Variables to consider in the fabrication of ultrasonic reference blocks

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Abstract
Flat bottom holes in cylindrical blocks have long been used as references for sensitivity settings of ultrasonic instruments. In addition to setting sensitivity, these blocks are sometimes used as a means of monitoring probes and instruments for change over time. A description of the fabrication requirements for the standard set of reference blocks can be found in ASTM standards E127 and E428. In ASTM E127 there is a tolerance allowed for the expected responses. This paper considers some of the variables that might be responsible for deviation from the ideal curve of amplitude responses expected and examines the degree of variability that might account for these variations.

Keywords: NDT, ultrasonic, reference blocks, flat bottom hole, ALCOA, simulation, modelling

1. Introduction
Flat-bottom-holes (FBHs) have long been a popular means of setting reference sensitivity for ultrasonic inspections. Although some applications use these targets with angled shear mode (as described in ASTM E1961 [1] for pipeline girth welds and in ISO 17640 [2] for general tandem applications), by far the most common use is with 0° compression mode inspections on plate and forgings.

The relationship between echo response and FBHs has been addressed since some of the earliest developments in ultrasonic testing. Krautkramer [3] referred to these as a disk shaped reflector (DSR) and developed the famous AVG (English DGS) method of relating amplitude responses from FBHs to curves made for each style of probe. The relationship between echo amplitude and probe and FBH size can be summarised in the form of an equation.

\[
\frac{V_i}{V_o} = \frac{SA}{\lambda^2 T^2} e^{-2\tau \delta}
\]

Where
\(V_i\) = the maximum amplitude of the echo from the target
\(V_o\) = the maximum possible signal amplitude if all energy is returned to the receiver
\(T\) = the distance along the beam axis to the target
\(A\) = the area of the probe
\(S\) = the area of the probe
\(\lambda\) = the wavelength of ultrasound (nominal)
\(\delta\) = the attenuation coefficient

Ermolov [4] subsequently developed a series of equations that related other ideal reflectors such as side drilled holes, rectangular targets and infinite plane to the responses from FBHs.

In the 1950s ultrasonic instruments relied on cathode ray tube (CRT) displays. These were prone to regions of non-linearity if the CRT deflector plates were misaligned. Misalignment could easily occur if the instrument was bumped. Relating the equivalent FBH size to a reference target (i.e. a FBH of a known size) was only valid in the voltage displacement (vertical scale) region assessed as being in the linear range of the instrument. From the
findings of Krautkramer it was possible to note that the amplitude change for a FBH was directly proportional to its area. Therefore, having set a response on the CRT to a specific amplitude (within the linear region of the instrument display) the response from a FBH half the area would produce a signal with half the amplitude and the response from a FBH double the area would produce a signal with double the amplitude.

With this feature of amplitude relationships between FBH targets of known sizes, the use of FBHs was also useful as an instrument and probe characterisation tool.

2. ASTM Standards

In 1977 Burley [5] described the work that led to the development of ASTM standards E127 [6] and E248 [7]. The first standard dedicated to standardising the process was for a specific alloy of aluminium, 7075-T6. The work started in 1951 and the ASTM document E127 was published in 1958.

Only two years after the task group responsible for the E127 document was formed, another task group was formed to consider a similar document for steel blocks. This led to the publication of ASTM E428 in 1971.

However, shortly after its publication it became apparent that the method of checking the blocks was no longer appropriate not even capable of being accomplished. Burley noted that precisely drilled holes in test blocks serve to:

- Establish test procedures
- Set sensitivity level
- Check equipment performance
- Permit test repeatability

These functions are well served when the blocks are used at a particular site. However, there is no guarantee that a similar set of reference blocks used with ultrasonic equipment at one site will produce identical results at a different site. The aluminium industry had hoped that by establishing a single standard method of setting sensitivity, all inspections industry-wide would produce a product of the same quality level. Better understanding of the sources of amplitude variations made it clear that the goal of a single traceable standard level of sensitivity was not possible. Although machining processes could be documented to conform to ASTM requirements, ultrasonic probes and instrumentation were changing so the ASTM requirements for ultrasonic response could not be certified. To add to these problems, the original metallurgical characteristics of the 7075 aluminium alloy had changed making it impossible to control the material to the same standard as the original.

