THE EFFECT OF EQUIPMENT BANDWIDTH AND CENTER FREQUENCY CHANGES ON ULTRASONIC INSPECTION RELIABILITY: ARE MODEL RESULTS TOO CONSERVATIVE? (a)

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INTRODUCTION

Reliable detection and sizing of material defects, which have been found in nuclear reactor piping and pressure vessels, has been shown [1,2] to be greatly affected by changing components of ultrasonic in-service inspection (UT/ISI) systems. The work reported here, in conjunction with our previous work [3-5], focuses on: providing a more rigorous analysis of equipment interaction and establishing a technical basis for current standards [6] for equipment operating tolerances which, before this work, were based on engineering judgement.

Presented here are experimental results and those derived from modeling studies; upon comparison, the model appears to be somewhat overly conservative. The conservativeness in the model can be attributed to the assumption that the receiving transducer is locally reactive. Even though the model was noticeably more sensitive to the effect of changes in system bandwidth and center frequency than experimental studies, it provided greater flexibility (in investigating equipment changes on a broader range of defects) than a similar study performed experimentally. Once a Worst-Case Defect Acoustic System (WCDAS) situation [5] was identified using mathematical models of the UT/ISI system it could then be analyzed experimentally, thus reducing the number of experimental studies, without compromising thoroughness.

Since the last QNDE meeting in Maine, this work has been broadened in scope, it now includes: a 60° shear wave modeling study on thin steel sections and 45° and 60° experimental studies. Based on results from these studies, changes to ASME code requirements [6] have been recommended.

MODEL RESULTS FOR 45° AND 60° SV WAVES

Most UT inspection systems used to detect flaws, which may exist, in nuclear power plant piping operate using either 45° or 60° shear wave
Table 1. Model Predicted Worst-Case Defects for Parameter Sensitivity

<table>
<thead>
<tr>
<th>Name</th>
<th>Probe Size</th>
<th>Material Thickness</th>
<th>Percent Through-wall (%)</th>
<th>Angle From Vertical ( \theta )</th>
<th>Beam Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect B</td>
<td>6 mm</td>
<td>19 mm</td>
<td>90%</td>
<td>-57( ^\circ )</td>
<td>45(^\circ) SV</td>
</tr>
<tr>
<td>Defect C</td>
<td>12 mm</td>
<td>19 mm</td>
<td>90%</td>
<td>6.5( ^\circ )</td>
<td>45(^\circ) SV</td>
</tr>
<tr>
<td>Defect D</td>
<td>12 mm</td>
<td>19 mm</td>
<td>90%</td>
<td>-48( ^\circ )</td>
<td>45(^\circ) SV</td>
</tr>
<tr>
<td>Defect E</td>
<td>12 mm</td>
<td>76 mm</td>
<td>90%</td>
<td>6.5( ^\circ )</td>
<td>45(^\circ) SV</td>
</tr>
<tr>
<td>Defect F</td>
<td>12 mm</td>
<td>76 mm</td>
<td>90%</td>
<td>-49( ^\circ )</td>
<td>45(^\circ) SV</td>
</tr>
<tr>
<td>Defect G</td>
<td>25 mm</td>
<td>76 mm</td>
<td>90%</td>
<td>3.5( ^\circ )</td>
<td>45(^\circ) SV</td>
</tr>
<tr>
<td>Defect H</td>
<td>25 mm</td>
<td>76 mm</td>
<td>90%</td>
<td>-45.5( ^\circ )</td>
<td>45(^\circ) SV</td>
</tr>
<tr>
<td>Defect M</td>
<td>12 mm</td>
<td>19 mm</td>
<td>90%</td>
<td>13( ^\circ )</td>
<td>60(^\circ) SV</td>
</tr>
<tr>
<td>Defect N</td>
<td>12 mm</td>
<td>76 mm</td>
<td>90%</td>
<td>11( ^\circ )</td>
<td>60(^\circ) SV</td>
</tr>
<tr>
<td>Defect P</td>
<td>25 mm</td>
<td>76 mm</td>
<td>90%</td>
<td>5( ^\circ )</td>
<td>60(^\circ) SV</td>
</tr>
</tbody>
</table>

* Minus sign indicates that the defect is angled away from probe.

Flaws M, N, and P have been combined into a table of an earlier report [4].

Sources. Modeling studies performed at PNL prior to this work [3,4] dealt primarily with 45\(^\circ\) shear wave, pulse-echo inspection of thin-wall (less than 76 mm) piping. Both mathematical modeling and experimental investigations presented here have been broadened in scope to include 60\(^\circ\) SV wave sources. The modeled configuration is shown in Fig. 1.

Defects, predicted by the model to be worst-case [5] for 60\(^\circ\) SV waves, are shown in Table 1. Previously found worst-case defects for 45\(^\circ\) SV waves have been included in Table 1 for comparison. Transfer functions for 60\(^\circ\) SV wave acoustical systems found to contain defects representing a worst-case situation (with respect to variations due to equipment changes) are displayed in Fig. 2. Notice the rapid changes in transfer function slope that occur near the acoustical system center frequency (typically 2.25 MHz), this is believed to be an indication of how sensitive the system will be to equipment changes.

