the lower right hand corner of the specimen. For reference, Figure 4(b) shows the C-scan image of a region containing several point discontinuities, a “hatchet” shaped bonding defect, and the shadow caused by transducer T3. The effects of all these discontinuities are visible on the AWI images. The void type flaws are believed to be from air bubbles trapped at the bonding layer between the aluminum sheets. These appear as

**FIGURE 4.** Selected AWI images for various propagation times of zoomed region with bonding discontinuities; (a) overall C-scan image of specimen with dashed lines highlighting zoomed region, (b) C-scan image of zoomed region, (c) 101 µs, (d) 103 µs and (e) 105 µs.
alternating light and dark spots as the waves traverse the region, but always at the same positions on each of the successive images. The “hatchet” shaped defect appears to “float on the surface” of waves traversing the region. The wave source was transducer T1, the same transducer used to generate the images displayed in Figure 3.

Processing steps are discussed next to remove the “bobbing” effect that results as RF waves propagate through the region and interact with local discontinuities. This effect is visible as alternating light and dark spots on the waveform images of Figure 4 where bubbles are trapped in the bonding layer. Additionally, the “hatchet” shaped defect appears to “float” on the surface of the waves traversing the region. The goal of the processing is to produce stable images free of these wave ripple effects, and smoothing operations such as simple rectification and energy accumulation were found to be very effective. The processing steps are to (1) calculate the envelope of the waveform via the Hilbert transform, (2) accumulate energy as a function of time along the waveform, and (3) take the square root of the accumulated energy to obtain an accumulated root energy waveform.

RF waveforms, envelope and root energy AWI images are shown in Figure 5 for the zoomed area depicted in Figure 4. The same “hatchet” shaped bonding defect and cluster of voids noted on the C-scan image of Figure 4 are easily recognized in all the plots of Figure 5. AWI images from envelope and energy processing steps are progressively less affected by the wave ripple, and discontinuities are resolved to a higher level of detail. The root energy AWI image best resolves the bonding defects, as was previously found [6].

The root energy AWI images are less sensitive to the propagation time than the RF and envelope images, and give optimum results if they are allowed to “develop” after the passage of the first wave through the region. Such was the case in Figure 5(c), where the root energy image is from waveforms delayed 15 µs from the other two images. The RF AWI image is the most sensitive of these three image types to wave ripple effects as was shown in Figure 4; i.e., the void indications oscillate in sign as the wave disturbance traverses the region.

Any of the four permanently mounted transducers placed on the specimen may be used as the wave source, and root energy AWI images are shown in Figure 6 for the same region depicted in Figures 4 and 5. For comparison purposes, these images have been intensity scaled to balance the contrast. All the major bonding defects and impedance discontinuities are resolved. A future processing challenge is to fuse such multiple transducer images to form a composite image for each area of the specimen.

![FIGURE 5. Comparison of various AWI images types for the zoomed region shown in Figure 4: (a) RF waveforms for a propagation time at 105 µs, (b) envelope of RF waveforms at 105 µs, and (c) the root energy waveforms at a propagation time of 120 µs.](image-url)
SUMMARY AND CONCLUSIONS

The usefulness of the AWI method has been demonstrated on a bonded aluminum plate specimen. Complicated defects intentionally placed at the bonding layer between two plates were effectively imaged by this method. A sparse array of four disk PZT transducers was permanently mounted to the back specimen surface, and an external, air-coupled, transducer was scanned over the plate to collect complete RF waveforms over a pixel grid of the specimen surface.

RF waveforms were recorded and processed to produce envelope and root energy waveforms, and AWI images were compared for all three data types. The AWI images, presented at various propagation times from transmit, all showed high spatial resolution images of defects at the bonding layer and from other impedance discontinuities in the specimen. The envelope and accumulated root energy images progressively smooth the data as compared to the recorded RF waveforms, and both minimize the oscillations associated with the passage of a wave disturbance through a region.

All regions of the specimen were subjected to waves separately transmitted from each of the four permanently mounted transducers. The separate AWI images of the waves from each source transducer give useful information about the local bonding conditions. A future processing challenge is to fuse such multiple transducer source images to form a composite image for each area of the specimen.

The sparse array of attached transducers is what might be envisioned for use on critical structures as part of future SHM applications. The advantage of the AWI method is

FIGURE 6. AWI images of the zoomed region shown in Figure 4 from separate transducers permanently mounted on the plate; (a) T1 (120 µs), (b) T2 (69 µs), (c) T4 (130 µs) and (d) T3 (55 µs).
to effectively use these same attached transducers as wave sources for subsequent, follow up NDE of potential regions with structural damage without requiring disassembly of built-up structures. This study has demonstrated that such follow up inspections, which have the further advantage of being non-contact, can produce images which approach the sensitivity of TTU NDE methods without the necessity of either using water as a couplant or having access to both sides of the part.

REFERENCES