Unlike the requirements in E127, E428 did not use an external reference for the standardising of the blocks. Instead, E428 relied on controlling the machining processes instead of standardising the ultrasonic responses of the FBHs. Although controls are made for target squareness, surface finish, and dimensional accuracy, the general variability of metal properties precludes any method that would require standardising of the ultrasonic response to an external “gold standard”.

Instead of relating the ultrasonic responses to an external gold standard, E428 uses a process whereby the blocks are treated as a “set” and any block that has an ultrasonic response within
a defined tolerance for the area-amplitude or distance-amplitude curves does not meet the requirements of ASTM E428.

The remainder of this paper will consider variables in the materials, targets, ultrasonic test equipment and the effect they have on the expected amplitude responses of the ideal targets. In order that the variable parameters be well known and well controlled, the analysis will be done using Civa simulation software. This is a well validated modelling programme that regularly demonstrates the accuracy of its algorithms in the QNDE Benchmark trials [8].

3. Variables Modelled

Simulation software permits analysis of the effect of individual or combinations of variables. Numerous examples of variables run using Civa software are seen in the literature. Typically the results are compared to tests set up using probes and physical targets of the same values as those modelled [9, 10]. When the inspection and modelling conditions are identical the amplitude results of modelled signals are generally within 2dB or less of the physically measured values.

When considering the setup to assess the ideal responses expected from FBHs in ASTM reference blocks numerous variables can have a bearing on the results. Sources of variation can be grouped into 3 categories;

1. Probe variables
2. Target variables
3. Material variables

Although each of these items is covered in the instructions of the ASTM standards, there are obvious tolerances in each category. For example, the stated 5MHz 0.375 inch diameter immersion probe is not defined with a specific bandwidth. Electrode size determines the actual active area of the probe and the electrode might be slightly off centre or slightly more or less than the nominal 0.375 inch diameter. Although a probe is given a nominal frequency, the effects of damping or variations in lapping can result in some deviation of the centre frequency from the nominal. Therefore within each category of variable, several parameters can be considered.

In order to obtain an idea of the degree of effect of each variable the modelled test will start with ideal conditions. Targets identified in E127 and E428 for area/amplitude and distance/amplitude assessments are configured as per the instructions in the ASTM standards. This allows the simulation software to obtain the optimum signals that can be expected. Variations in selected parameters are then used to determine the effect on amplitude when the simulated scanning is repeated.
Each of the three variation categories is identified with parameters that will be varied within the tolerances identified:

1. **Probe variables**
   a. Centre frequency 5MHz +/- 10%
   b. Bandwidth 70% +/- 20%
   c. Active diameter 9.5mm +/- 0.5mm
   d. Incident angle 0° +/- 2°

2. **Target variables**
   a. Diameter Nominal +/- 20%
   b. Surface finish of entry surface 0.76µm +3.2µm
   c. Tilt off perpendicular 0° +/- 2°

3. **Material variables**
   a. Velocity (compression only) Nominal +/- 1%
   b. Attenuation Nominal +/- 50%

4. **Observations and comparison to historic plots**

Data collected is compared over the range of variations in parameters of the modelled aspects. A further comparison is made by comparing historically generated plots of amplitude variations from several lab tests carried out over the past 50 years.

4.1 **Baseline test**

Area/amplitude and distance/amplitude curves are generated for the ideal conditions. The probe modelled is an immersion 5MHz probe with 9.5mm (3/8 inch) diameter and a bandwidth of 70%. The immersion setup assumes a water velocity of 1483 m/s.

The beam pressure plot is illustrated in Figure 1. The echo-dynamic plot of the amplitude along the beam axis in water is seen below in the colour plot. As predicted, the end of the near zone (termed the \( Y_{o}^{+} \) in ASTM) is seen at 77mm (3.03 inches).

![Figure 1](Standard immersion probe for ASTM E127 assessments)
Measurements for the standard block assessments in ASTM require that the immersion probe have a waterpath to the block surface equal to the near zone distance as determined by immersion assessment of the beam using a small ball target. ASTM E127 (para. 11.5.4) indicates that the expected near zone in water for such a probe occurs between 3.2 inch to 3.6 inch (81-91mm). This does not coincide with the modelled condition seen in Figure 1 nor does it follow from the expected distance from the standard equation.

\[
N = \frac{D^2 f}{4v}
\]

Where;
\( N \): Near Field Distance
\( D \): Element Diameter
\( f \): Frequency
\( v \): Material Sound Velocity

This equation confirms the Civa model and predicts a near zone in water \((v=1483m/s)\) for the 5MHz probe of 76mm (2.0 inch).

