SETTING REALISTIC TOLERANCES ON EQUIPMENT SUBSTITUTION FOR CONVENTIONAL, PAUT AND TOFD ULTRASONIC METHODS

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ABSTRACT

The paper presents a new approach to set realistic tolerances on equipment substitution for detection and sizing of cracks in pressure components based on inspection specification. The following aspects will be presented:

- Tolerances on conventional UT equipment substitution for center frequency, bandwidth, pulse length, refracted angle and gain-in reserve
- Tolerances on PAUT features probe, wedge, and test piece velocity compared to reference block velocity
- Tolerances on TOFD parameters, namely PCS offset.

Examples are given for different inspection scenarios for detecting and sizing fatigue cracks. Recommended tolerances are presented based on experimental work, field data and basic principles of UT method. Tolerances for a procedure qualification shall be set based on its scope, not arbitrary, based on ASME XI or other national/international standards. Tolerances quoted are given for clearly resolvable individual defects. Unresolved multiple flaws would not be sizable to tolerances quoted in this paper. Separate tolerances will be discussed with respect to UT, PAUT and TOFD

Introduction

Inspection Qualification process is a complex, costly and long-term process. It addresses a large variety of issues based on Inspection Specification, components specific issues to be inspected: geometry, thickness, access, environmental issues, equipment, procedure, influential and essential parameters, human factor and qualification process on representative mock-ups-just to mention some of most important ones. Most ISI vendors and regulators refer to EPRI PDI program and ASME V/XI Articles / Appendices (ref.1-3), which set minimum requirements for qualification process, including essential parameters (variables) and conditions for equipment checking and substitution. A long list of ASTM Guidelines/Standard practices and ASME Code Cases how to use PAUT in S- and/or E-scan were published within the last decade (ref.4-8). PAUT is an emerging technology, with a fast-pace developing new pieces of hardware, software and accessories (beam simulation, scanners, new type of probes) to solve the needs of ISI in nuclear and/or turbine conventional inspections. Re-qualification process is based on technical justification and fitness-for-service (inspection) approach. The diversity of UT equipment and PAUT hardware/software led to new approaches of inspection qualification/equipment equivalency.

Parallel activities took place at OPG (9-10) and EPRI (ref.11-14), which issued reports and technical justifications for equipment/software equivalency for PAUT application for large-scale turbine components and piping welds (ref.15).

Different approaches are presented in USA for TOFD method (ref.16-17).

In spite of these make-sense approaches, few standards are dealing with realistic tolerances on main system features, in such a way to keep the main scope of inspection (detection, location, sizing, nature, orientation and pattern) within the accepted tolerances by IS or fitness-for-service documents related to specific component.

The present paper is dealing with all three aspects of UT inspection: conventional, PAUT and TOFD, trying to stress the logical approach how to set realistic tolerances based on inspection scope.
Conventional UT

Conventional UT is still a reliable inspection method for weld inspection (ref.18). Redundancy of two angles and a freedom of probe movement may outperform a one-line scanning from one side with PAUT, namely for skewed and branched SCC. Partial qualification of conventional UT may be performed as a detection, length sizing and location tool. Discrimination between geometric indications and weld flaws must also be included in the procedure, in order to avoid the false calls or missed flaws. Tolerances on equipment substitution were developed in mid’80s by PNL-Battelle-USA (ref.19), studying the amplitude variation for the worst-case scenario of a large reflector for specular mode reflection. It was a strong belief in USA and Europe that a tighter tolerance on probe and UT instrument (system) will contribute to a repeatable response of flaw amplitude within ±2dB. Our experimental results regarding the frequency measurement methods (target, distance, method, etc.), including the 10% absolute tolerance between system-to-system concluded (ref.20) the ASME XI tolerances are un-realistic and impossible to be met (see Table 1).

Table 1: Factors affecting experimental errors for center frequency and relative bandwidth (ref.18).

