When pipe welds are inspected using phased array ultrasonic testing (PAUT), the common problem of beam divergence is amplified by the curved geometry. To compensate the adverse effects of beam divergence in curved parts, a focusing wedge can be used.

Many acoustic and inspection setup parameter validations are performed on flat blocks or plates even though the inspections are conducted on curved surfaces. Since the beam is affected by the radius of curvature at the various interfaces (for example, the wedge-to-part interface and back wall interface), the response to a discontinuity measured on a plate can be quite different from the response measured on a pipe. Recently developed passive-axis focusing (PAF) wedge technology can be used to address this challenge.

When an ultrasound beam propagates through a curved surface, the interface acts as a converging or diverging lens depending on the medium’s velocity ratio. In most typical nondestructive testing (NDT) applications, the ultrasound passes from a low-velocity medium (such as a Rexolite wedge) to a high-velocity medium (such as carbon steel) through a convex interface like an external pipe surface. This results in a diverging lens effect that causes the beam width to broaden. The images shown in Figure 1 illustrate beam simulations showing the differences between the beam in the passive axis on a flat surface (Figure 1a) and its equivalent when entering a 4.5 in. (11.43 cm) outside diameter (OD) surface (Figure 1b). The first medium is Rexolite (which has a pressure wave velocity of 2330 m/s), and the second medium is carbon steel (which has a shear wave velocity of 3240 m/s).

As illustrated in Figure 2, the inside diameter (ID) surface (or back wall) of the pipe acts as yet another diverging lens, broadening the beam even more.
Importance of the Beam Width for Scan Length Measurement

In most NDT applications, including girth weld inspection, the scan direction is along the phased array probe’s passive axis, and the discontinuity length measurement is performed using an encoded system. The most commonly used amplitude-based sizing method is the 6 dB drop technique. The advantage of this technique is that the discontinuity length is not affected by the beam width. However, this is only true if the discontinuity is longer than the beam width. The measured length of a discontinuity shorter than the beam width will correspond to the beam width itself. For example, the shortest indication that a 5 mm wide beam can measure is 5 mm long. This means that all indications smaller than 5 mm will be oversized and measured as 5 mm.

Focusing Phased Array Probes

Historically, standard phased array probes have been designed with plane elements because of their simplicity and versatility. Some probes that are specially designed for the inspection of smaller diameters feature curved elements (such as concave curvature in elevation probes) to counteract some
of the divergence occurring at the part interfaces. However, this curvature value is fixed and therefore not optimized for a wide range of diameters.

**Passive-Axis Focusing Wedges**
Wedge technology now exists that enables beam focusing that is optimized for specific pipe diameters. This PAF wedge technology uses two materials of different acoustic velocities, and the interface between the materials is shaped as a converging lens. The goal is to create a beam with a width similar to what is achieved with a flat wedge on a flat surface. PAF wedges used for smaller pipe diameters have smaller lens radiuses for a greater focusing effect, while larger-diameter wedges are fitted with larger lens radiuses. The top surface of the wedge is flat, enabling it to be used with standard probes (Figure 3) (Zhang et al. 2015).

**Experimental Results**
Two parts were manufactured with 1 mm diameter vertical through-holes separated by different distances. The parts and wedges used are shown in Figure 4. The first part is a plate (on the left), and the second one is a half pipe (on the right) with an outside diameter of 4.5 in. A standard Rexolite wedge with planar bottom face was used to acquire data on the plate, and two other wedges with curved bottom faces matching the half pipe’s diameter were used to acquire data on the curved part. One of the curved wedges was a standard Rexolite model, and the other was a PAF composite focusing wedge with a lens radius of 18 mm.

The objective of the experiment was to measure the beam width obtained with the three different wedges using the corner trap reflections of the through-holes on the ID (direct hit) and the OD (second leg) using the 6 dB drop technique.

The same ultrasound setup was used for all three wedges: a linear scan at a 55° refracted angle (natural angle of the wedge) in shear wave with apertures of eight elements using a phased array probe. The probe’s active aperture characteristics are as follows:
- 32 elements
- 0.6 mm pitch
- 19.2 mm active area
- 10 mm elevation

Figure 5 shows the relation between the C-scan view, the S-scan view, and the ray-tracing representation. On the left, a schematic from the inspection configuration software shows the lower beams hitting the OD corner trap after a reflection on the back wall and the higher beams hitting the ID corner trap. In the
S-scan view (center), the ID corner trap appears higher than the OD corner trap as it arrives earlier in time. On the C-scan view (right), the OD and ID corner traps are represented on top of each other for every through-hole in the scan direction.