It is understood that the intent of the instructions in ASTM E127 is to maintain the detection of the targets in the far zone of the beam so that there is no chance that beam fluctuations could account for erratic amplitude responses to the targets.

Two calibration specimens were designed to assess the amplitude responses of the ASTM reference block sets;
- Area/amplitude set
- Distance/amplitude set

The area/amplitude set consisted of eight FBHs arranged to have a 3 inch metal path distance to the FBH targets. The FBH targets range from \(1/64^{th}\) inch to \(8/64^{th}\) inch in \(1/64^{th}\) inch increments. The modelled block for the area/amplitude work is seen in Figure 2.

**Figure 2**  Model of block with FBHs for area/amplitude assessment
The distance/amplitude set consisted of four rows of 19 FBHs arranged to have stepped metal path distances equal to the 19 metal path distances identified as “customarily included in commercial 19 block distance-amplitude sets”. The FBH targets in the first row are 1/64\textsuperscript{th}, in the second row 3/64\textsuperscript{th}, in the third row 5/64\textsuperscript{th} and in the fourth row they are 8/64\textsuperscript{th} inch diameter. The modelled block for the distance/amplitude work is seen in Figure 3.

![Figure 3](image)

**Figure 3** Model of block with FBHs for distance/amplitude assessment

Modelling requires that the material properties be known. For the aluminium assessments the following properties were used:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy</td>
<td>Aluminium 7075-T6</td>
</tr>
<tr>
<td>Density</td>
<td>2.79 g/cm(^3)</td>
</tr>
<tr>
<td>Longitudinal acoustic velocity</td>
<td>6350 m/s</td>
</tr>
<tr>
<td>Transverse acoustic velocity</td>
<td>3100 m/s</td>
</tr>
<tr>
<td>Attenuation</td>
<td>0.4 Np/m @ 10MHz [11](^1)</td>
</tr>
<tr>
<td>Power of the attenuation rate</td>
<td>2</td>
</tr>
</tbody>
</table>

\(^1\) 0.4 Np/m converts to 3.5dB/m or 0.0035 dB/mm
4.2 Area/Amplitude Baseline

The echo dynamic plot of amplitude as the targets are scanned is illustrated in Figure 3.

![Echo-dynamic plot of amplitude in aluminium](image)

**Figure 3** Echo-dynamic plot of Standard Reference Block set for Area/Amplitude FBHs in aluminium

The resulting curve is seen in Figure 4 and compares well with the ASTM curve from ASTM E127 (Figure 5 in E127). Note that the ASTM figure does not relate to an absolute value but uses relative area starting with 1 and doubling each point.

![Area-amplitude responses](image)

**Figure 4** Area-amplitude plot (Civa results left, ASTM E127 results right)
4.3 Distance-amplitude baseline plots

ASTM E127 provides a reference-type curve for the 3/64\(^{th}\) inch diameter FBHs. It lists 24 metal path distances from 0.5 inch to 6.0 inch and plots the curve shape in two separate curves. This is done to allow improved amplitude resolution when making visual assessments on the ultrasonic instrument A-scan display.

![Distance Amplitude Plots](image)

**Figure 5** Distance-amplitude plots (Error bars on Civa plots indicate +/-3% error)

Civa plotted points in Figure 5 include the 4 metal paths in the 19 block set that are not used in the graph illustrated in ASTM E127.

A high resolution linear scan over the first 5 targets in the Civa model is seen in Figure 6. This is shown as a B-scan that includes the entry surface and backwall signals. When the gain is increased to a value suitable for making amplitude measurements the water-metal interface signal becomes large and can obscure the signal from the FBH if it is close to the entry surface. Bandwidth of the probe modelled is 70%. This would be slightly more damped than most probes available in the 1950s and 1960s so the use of the holes with a metal path of more than 0.5 inch would have been a practical solution for those using a 5MHz narrow bandwidth probe.
4.4 Variables

Having established a baseline set of curves for the reference blocks using a specified set up, we can now examine the effects of some common variables. These were noted above and some tolerances were suggested:

1. Probe variables
   a. Centre frequency 5MHz +/- 10%
   b. Bandwidth 70% +/- 20%
   c. Active diameter 9.5mm +/- 0.5mm
   d. Incident angle 0° +/- 1°