<table>
<thead>
<tr>
<th>Transducer feature</th>
<th>Maximum deviations/experimental errors due to: [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wedge angle</td>
</tr>
<tr>
<td>2.25</td>
<td>Fc</td>
</tr>
<tr>
<td></td>
<td>BW</td>
</tr>
<tr>
<td>3.5</td>
<td>Fc</td>
</tr>
<tr>
<td></td>
<td>BW</td>
</tr>
<tr>
<td>5.0</td>
<td>Fc</td>
</tr>
<tr>
<td></td>
<td>BW</td>
</tr>
</tbody>
</table>

Other sources of errors (ref.21-22) are more important for amplitude response and flaw characteristics (length, location, height, orientation).

The ENIQ process for inspection qualification based on inspection specification (IS) and classification of influential parameters improved the process of procedure validation qualified for a specific task. The following example (see Figure 1) illustrates a partial qualification procedure for detection and length sizing using different frequencies, but with the same end effect: flaw was detected, located and measured within specified tolerances, acceptable by IS.

Figure 1: Example of detection and length sizing of root crack, root LOF and nest of porosity by conventional UT probes of 12.7 mm / 45ºT ; frequency range: 1.5 MHz – 5 MHz.
Crack height sizing based on back-scattering tip echo diffraction depends on waveform duration. Our results (ref.22) demonstrated the capability of crack height sizing by a large variety of probes (diameters, frequency, damping factor), under the condition to have enough gain in reserve for corner trap detection and a 3:1 (10 dB) or greater SNR for crack tip versus general noise (see Figure 2). If the IS requirements for crack height are \( h > 3 \) mm, with a specific RMSE (let’s say \( \pm 2 \) mm), a large variety of probes with a waveform duration \( > 1 \) µs may be used. Appendix VIII- Article 4110 pct.i) may be used as an option for system characterization and equivalency.

![Figure 2: Dependence of crack height on waveform duration-conventional probes.](image)

We suggest the following values for:

- useful gain-in-reserve vs DAC curve > 34 dB
- refracted angle tolerance: \( \pm 2^\circ \)
- center frequency tolerance: \( \pm 15\% \) to \( \pm 25\% \) vs manufacturer value
- waveform duration: \( \pm 30\% \), but < 2.5 µs
- SNR of crack tip > 3:1 (10 dB)

These features may be tighter or relaxed, based on specific IS requirements. Using 1.5\( \lambda \) probes of higher frequency (>7 MHz) may be limited to thickness > 40 mm due to small gain-in-reserve, higher scattering and low SNR for crack tip. Our experimental data (ref.23) provided a chart with minimum crack height sized by tip-echo back-scattering using medium-damped probes (see Figure 3).

![Figure 3: Example of minimum crack height sized by tip-echo back-scattering by medium damped piezo-composite mono-crystal probes.](image)
In conclusion: equipment substitution and system performance shall be based on IS requirements and a realistic assessment of essential variables tolerances. A technical justification with experimental evidence will allow a diversity of UT machines and probes to detect, to size and to locate weld flaws within acceptable tolerances.

A short demo to the customer and regulator (open/blind trial) will increase the confidence of all parties. Using the tolerances of ASME XI Appendix VIII-Art.4000 will limit the problem-solving capability. Some measurements can’t be met not even for the same family of probe type. Relaxing the tolerances for a double-reason: experimental errors and sizing cracks with h>3 mm will give an overlapping domain and a make-sense choice for ISI vendor: use the best probe with a good detection power and better SNR for crack tips. An example on a 25% tolerance on center frequency in combination with 30% tolerance on waveform duration is presented in Figure 4.

![Waveform duration for MSW-QC 2.5 cycles](image)

**Figure 4:** Example of overlapping frequency domains for medium-damped probes of 2.5 cycles.

This approach was used to detect and size weld flaws as per Figure 1, using a range of frequency 1.5-5 MHz. Height sizing and axial resolution was based on higher frequency range (3.5-5 MHz) and shorter waveform duration( < 1µs).