This first data set (Figure 6) was acquired with the standard wedge on the flat plate. Although the reflectors are not perfectly uniform, the different corner traps of the seven through-holes are easily identifiable. The amplitude on the ID and OD indications are similar. Using the 6 dB drop technique, the beam width was measured to be 5.0 mm on the ID and 4.1 mm on the OD. The results are summarized in Table 1.

Figure 7 shows the second data set acquired with the standard wedge on the 4.5 in. OD half-pipe sample. The signal amplitude and discontinuity representation in the C-scan view are degraded compared with the previous results. It is difficult to determine the number of distinct indications present in the sample. The beam width was measured to be 5.7 mm on the ID and 7.5 mm on the OD. A beam width of 7.5 mm signifies that all indications would be measured to be at least 7.5 mm long. According to a common code such as ASME B31, which states that the maximum acceptable defect length is 6 or 6.4 mm depending on the code case, all indications detected with this setup would be rejected (ASME 2020).

The third and final scan (Figure 8) was acquired with a PAF wedge on the 4.5 in. OD half-pipe sample. The C-scan view is greatly improved compared with the standard wedge (Figure 8c). Furthermore, the overall image is sharper than the one acquired on the flat plate. The measured beam width was 3.5 mm on the ID and 4.2 mm on the OD.
Conclusions
This experiment demonstrated the negative impact of the part curvature on the length-sizing resolution capability. However, it also showed how the beam divergence caused by the part’s external curvature can be compensated for using a PAF wedge with a standard phased array probe. Because of the resulting smaller beam width, this combination of a PAF wedge and phased array probe can enable the measurement of smaller discontinuities and provide sharper images to simplify data interpretation and decrease the rejection rate.

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<table>
<thead>
<tr>
<th>ID (mm)</th>
<th>OD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard wedge – plate</td>
<td>5.0</td>
</tr>
<tr>
<td>Standard wedge – pipe</td>
<td>5.7</td>
</tr>
<tr>
<td>PAF wedge series – pipe</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Table 1: Summary of beam width measurements

Figure 7. Views of data acquired with a standard wedge on a 4.5 in. (11.43 cm) OD pipe: (a) A-scan; (b) S-scan; (c) C-scan.

Figure 8. Views of data acquired with a passive-axis focusing wedge on a 4.5 in. (11.43 cm) OD pipe: (a) A-scan; (b) S-scan; (c) C-scan.
Editor's Note: This article has been divided into two parts. Part 1, published in April 2021, included a basic description of the acoustic emission testing (AE) method and other important factors. Part 2 will discuss the various materials used in construction, including both metals and composites, and the influence they have on the AE data.

Metal Materials
Discontinuities (such as cracks, inclusions, and other defects) in metals can be revealed by the detection of plastic deformation development around them. At the crack tip, stresses can exceed the yield stress level, causing plastic deformation (Figures 1 and 2).

![Figure 1. Stress/strain versus acoustic emission activity.](image1)

The size of the plastic zone can be evaluated using the stress intensity factor $K_I$, which is the measure of stress magnitude at the crack tip:

$$r_y = \frac{1}{2\pi} \left( \frac{K_I}{\sigma_{ys}} \right)^2$$

where

$r_y$ is the plastic zone size in elastic material.

The critical value of the stress intensity factor, $K_{IC}$, is the material property called fracture toughness (Figure 3). The behavior of the discontinuity and its corresponding acoustic emission hit signature is also influenced by other conditions, both in service and within the metallurgical structure itself.
Figures 4 through 8 show some examples and the typical signatures from these cases. To evaluate the acoustic emission data that is recorded in a tabular format, real-time plots called “correlation plots” are used to show the relationship between the amplitude versus the energy and duration of the hit. Figure 9 shows a typical correlation plot of the acoustic emission hits recorded during an AE test. It is noted that several types of acoustic emission sources can be identified from these graphs.