2. Target variables
   a. Diameter Nominal +/- 20%
   b. Surface finish of entry surface 0.76µm +1.0µm
   c. Tilt off perpendicular 0° +/- 6°

3. Material variables
   a. Velocity (compression only) Nominal +/- 1%
   b. Attenuation Nominal +/- 50%

Comparison of the amplitude responses of the setups with the variables applied is made to the reference curves.
4.4.1 Probe Variables

Bandwidth
The first variable considered is probe bandwidth (BW). The baseline models use 70% BW. When remodelled with 50% and 90% BW the centre axis plot of pressure indicates no change occurs in the location of the near field length and only a slight difference in amplitude is expected with the 50% BW (least damped) having approximately 0.4dB more sensitivity than the 90% BW (most damped) probe.

![Figure 7](image1.png)

**Figure 7** Bandwidth effects on the beam-axis pressure plot (70% blue line, 50% red line, 90% black line)

The effect on the distance-amplitude curve is negligible with a maximum variation less than 1% on any point of the 19 reference blocks. The similarity of curves is illustrated in Figure 8.

![Figure 8](image2.png)

**Figure 8** Bandwidth effects on distance-amplitude curve
Centre Frequency
Centre frequency would be expected to have a greater effect on the prober performance. Not only does it affect the distance to the end of the near field, the efficiency of the output can be affected. Three centre frequencies are compared all having a bandwidth of 70%. Frequencies assessed are 4.5MHz, 5.0MHz and 5.5MHz (i.e. the nominal 5MHz +/-10%). These centre frequencies have near fields in water of 68.5mm, 77mm and 84mm respectively as illustrated in Figure 9.

![Figure 9](image)

**Figure 9** Near field shift with centre frequency change of +/-10% from 5MHz (4.5MHz black line, 5MHz blue line, 5.5MHz red line)

ASTM requirements for setting waterpath require determining the near zone distance prior to scanning. To assess the effect of frequency on the amplitudes of the reference targets it is therefore necessary to adjust the waterpaths to match those of the centre frequencies. Scanning of the targets at 4.5MHz and 5.5MHz are therefore compared using 68.5 and 84mm waterpaths. The results of this comparison are seen in Figure 10.

![Figure 10](image)

**Figure 10** Comparing relative responses to centre frequency for distance amplitude curves (+/-3% error bars on 5MHz curve)
Figure 10 illustrates the relative amplitudes with the largest amplitude normalised to the shortest metal path. However, if the values are normalised to the highest amplitude from all three probes, the effect of frequency on each target relative to the other frequencies can be seen. This is illustrated in Figure 11.

![Distance-Amplitude Plot](image)

**Distance-Amplitude Plot**

Normalised to 4.5MHz probe

**Figure 11** Comparing target-to-target responses to varying centre frequency on the reference targets in the distance-amplitude set (+/-3% error bars on 5MHz curve)

**Active Diameter**

Probes are sold with a specified nominal diameter. The piezo-electric effect is controlled by the area between the electrodes on the opposite surfaces of the piezo-element. Most modern NDT probes are now made with the entire surface of the piezo-element coated with a conducting electrode. This makes the effective diameter of the element the same as the electrode. However, it is conceivable that a portion of the element might miss getting a full electrode deposited. Not only could this reduce the effective diameter, it could off-set the centre of the beam from the centre of the element. For the purposes of this comparison paper, we will look at just the reduction in size as a variation in diameter.

The nominal probe identified in ASTM E127 (note in para. 11.3.5) is 0.375 inch probe with a metric equivalent given as 9.53mm. Modelling in this paper has been using the rounded value of 9.5mm. To investigate the effect on size of the element a small range of tolerance is applied (+/- 0.5mm or about +/-0.02”).

Element diameter is a controlling factor in the near field length. As with the frequency we can expect the near field to vary depending on the diameter of the peizo-element. Figure 12 illustrates the degree of change with a +/-0.5mm diameter change in the nominal 9.5mm
element. The near field is seen to change from 68.5mm for the 9mm diameter condition to 84mm for the 10mm diameter condition.

