Advances in Non-invasive Tube Inspection using Pulse Reflectometry

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Abstract
Pulse Reflectometry (PR) based on acoustic signals has been gaining acceptance in recent years as a non-invasive technique for inspection of tubes in boilers and heat exchangers. In this implementation, acoustic pulses are sent into the air enclosed within the tubes and the reflections which are generated by defects on the internal diameter are recorded and analysed. This enables detection of various defects such as bulges, blockages, holes and ID wall loss. Recent advances in this technology enable the detection of a wider range of defects, with higher accuracy and sensitivity than previously possible. In this paper we present the technological background and a set of cases studies demonstrating the technique's capabilities.

Keywords: Pulse Reflectometry, Guided waves, Heat exchangers, Tube inspection

1. Introduction
A variety of tube inspection techniques exist today, though they all suffer from various drawbacks. The fastest technique in widespread use is eddy current (ET), which can inspect about 60 tubes per hour, but is limited to non-ferromagnetic tube materials. It is also heavily reliant on technician expertise – a study by MTI and EPRI [1] has demonstrated fault detection scores varying between 87% and 50%, depending on the technician using the equipment. Ferromagnetic tubes require the use of alternative electromagnetic methods, mainly remote field testing (RFT), which is slower, less accurate and also depends heavily on the technician’s expertise. Alternatively, an ultrasound based technique is the Internal Rotating Inspection System (IRIS), which is also accurate, but extremely slow and requires a very high degree of tube cleanliness – down to the bare metal. In addition it cannot be applied to tubes having walls thinner than 0.9 mm.

Overall, current methods are too slow to enable full inspection of heat exchangers during typical shutdown periods. They are also limited with respect to tube materials or tube dimensions, leaving much room for improvement in the field. Ideally, a tube inspection technique should provide several key properties: high sensitivity and accuracy, a high level of consistency regardless of the operator, short inspection times and applicability to a wide variety of tube materials and dimensions. Preferably, it should also require minimal pre-inspection preparation of the tubes

2. Principles of Pulse reflectometry
Pulse Reflectometry (PR) is a generic term for methods based on a simple physical principle: a mechanical pulse that is transmitted into a medium will propagate uninterrupted until it encounters any discontinuity. Such a discontinuity will cause scattering, generating reflections which will propagate back to the source where they can be recorded and analyzed. An appealing feature of PR is that it is non-traversing, enabling the medium to be examined without the need to traverse it with a physical probe.

One form of PR, Acoustic Pulse Reflectometry (APR) has already been applied to tube inspection. In this technique, an acoustic pulse is created by a loudspeaker and sent down the column of air enclosed by the tube. Any discontinuities on the Internal Diameter (ID), such as wall loss, blockages or through-holes create reflections that can be measured by a microphone
and analyzed to determine the type of discontinuity that caused them. This method has been refined and implemented successfully as an industrial tool [2]. The main drawbacks of APR, however, are that it does not detect any Outer Diameter (OD) defects nor cracks, which are also prevalent in many heat exchangers. In addition, it cannot provide any azimuthal localization of defects.

An alternative form of PR, known commonly as the Guided Wave (GW) technique, is based on propagating ultrasonic pulses within the tube walls. To date, this method has been applied mainly as a screening tool for large diameter pipes rather than for heat exchanger tube inspection. It is far more complicated to implement than APR, requiring an array of sensors rather than a single loudspeaker and microphone. However it can detect both ID and OD defects and it also provides a degree of azimuthal resolution. On the downside, this technique cannot detect internal blockages, and cannot easily detect through-holes having very small diameters. In the context of narrow tubes, rather than pipes, we will refer to this method in the following sections as Ultrasonic Pulse Reflectometry (UPR).

Taken together, APR and UPR are largely complementary. Thus, a tool combining these two techniques can offer a comprehensive solution to heat exchanger tube inspection, while retaining several key advantages over other techniques: (a) Non traversing inspection; (b) Short inspection time per tube; (c) Detection of all relevant ID/OD faults; (d) Minimal sensitivity to tube material, dimensions and configurations.