Composite Materials
These materials are regarded as nonhomogeneous and typically contain two or more components in their makeup. For example, fiber-reinforced plastics (FRP) contain both the fiber and the bonding resin, and concrete will have sandstone and cement along with possible steel reinforcing it. Therefore, the sources of acoustic
emission activity may be complex. In addition to this, FRP tends to be viscoelastic and does not exhibit the same elastic behavior as steel.

The following is a short discussion of some of the types of acoustic emission activity that will be encountered during the AE of structures that use this type of material (Figure 10).

It is important to understand that each failure mechanism has its own acoustic emission signature, and it is strongly advised to follow ASME Section V, Article 11 (ASME 2019a) or CARP (Committee for Acoustic Emission in Reinforced Plastics) (CARP 1987) procedures when conducting an AE test of this type. Numerous studies and research have gone into the setting of the accept/reject criteria and recommendations in these procedures.

Types of Acoustic Emission Activity

The amplitude of the AE sensor response to the stress wave received is very much dependent on the following factors:

- Distance: the distance from the source to the AE sensor.
- Attenuation: the attenuation of the stress wave is a function of the absorption of the hit energy by the material carrying the hit. Coarse grain = high attenuation; fine grain = low attenuation.
- Frequency: the acoustic emission stress wave at the source is broadband in frequency. Therefore, in order to detect and measure the acoustic emission hit, special-frequency bandwidths are used during data collection to avoid background noise.
Figure 9. Correlation plots of the acoustic emission hit data showing mechanical rubbing, microcracking, and macrocracking: (a) energy versus amplitude versus hits; (b) duration versus amplitude versus hits.

Figure 10. Typical discontinuities in fiber-reinforced plastic material.
sources. The choice of the bandwidth used in the data collection should consider the effect of the frequency on the attenuation, thus reducing the effective sensor-to-source distance. The higher the frequency of the bandwidth that is used, the greater the reduction on the sensor-to-source distance.

Most common background noise sources are in the audio range of below 20 kHz. For normal field testing, the range is typically 100 to 300 kHz, where a typical 150 kHz resonant transducer is used. This restricts the source-to-sensor distance to approximately 20 ft (6 m) in steel. In special cases and where the environmental noises allow lower frequencies, bandwidths of 20 to 100 kHz can be used with a 60 kHz resonant transducer. On average, this will increase the source-to-sensor distance to 40 ft (12 m) in steel under the same conditions. Under extreme conditions, AE monitoring can be done with bandwidths as low as the 10 to 20 kHz range by using 30 kHz resonant transducers with the knowledge that low-frequency background noise levels are likely to make interpretation of the AE data difficult.

Crack Sizing Using AE

It is particularly important to understand that without very extensive study of the acoustic emission signature from a specific material and crack size, it is impossible to estimate the size of the crack from the hit data. However, when using a controlled stimulus (such as load or pressure), the acoustic emission activity and signature is a reliable tool to determine if the discontinuity detected is critical to the operation of the structure. For this reason, the structure being tested is always loaded in stages. For example, in ASME Section V, Article 12 (for new and in-service structures) the typical load schedules are recommended as shown in Figure 11 (ASME 2019b). More details about the loading procedure are available in Article 12 (ASME 2019b) and MONPAC procedures (Fowler et al. 1989).

Conclusions

Many papers have been published concerning the advantages and disadvantages of the use of AE as an NDT tool. However, many of these papers fail to reference the material factors and their influence on the results recorded and the interpretation of the recorded results. AE practitioners who have many years of experience in conducting AE tests in most cases realize this, but nothing to date has been published concerning the factors that determine the success of the use of this method. This paper is an attempt to clarify the data analysis process and lead to better results.

AE has now come of age, and it is important to note that the success or failure of a test is in the hands of the user, and not the instrumentation or the software.

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Practitioner Profile

Roger Jordan

Samuel "Roger" Jordan is the owner and president of Turbo NDT Inc. in Houston, Texas, but he still enjoys working hands-on in the field. He is an ASNT NDT Level III (MT and PT) and certified in positive materials identification (PMI) by the American Petroleum Institute.

Q. How did you become involved in NDT?
A. I started my career in NDT on 1 October 1980, right after high school. I went to work for Industrial Inspection Inc. in Houston, Texas, which was owned by Earl D. Hayley. He was my first mentor.