**PAUT**

PAUT method was quick approved by the customers and regulators because of the three main futures:
- is still a pulse-echo technique using a large variety of angles (redundancy)
- could easily relate the UT results to the part by S-scan display (overlay)
- is using “focused beams’ and has a better SNR (detection and sizing of small mis-oriented cracks)

The main weapon of PAUT is the flaw **PATTERN**. The same concept based on IS requirements must be applied to PAUT tolerances, namely for S-scan calibration. It is very important to set realistic tolerances on depth, angle range, index/scan readings, gain-in-reserve vs DAC, SNR for crack tips based on acceptable tolerances from an IS or specific OEM procedure. Table 2 illustrates a 4-class event in PAUT applications:
- detection only
  - sizing within ± 0.5 mm tolerances
  - sizing within ± 1.0 mm tolerances
  - sizing within ± 2.0 mm tolerances
Table 2: Example of tolerance range based on inspection scope for PAUT.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tolerance vs calibration</th>
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<tbody>
<tr>
<td></td>
<td>Detection</td>
</tr>
<tr>
<td>Wedge angle</td>
<td>±3°</td>
</tr>
<tr>
<td>1-st el. height</td>
<td>±2 mm</td>
</tr>
<tr>
<td>Wedge velocity</td>
<td>±80 m/s</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>1°</td>
</tr>
<tr>
<td>Test piece velocity</td>
<td>±150 m/s</td>
</tr>
<tr>
<td>Index</td>
<td>±15 mm</td>
</tr>
<tr>
<td>Sampling A-scans</td>
<td>320</td>
</tr>
</tbody>
</table>

Another example from turbine components inspection was presented in ref. 24. Some tolerances may be too tight, but in turbine components cases they are crucial for a reliable large-scale inspection. The conservative values are:

- Wedge velocity: ± 50 m/s
- Wedge angle: ± 1.0°
- Height of 1st element: ± 1 mm
- Probe pitch: ± 50 microns for \( F_c \geq 6.5 \text{ MHz} \)
- Probe pitch: ± 100 microns for \( F_c = 3.5 \text{ MHz} - 6 \text{ MHz} \)
- Test piece velocity: ± 80 m/s
- Angular resolution: < 0.5°

In this approach OPG was aiming to detect and size cracks within ±0.7 mm and location of indications within ±2 mm.

Few PAUT practitioners are using the correct number of sampling along the A-scan, in order to deduce the pixel error (ref.25). A combination of independent events – all tolerated to the best of manufacturer/practitioner-may lead to an overall sizing capability of ± 1.1 mm or higher (see Figure 5).

Figure 5: Example of error trend due to independent events, such as point quantity, angular resolution, wedge angle, wedge velocity, and probe pitch tolerances (from ref.25).

Another aspect which is misleading the PAUT practitioners is calibration aspects: velocity, wedge delay, ACG/TCG, encoders) versus the reality of PAUT application. If you want to keep the pattern and use 2-3 types of waves in a single mid-size 1-D probe, you will have to give up some information from the pattern for the sake of calibration process. Few PAUT practitioners are aware about the effective beam aperture, the power steering and the fact a complex set-up may in fact contain 2-3 velocities (L-, T,- and Surface).

Figure 6 demonstrates the sizing of SCCs from surface-waves domain to mode-converted domain, using a calibrated pattern within ±2 mm tolerances (ref. 26). The beam was totally divergent; some of focal depths were in the wedge!
Figure 6: Example of SCC detection and sizing by PAUT using a complex set-up and confirmation of cracks parameters by MP and fracture mechanics. PAUT called 16 x 4 mm (conservative decision), with a ligament of 5 mm (ref. 26).