Fig. 1. Configuration used in modeling study when the wedge angle was adjusted to provide either 45\(^\circ\) or 60\(^\circ\) SV waves.
SENSITIVITY STUDY

Sensitivity studies were performed as mentioned in our earlier work [4] with 45° SV waves, i.e., WCDAS transfer functions were combined with spectra representative of equipment systems with bandwidths and center frequency varied independently, over a wide range. All amplitudes were normalized to ASME 10% notches and center frequency was varied about a central value of 2.25 MHz. In the past, it was assumed that after an equipment change acceptable repeatability remained between ±2 dB. The sensitivity to equipment change predicted by our model, and also measured in experimental studies, shows that this may not always be true, for WCDAS.

![Fig. 2. Transfer functions plotted as Amplitude versus frequency for all of the 60° and 45° SV wave acoustical systems listed in Table 1.](image)

Figure 3 shows the dependence of the system transfer function on bandwidth for each of the WCDAS described in Table 1. These results were computed at a center frequency of 2.25 MHz. Slope of the system transfer function, plotted as a function of bandwidth, is a measure of system sensitivity to bandwidth change that may result from an equipment change. As can be seen in Fig. 4, the model predicts that for both 45° and 60° SV wave systems, amplitude changes remain below the required ±2 dB per 10% change in bandwidth.

System sensitivity to changes in center frequency, at a given bandwidth, was also modeled for 60° SV wave pulse echo systems. These results are plotted on the left-hand side of Fig. 5, and for comparison, results from defect E are plotted on the right-hand side.

In this study, amplitude–center frequency dependence was determined for each of seven different bandwidths. The modeled system's sensitivity to center frequency change was found to be bandwidth dependent. When the bandwidth became less than about 50% (of the center frequency)
Fig. 3. Normalized amplitude versus system bandwidth for both 45° and 60° SV waves.

Fig. 4. Slope (derivative) of the normalized amplitude response shown above in Fig. 3, plotted as a function of system bandwidth.
the model predicted sensitivity to center frequency in excess of the 
desirable (±2 dB) levels. Figure 6 shows the slope of the transfer 
function amplitude plotted versus center frequency, which emphasizes 
this effect. Results from both 45° and 60° SV waves, displayed in Fig. 
6, show bandwidth to have a lessor effect on sensitivity for the 60° SV 
wave system than the 45° SV wave system.

![Graph showing normalized amplitude versus center frequency for different bandwidths for 60° and 45° SV waves.]

**Fig. 5.** Normalized amplitude versus center frequency, at selected 
bandwidths, for both 45° and 60° SV waves.

**EXPERIMENTAL RESULTS**

With model studies as a guide to WCDAS, and their expected 
response, experiments were performed for both 60° and 45° pulse echo 
systems. Bandwidth was limited using bandpass filters. The results 
depicted in Fig. 7 were obtained from a bandwidth sensitivity study of 
this type. Just as the model predicted, amplitude was found to vary 
less than 2 dB per 10% change in system bandwidth.

Data gathered from a center frequency sensitivity study, and shown 
in Fig. 8, represents the system response, measured at several dif­ 
ferent center frequencies when bandwidth was limited to varying degrees. 
Amplitude was found to be less sensitive to center frequency variations 
than predicted by our model, yet still more sensitive than desired. 
Therefore, even though the model is believed to be somewhat overly 
conservative, the above model predictions and subsequent experimental 
verification, still indicate sensitivity trends and where improvements 
to present code requirements were needed for allowable equipment 
parameter changes.
Fig. 6. Slope (derivative) of the normalized amplitude response shown above in the previous figure, plotted as a function of center frequency.

Fig. 7. Normalized amplitude measured as a function of system bandwidth using artificial narrow banding.
RECOMMENDATIONS

Based on our findings, the ±10% bandwidth tolerance should remain unchanged. Furthermore, even though experimental results show significantly less sensitivity to system center frequency changes than the model, the center frequency tolerance should be altered and specified according to system bandwidth: where systems with bandwidths less than 30% should have a center frequency tolerance of ±5% and systems with bandwidths greater than 30% should reduce center frequency tolerances to ±10%. The current ASME code section XI requirement of ±20% center frequency is not sufficient to guarantee inspection repeatability to within 2 dB for typical ISI systems.

The conservatism in the model, in comparison with experiment, is under investigation and is believed to be due to the assumption that the receiving transducer is locally reactive.

WORK IN PROGRESS

Results presented here pertain to relatively thin (thicknesses less than 76 mm), flat steel samples. Nuclear reactor piping and pressure vessels are fabricated from steel parts consisting of many shapes and wall thicknesses. Therefore, to make our work applicable to these structures, we are extending our model study to include samples of arbitrary shape (i.e., nozzles) and thickness (up to 12 inches). It will be interesting to determine what effect sample thickness and geometry may have on equipment parameter sensitivity.
REFERENCES


6. ASME Section XI, Appendix VIII, Article 4000.