![Figure 12](image)

**Figure 12** Comparing near field distances and relative amplitudes for element diameter variations; 9mm diameter (blue curve), 9.5mm diameter (red curve) and 10mm diameter (black curve)

When the distance amplitude reference block set is scanned using the three different probe sizes the responses from the 10mm diameter element are seen to be slightly greater than the reference 9.5mm diameter. Similarly, the 9mm diameter element responses are slightly less than the reference 9.5mm diameter element. The relative responses are seen in Figure 13.
Figure 13  Comparing target-to-target responses to varying probe diameter on reference targets in the distance-amplitude set (+/-3% error bars on 9.5 mm diameter probe curve).

Beam tilt

The final parameter we examine that relates to the scanning setup is the tilt of the beam to the test surface. ASTM E127 suggests that a 1° accuracy is feasible when using a standard angulation mechanism. The effect of 1° tilt from the perpendicular is illustrated in the plot comparison in Figure 14. A 1° change in the angle of incidence results in a refracted angle of 4.3°.
When viewed as a target to target comparison using the largest response as the reference, there is no significant difference noted between perpendicular incidence and 1° or 2° incidence. The three curves overlay each other nearly identically. However, when the curves are compared relative to the highest response (0° incident angle) there is a noticeable and relatively consistent 1.5 dB difference between 0° and 2° incident angle. The difference between 0° and 1° responses is generally lower, around 0.5 dB.

Figure 14  Comparing target-to-target responses to varying incident angle

When viewed as a target to target comparison using the largest response as the reference, there is no significant difference noted between perpendicular incidence and 1° or 2° incidence. The three curves overlay each other nearly identically. However, when the curves are compared relative to the highest response (0° incident angle) there is a noticeable and relatively consistent 1.5 dB difference between 0° and 2° incident angle. The difference between 0° and 1° responses is generally lower, around 0.5 dB.

Figure 14  Comparing target-to-target responses to varying incident angle by scanning echo-dynamic amplitude (0° tilt is indicated by the black line, 1° tilt by the red line and 2° tilt the red line)
4.4.2 Target Variables

Diameter

Diameter variation of targets has been addressed in the assessment of the responses in the area-amplitude blocks. The amplitude response is directly proportional to the area of the FBH.

To indicate the degree of sensitivity of the ideal curve to potential variations in machining, a scan is made comparing three of the 19 distance-amplitude targets that have been adjusted to errors in diameter. By selecting a short, medium and long metal path and adjusting the same three targets by 10%, 20% and 30% of the nominal 3/64 diameter, isolated deviations from the trend can be expected.

Targets selected for adjustment of diameter with the 3/64th inch diameter FBHs with metal paths of 0.5 inch, 2.25 inch and 5.25 inch. These were adjusted in increments of 10% of the nominal diameter. Starting with the nominal 1.19mm diameter, the decrease of 10% changes the diameter to 1.07mm and the increase changes it to 1.31mm. With a 20% change the diameter changes to 0.95mm at a 20% decrease and 1.43mm for an increase of diameter.

Since the amplitude of a response is directly proportional to the relative area of the FBH, the amplitude changes seen on the plots in Figure 15 indicate the area change of the hole relative to its ideal diameter. E.g. an increase of 10% in diameter results in an increase in area of 21%. This translates to a 21% increase in amplitude over the value that would have been read.
if the FBH was the ideal $\frac{3}{64}$th inch diameter. For the 0.5 inch metal path FBH the initial Civa-modelled amplitude was 68.5% and the amplitude noted when the diameter increase by 10% is seen as 82.5%. Errors in the amplitude estimations increase with lower display amplitudes. Amplitude estimates might feasibly be made to +/-1% of the display height so for amplitude readings below 10% screen height the potential error is greater than for readings taken in the range of 80-90% display height.

**Surface finish (entry)**

ASTM E127 specified the surface finish of the entry surface of the reference blocks. This is stated as 30µin (0.76µm) or smoother for the final finish quality. Prior to end facing the surface finish is permitted to be 63µin (1.6µm).

When modelled, the effect on amplitude response between these two finishes is negligible at less than 0.1% of the full display height. Even at a surface roughness of 3.2µm (i.e. 8 times rougher than the required surface finish) the effect on amplitude is less than 0.5% of the full scale display when the signals are set to 100% display height.

At 5MHz nominal frequency, the wavelength of the pulse in water is 0.3mm. The surface roughnesses considered are 0.00176mm to 0.0032mm.