In the following sections we describe such a combined APR/UPR implementation, outlining some of the design challenges and showing some performance examples on laboratory mock-ups.

3. Acoustic Pulse Reflectometry

The principles and implementation of APR have been described in detail in several previous papers [2], therefore they will not be discussed here extensively. Generally speaking, APR involves sending a wideband acoustic pulse down the tube under inspection. Any change in the tube cross section then creates reflected and transmitted waves. Typical defects present two discontinuities: a local blockage, for example, will present first a reduction in cross section, then an increase to the nominal cross section at the end of the blockage. This creates a dual reflection, a positive peak followed by a negative one. The polarity of the peaks is very important in interpreting APR results – wall loss will have polarities which are reversed in comparison to blockages. The net effect when encountering several typical defects is presented in Figure 1.
The key to obtaining signals with sharp peaks and minimal ringing is in transmitting pulses with a wide and relatively flat spectrum, with smooth rolloff in high frequencies.

APR has been applied successfully to heat exchanger and boiler tube inspection, providing useful ID information. A key property of APR is its high sensitivity to through holes. Since these present a short circuit to the air outside the tube, they create a reflected wave qualitatively different from the reflection created by partial wall loss. Thus it is easy to distinguish a pit from a through hole with this technique. In lab and field tests APR has been demonstrated to detect such holes as small as 0.5 mm in diameter.

4. Ultrasonic Pulse Reflectometry

To date, Guided Waves have been applied mainly as a screening tool for inspection of large diameter pipes. In this case, a collar of transducers is coupled to the outer diameter of the pipe. To maximize detection range, ultrasonic frequencies lower than 200 kHz are usually employed. Signals are usually narrowband pulses around the centre-frequency, resulting in extensive ringing and mostly unusable phase information. The literature reveals very few attempts to apply this technique to tube diameters found in heat exchanger tubing [3]. Two main challenges make this a difficult task: 1) in this case the array of transducers must be inserted into the limited space inside the tube and coupled to the interior surface in a manner that can enable rapid deployment; 2) excitation and signal analysis must be refined in order to provide a full analysis of defects, if this technique is to be used as more than just a screening tool. Our approach to overcoming these challenges is outlined below.

4.1 Probe structure

Guided Waves propagating in a cylindrical shell can be decomposed into several generic mode types: Torsional, Longitudinal and Flexural. Each mode type is in itself composed of an infinity of modes, which are usually dispersive. Distinguishing between these different modes of propagation requires an array of piezoelectric transducers around the circumference of the tube. Implementing such an array demands a high degree of complexity, however correct interpretation of the information provided by these modes provides azimuthal information lacking in APR. For example, 12 such transducers can in theory provide an azimuthal resolution of 30 degrees. Squeezing such a large number of transducers into a single ring within the narrow confines of typical heat exchanger tubes, ranging in OD from 3/4” to 1.5”,

Figure 1. Schematic depictions of signatures corresponding to the typical defects.
is extremely difficult. Therefore we have opted for a design employing a stainless steel cylindrical shell with two staggered rings of 6 slots each, as shown in Figure 2. When inserting the probe into a tube, the transducers are situated inside the shell. In order to initiate a measurement, the transducers must be dry-coupled to the tube's inner wall. This is accomplished by inflating an internal balloon that causes the transducers to emerge from the slots and press against the tube walls.

Figure 2. The slotted cylinder holding the piezoelectric transducers, with two staggered rings of six slots each

4.2 Excitation and defect signatures

The excitation signal most commonly used in GW implementations is a pulsed sine. The result is a relatively narrowband signal, which translates to extensive ringing in the time domain. This ringing makes it difficult to utilize phase related information, and to distinguish between closely spaced defects. In contrast, in developing UPR we have strived to follow the approach taken in APR, using a wideband signal extending from below 50 kHz to above 500 kHz. Though this has required developing of custom piezoelectric transducers, the resultant signal can be interpreted using the same methodology as in APR. Similarly to APR, any discontinuities will cause reflected waves to propagate back up the tube, however the signature of a certain defect may appear differently to APR and to UPR.