Q. Can you describe the work you do?
A. Currently I am the president/owner of Turbo NDT Inc., which I started in April 2006. Today I have 10 employees. We provide NDT work in our lab and in the field. I do supervise some jobs and work with my crew as required, but I typically work hands-on and solo. I perform magnetic particle testing (MT), liquid penetrant testing (PT), ultrasonic testing (UT), positive materials identification (PMI), and hardness inspections on a daily basis for various clients.

I am also involved in the reviewing of specifications and personnel qualifications, and providing technical support to clients, including quoting, writing procedures, and purchasing.

Q. What kind of certifications do you hold?
A. I completed my classroom and training hours on the job with Industrial Inspection Inc. for my Level I and II in MT, PT, VT, and UT in 1982. I completed my NDT Welding Inspection Technology degree from San Jacinto College in 1988. I became an ASNT NDT Level III in MT and PT in 1990, and I’m also API RP 578 PMI certified. As well, Turbo NDT is an ISO 9001:2015 certified company.

Q. Is your work focused on a particular field?
A. We do NDT work for machine shop and fabrication facilities, but we are most notable for our work with rotating equipment and our specialized demagnetization services. For example, we utilize large MT HWDC (half-wave direct current)/AC (alternating current) machines from 3000 up to 6000 amps, using cables to wrap rotating equipment in two directions.

Q. Are you involved in your local ASNT section?
A. I have been involved in the Greater Houston Section for many years as a director. I oversee the Technician of the Year award and the golf tournament. My message to all NDT personnel is to join your local section and attend meetings to learn and collaborate with your fellow ASNT members.

Q. What innovations have impacted your work?
A. The advancements in PMI utilizing laser induced breakdown spectroscopy (LIBS) versus optical emission spectroscopy (OES) for carbon detection has had the most effect on my technicians. The OES machines are large and cumbersome to haul around. In contrast, the LIBS analyzers are light and handheld.
Q. **What is your most interesting NDT application?**
A. Of course, that would be the demagnetization of parts. We are one of a few companies that can handle specialty demagnetization of large and small components. A few years ago we had a request from a local car dealership to demagnetize a pickup truck that had been struck by lightning. The dealership needed to replace the rearview mirror, which had a compass, and the magnetism damaged the compass each time. When we received the truck, we scanned the entire truck with a gauss meter and found a hot spot of magnetism (20+ gauss) located on the roof, near the windshield. We wrapped the truck in foam to protect the paint. We then placed our demagnetizing cable around the truck and induced downcycle DC. Final result: the truck was demagnetized to an acceptable limit of 2 gauss or less. The dealership’s insurance company was happy that they did not have to scrap the expensive truck.

Q. **What is the best part of NDT?**
A. I take great pride in my and my employees’ ability to find discontinuities that could lead to catastrophic issues. The NDT methods we use can save equipment from failures, and even save lives. One example is a brand-new ring bevel gear that had been shipped from an overseas manufacturing facility and had never been inspected. We conducted wet fluorescent MT and found serious defects (see photo on left). If this gear had been installed in operation, it would have eventually destroyed all the gears in the gearbox.

Q. **How has NDT changed in your career?**
A. Many new methods have evolved, but the old methods such as MT and PT still play a huge role in our industry. I look at phased array ultrasonic testing (PAUT) and digital radiography as growth areas. I would like to learn more about PAUT.

Q. **Have you ever had a mentor or been an NDT mentor?**
A. I have been mentored by some of the best in the NDT industry. My experience has taught me how to mentor my employees and the younger, up-and-coming members of the Greater Houston Section. I received a mentor award from the Greater Houston Section in the past. It was a very proud moment.

Q. **What can industry do to encourage careers in NDT?**
A. I think we need to bring back trade schools at our local high schools once again with an emphasis on NDT.

Q. **What is the best way to advance a career in NDT?**
A. Continued education, certifications in multiple methods, a great attitude, and hard work.

Q. **What advice do you have for individuals considering careers in NDT?**
A. It can be a very rewarding and profitable career. Remember that the effort you put into studying, training, and working is what you get out of it.

Q. **Do you have a favorite quote that inspires your work?**
A. Treat people the way you want to be treated.

Roger Jordan can be reached at roger@turbondt.com.