**Tilt**

Perpendicular incidence of a beam on a planar target is assumed to provide the optimum response. However, the effect on small targets is not as pronounced as might be expected. A simulated scan of the $\frac{3}{64}$th inch diameter FBHs was made with tilt adjustments made to the same 3 selected targets as were used for the diameter change assessments. Tilt was adjusted by 1°, 2°, 4° and 6° from the perpendicular. Figure 16 illustrates the centre of beam ray incident on the 6° tilted FBH with the 0.5 inch metal path.

![Figure 16](image)

The effect of tilt on amplitude response for these three targets is small e.g. the ideal amplitude from the perpendicular incidence for the 0.5 inch metal path target was 68.5% display height and the amplitude when the FBH was tilted 6° dropped to 63%. As with the diameter variations, the effect is best seen for signals above 60% display height. The effect of tilt
deviating from the ideal perpendicular condition, for an isolated reference block in a 19 block set, would probably be difficult to identify in a typical test environment. As displayed in the curve, the effect is seen in Figure 17. Note that the variations at 2.25 and 5.25 inch metal paths are barely discernible from the standard curve.

![Distance-amplitude plot](image)

**Figure 17** Effect of target tilt on distance-amplitude for 3/64 th in FBHs at 0.5”, 2.25” and 5.25” metal paths

### 4.4.3 Material Variables

**Acoustic Velocity**

Acoustic velocity not only changes the arrival time of signals, it can change the acoustic impedance of the material assuming the density is constant. The nominal velocity used for the baseline curve was 6350m/s. When the velocity is lowered by 5.5% to 6000m/s the acoustic impedance is also lowered. This has the effect of allowing more pressure to transfer to the block. The result on the distance amplitude curve is to adjust it up relative to the higher velocity curve. This is shown in Figure 18.
Attenuation

Of the many potential variables influencing amplitude response of the targets in the reference blocks, attenuation is perhaps the most difficult to assess. Generally the assumption is made that the material being used for the block has been tested to be free of any processing imperfections (e.g. inclusions). However, there are processing conditions that do not take the form of imbedded inclusions or fractures that can have significant effect on the ultrasonic properties. Perhaps the most sensitive ultrasonic parameter to processing is attenuation. A 1977 report [12] identified variations in responses from ASTM reference blocks made in accordance with E127 based on whether the material was rolled or extruded. ASTM E127 allows both options of processing. It is worth noting that ASTM E428 is primarily concerned that the reference block duplicates the material to be tested so presents a more generic approach in para. 6.1:

6.1 The material to be used for reference blocks should be similar in its acoustic attenuation to the material which is to be examined. The grain size, heat treat condition, physical and chemical composition, surface finish, and manufacturing procedure (rolling, forging, and so forth) are variables to be considered in matching acoustic responses.

An assumption that seems to be made in the use of the reference blocks is that the material is ultrasonically isotropic. When a material is wrought into a shape, the forming process tends to align the crystal grains. The Sushinsky report [12] noted significant differences in the alignment patterns of reference blocks made from extruded rod as compared to rolled plate. In that report it is stated that “an extruded rod would probably give a more uniform response in ultrasonic attenuation than a rolled rod. As ultrasonic attenuation is effected by crystal orientation, this texture would introduce variations in the ultrasonic response through the block.”
If treated as isotropic, attenuation of ultrasound is easily addressed by the attenuation coefficient. Attenuation quoted for the baseline (0.0035dB/mm at 10MHz) is a low value and failure to adequately refine the grain structure would result in a higher attenuation coefficient. But even at a factor of 10 (i.e. 0.035dB/mm at 10MHz) the contribution to just attenuation would be small. The Civa input parameter window allows us to derive the attenuation at the nominal test frequency with a frequency slider. This indicates that for 5MHz the attenuation in the modelled 7075-T6 aluminium would be 0.000875dB/mm (see Figure 19). At a factor of 10 more attenuation, this would be 0.00875dB/mm.

![Figure 19](image)

**Figure 19**  Civa attenuation calculation for 5MHz

At the 0.5” metal path (12.7mm) the signal reduction the change in amplitude between the two conditions would be about -0.2dB. At the 5.75 inch (146.1mm) metal path it represents about 2dB. If a set of the reference blocks was made with materials varying in attenuation within this range would all fall within the range of tolerance in E127. Only those blocks with significantly different attenuation and having longer metal paths might result in signals deviating noticeably from the ideal curve.