**TOFD**

The TOFD method was accepted by ASME and UE based on Code Case 2235 and experimental results during different programs, such as PISC II-III and DNV. European and US standards (ref. 30-35) detail the procedural steps for a good-practice in applying the TOFD in lieu of radiography or as a quick one-pass weld scanning. It is well-known the limitations of TOFD method (dead zones due to lateral waves, back-wall, LL/TL/LT loci). Examples in Figure 7 to Figure 11 concluded the detection is a challenge for ID surface breaking cracks with height < 4 mm and ligament < 3 mm. A PCS off-set of more than 10 mm versus 2/3t flaw center may lead to a dead zone and unreliable inspection (see also ref. 37-38). The same problem does not exist for OD cracks where conversely cracks located offset to the scan axis become extended in time resulting in significant oversizing.

Figure 7: TOFD results for 11 implanted flaws in a welded mock-up of 25 mm. Flaws #1, #3, #6 and 8 are difficult to be detected and sized due to lateral waves and back-wall echoes.

Figure 8: Example of modeling the blind zones for TL/LT loci (left) and LL back wall reflection (right).
Figure 9: Example of back wall dead zones for t=25 mm and PCS offset ± 30 mm (left) and lateral wave dead zone (right). Removal of lateral waves may increase the information about the OD ligament.

Figure 10: Principle of location error (mono-crystal-left) and height (PAUT-TOFD-right) due to TOF loci.

Figure 11: Example of crack undersizing due to probe offset versus crack center line.

Tolerances for PCS offset shall be < 10 mm for an undersizing of 1 mm. A combination with time delay in the couplant, index migration and actual velocity value will contribute to an overall undersizing by more than 2 mm. Use of parallel scans is recommended to eliminate off axis errors. It is highly recommended that multiple offset scans are used to inspect welds with the cap ungrounded. Improved precision in defect size is obtained by measuring the scan which imaged the defect at the shortest arrival time. Data analysts are able to open multiple scan files and make comparative arrival time measurements to ascertain the true defect location and size.

Concluded Remarks and Recommendations

Setting realistic tolerances on essential parameters which might affect inspection results shall be based on IS requirements and its acceptable tolerances for length, height, ligament, location and orientation (ref.27). Assessing the possibilities and limitations of PAUT setting (ref.28-29) will lead to a realistic detection and sizing within achievable tolerances. TOFD tolerances may also be specific to the task (see ref.36-39), but a basic do-don’t line must be drawn in setting the TOFD parameters to meet these requirements(detection, sizing accuracy, flaw positioning). Some hints to reduce the sizing errors and flaw location are given in ref.40-42, but the height error could still reach 20% of the actual crack height.
A value of ±1 mm accuracy for ID surface-breaking crack height with a repeatability of ±0.3 mm is unrealistic to be achieved in the field unless parallel scans conducted across the weld, cap dressed flush, where the location of crack is known and time-of-flight errors are < 0.1 μs. Flaws in the root area, in counterbore, misalignment and closer to the ID/OD surfaces within 3 mm ligament are very difficult to be detected and characterized unless a diversity and/or a combination of two methods/scanning types are not used. Cracks with height 5-8 mm were not detected in one blind trial by TOFD. It is not recommended that TOFD method be used as a stand-alone method to replace RT. TOFD has inherent defect detection and sizing problems for OD and ID cracks. Crack detection is possible when centered on to an ID crack. Scans off-center to ID cracks can lead to defects being missed or significantly undersized. Surface breaking cracks at the OD will be plotted erroneously deep when they are located off center to the PCS. Taking into account the operator variability, a more realistic tolerance of ±3 mm is recommended for TOFD method when non-parallel scans are solely used (ref.37, 38 and 40). Improved precision with TOFD can be obtained by using very high sampling rates >100MHz, high frequency highly damped transducers, PCS values set to focus at defect locations and use of parallel scans across the defect eliminating off-axis defect errors. Tolerances could be relaxed for PE and PAUT for detection and are very tight for TOFD. SCC/fatigue crack sizing and plotting in stress areas for turbine components require tighter tolerances than ASME XI. More experimental evidence is needed to draw a generic class-based tolerances for essential parameters on all three methods based on ENIQ/ASME approach.

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