When metal grain structure is such that the grains are columnar shaped and there is a preferential orientation to the columnar direction, the acoustic velocity and attenuation measured will be different in different directions, i.e. the acoustic velocities and attenuation are anisotropic.

The energy of the wave in an isotropic metal propagates in the same direction as the wave fronts and has the same velocity. Therefore the energy or group velocity of the wave equals phase velocity and the group velocity surface and phase velocity surface are spherically shaped.

In an anisotropic metal (i.e. one in which there is a preferred grain direction) the phase velocity of compression waves is a function of the angle between the wave normal direction and the long axis of the columnar grains. This results in the group velocity not having the same direction and magnitude. In anisotropic metals neither the wave front of the phase velocity surface, nor the group velocity surface will have a spherical shape.

Therefore, in addition to a simple decrease in amplitude due to spherical divergence from the probe and absorption of energy in the metal and simply absorption as stated in the attenuation coefficient, a further reduction in amplitude may result due to the beam energy (group
velocity) being re-directed off the path defined by the phase velocity surface. This is illustrated in Figure 20.

![Diagram of UT Probe, slowness surface, crystal grain orientation, group velocity (Vg), phase velocity (Vp), and skewing angle.]

**Figure 20**  Effect of anisotropy on group velocity of compression wave

Although velocity anisotropy can be determined, the bulk effect is generally provided for in the attenuation coefficient. In the Civa modelling of the aluminium 7075-T6 material we have used the value 0.0035dB/mm at 10MHz and assumed the material to be isotropic. That value for the attenuation factor is very low but results in a reasonably close match to the curves seen in ASTM E127 in the distance-amplitude plots.

In a recent paper, Warchol made pertinent observation on the nature of the materials used in the fabrication of the E127 reference blocks. They noted that

*Material processing differences in the reference standard itself affect the attenuation characteristics and the response of the standard.*

Even without processing effects, aluminium is well known to be ultrasonically anisotropic. Aluminium is in the cubic class of crystals and the elastic stiffness constants for the alloy 7075-T6 have been derived by Wong [14].

Stiffness constants published by Wong are indicated as:

<table>
<thead>
<tr>
<th>C_{11} (GPa)</th>
<th>C_{12} (GPa)</th>
<th>C_{44} (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>102.223</td>
<td>59.641</td>
<td>57.001</td>
</tr>
</tbody>
</table>
When these values are entered in the Civa simulation for the specimen material properties of an anisotropic cubic medium, the slowness curves are generated. These are illustrated in Figure 21.

![Slowness curves for acoustic velocities in 7075-T6 aluminium (inner green curve is relevant compression mode curve. Outer curves are shear modes).]

Figure 21  Slowness curves for acoustic velocities in 7075-T6 aluminium (inner green curve is relevant compression mode curve. Outer curves are shear modes).

By rotating the crystal orientation (assumed to be constant for the entire volume of the blocks) it is possible that some orientations will result in obviously non-conforming attenuations whereas other crystal orientations can produce results nearly identical to the isotropic (or even the ideal ASTM curve as seen in ASTM E127 Figure 6). Orientation of the modelled crystal axes is illustrated in Figure 22. The larger set of 3 arrows within the material represents the crystal axes. To the left the Z axis is parallel with the specimen Z-axis. To the right, the crystal axes have been rotated 45° around the Y axis so that the Z-arrow (blue) points towards the lower right.

![Cubic crystal orientation; left 0°, right 45°]

Figure 22  Cubic crystal orientation; left 0°, right 45°

When the forming processes can assure a fine grain structure with totally random crystal orientation, the block may exhibit nearly isotropic characteristics. However, when the rolling processes result in an elongated grain shape that tends to orient the crystal structures in preferred directions, the anisotropy effects can result in significant variations in amplitude response.

Figure 23 compares the targets used in the isotropic model to the ideal as described by the illustration in ASTM E127 (Figure 6).
Figure 23  Comparison of ASTM Curves to Isotropic model

Figure 24 compares the targets used in the anisotropic model with the Z-axis aligned perpendicular to the entry surface (i.e. 0°).

Figure 24  Comparison of ASTM Curves to Anisotropic model Z=0°

Figure 25 compares the targets used in the anisotropic model with the Z-axis tilted (45°).
Figure 25  Comparison of ASTM Curves to Anisotropic model Z=45°

Note that in the anisotropic model with the 45° tilt (Figure 25), the curves are nearly identical when normalised to the 78% amplitude for Curve A and the 79.5% amplitude for Curve B. However, when an absolute comparison of amplitudes is made between the isotropic model and the anisotropic model with 45° crystal tilt, it is seen to have a lower amplitude in the first 10 steps (from metal path 0.0625 inch to about 1.75 inch) and then for the longer metal path distances the responses are higher. This is illustrated in Figure 26 using an echo-dynamic representation of the peak amplitude for each of the 19 targets in the model.

Figure 26  Comparison of isotropic and anisotropic model echo-dynamic amplitudes. Black curve represents isotropic model amplitudes, anisotropic amplitudes in red.
In their report, Warchol and Warchol [13] provided an attenuation C-scan that illustrated the pattern of attenuation in a selection of blocks processed in different ways. Not only was there a difference from block to block, there was also a patterned variation in each block.

4. Other materials
ASTM E127 recommends using only the 7075-T6 aluminium alloy for the fabrication of reference blocks conforming to the requirements of that standard. Similar fabrication instructions are provided for reference blocks made of other materials in ASTM E428. Unlike E127, there are no prescribed reference curves and no requirements to qualify the equipment using the reference blocks in E428. Instead, the standard simply has the user identify the near field distance in water for a nominal 3/8 inch diameter probe with a nominal 5MHz centre frequency.

For relatively isotropic materials, such as titanium, deviation of expected amplitude responses from a typical curve can be a suitable method of assessing ultrasonic performance of the blocks. An example of the distance-amplitude curve assembled for a set of titanium blocks is seen in Figure 27. The variation in amplitude at the shortest metal path is due to the operator using a 5MHz probe with a 0.5 inch diameter. The example taken from E428 matches closely with the industrial example. The Civa model for this titanium example was configured to duplicate the industrial example using the non-standard probe size.

![Distance-Amplitude curves: modelled and real Titanium block sets](image)

**Figure 27** Comparison of isotropic and anisotropic model echo-dynamic amplitudes.

5. Conclusions and Recommendations
Modelling of the significant parameters in the application of assessment of the variation in amplitude responses for reference blocks made in accordance with E127 and E428 has been carried out.
Degree of variation for identified parameters has been assessed. The most significant parameter affecting amplitude response has been identified as the anisotropy of the material.

For applications using E127 where efforts have been made to standardise all responses of fabricated reference blocks to a master set using a master set of probes, the goal seems to be impractical.

Unless all blocks being assessed have identical attenuation (anisotropy) characteristics, it can be difficult to identify a single source of deviation from the expected ideal curve.

Guidance in E428 for material selection should be expanded to identify the degree of anisotropy that is acceptable. Then the instructions in E428 could be applicable to aluminium alloys as well. I.e.:

6.1 The material to be used for reference blocks should be similar in its acoustic attenuation to the material which is to be examined. The grain size, heat treat condition, physical and chemical composition, surface finish, and manufacturing procedure (rolling, forging, and so forth) are variables to be considered in matching acoustic responses.

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Appendix 1

Comparison of the modelled results in Civa to expectations for industry was simplified where there was a premade curve in ASTM E127 and E428. However, constructing a modelled curve for a different material becomes somewhat iterative when no master-curve is published.

Because the area-amplitude blocks use a constant metal path the concerns for attenuation do not apply for an isotropic material. However, for the distance-amplitude curves the cumulative effect of attenuation with increasing distance requires estimates of the attenuation coefficient and the dependence of attenuation on frequency.

As an example of how this might be done, a sample is used from industry where a steel set of blocks was assessed by a nationally approved laboratory. The attenuation in dB/mm and the exponent for the frequency dependence were adjusted until a reasonable fit to the data was achieved. The curves are then used to look for anomalous points. Figure A1 and A2 are the area-amplitude and distance-amplitude curves for the industrial examples compared to the Civa modelled values.

In the area-amplitude plot it can be noted that the direct relationship of the amplitude to area is preserved and the real specimen has a point (4/64 inch diameter target) that deviates noticeably from the trend.
In the distance-amplitude plot in Figure A2 the shorter metal path points have reasonably close comparison with all modelled points within 5% of the observed real values. The longer metal path points have a few points that exceed the 5% screen height difference but none of the points in the far region exceed a difference of 1.9dB between modelled and real.
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