The primary type of defect for which UPR is useful is wall loss. To APR, wall loss appears as a local increase in cross section, whereas for UPR it appears as a decrease in cross section of the wall itself. Thus, an ID wall loss defect will show up in APR as a negative pulse follow by a positive one (as shown in Figure 1 above), whereas in UPR the polarities will be reversed. More importantly, the amplitude of the UPR reflection will be relatively larger. This is because the cross section of the wall itself (the medium for UPR waves) is much smaller than the cross section of the air enclosed in the tube (the medium for APR waves). Considering a typical wall loss defect such as a 50% deep pit with a 5mm diameter in a 1” tube with 2mm wall thickness (Figure 3): At the pit's widest point, it decreases the wall cross section (which is what UPR detects) by 6.5%, whereas it increases the internal cross section (which is what APR detects) by only 1.2%. Thus, though the basic detection methodology is similar in both techniques, the polarity of the peaks is reversed, and at similar SNR levels we can expect UPR to be more sensitive to wall loss defects than APR. In addition, UPR is also able to detect OD defects. On its own, however, it cannot distinguish OD from ID defects, but this can be established by cross referencing APR and UPR detection results.
Figure 3: A 5mm ID pit, 50% deep, in a 1” tube (not drawn to exact scale)

Cracks present a discontinuity only in the wall itself, therefore they are detectable by UPR but not by APR. The reflections they create depend on their orientation. Considering the extreme cases, a circumferential crack causes a large disruption in cross section over a short axial distance, whereas an axial crack causes a small disruption in cross section over a large axial distance. Both of these can be detected by UPR, and details of the reflections such as peak heights and inter-peak distances must be used to correctly diagnose this type of defect.

5. Combining APR and UPR – sample measurements

In this section we present several sample measurements from two tubes in a heat exchanger mockup containing typical defects. The tubes were 3/4” Carbon steel, with wall thickness of 0.083” and a length of 1.2 meters. Some defects show up in both APR and UPR modalities, though often more strongly in one than in the other. Other defects show up in one of the two only. Table II shows the layout of the defects in the tubes presented here.

Table II: Layout of the defect in 2 of the mock-up tubes

<table>
<thead>
<tr>
<th>Tube #</th>
<th>Distance</th>
<th>Flaw size</th>
<th>Flaw type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>70 cm</td>
<td>60%</td>
<td>7/64” diameter OD pit</td>
<td>UPR</td>
</tr>
<tr>
<td></td>
<td>100 cm</td>
<td>80%</td>
<td>5/64” diameter OD pit</td>
<td>UPR</td>
</tr>
<tr>
<td></td>
<td>110 cm</td>
<td>0.052”</td>
<td>Through wall hole</td>
<td>Both</td>
</tr>
<tr>
<td>B</td>
<td>65 cm</td>
<td>40%</td>
<td>3/16” diameter OD pit under baffle plate</td>
<td>UPR</td>
</tr>
<tr>
<td></td>
<td>70 cm</td>
<td>10%</td>
<td>Internal Blockage</td>
<td>APR</td>
</tr>
<tr>
<td></td>
<td>100 cm</td>
<td>40%</td>
<td>0.01” wide, 1/2” long OD circ notch</td>
<td>UPR</td>
</tr>
</tbody>
</table>

The APR and UPR measurements from each tube in Table II are presented below along with a short discussion.
**Tube A:** APR and UPR signals for this tube appear in Figure 4.

![Figure 4: APR (top) and UPR (bottom) signals from tube A, with defects highlighted in light blue](image)

The APR signal reveals only the through hole located at 110 cm., having a strong signature that lasts till the reflection from the end of the tube. The UPR signal shows all three defects, at 70, 100 and 110 cm.

**Tube B:** APR and UPR signals for this tube appear in figure 5.

![Figure 5: APR (top) and UPR (bottom) signals from tube B, with defects highlighted in light blue](image)

The APR signal reveals the blockage located at 70 cm., again having a strong signature. The UPR signal shows the remaining two OD defects at 65 and 100 cm.
5. Conclusions
Pulse reflectometry has two properties which hold a special appeal for tube inspection: high speed and the fact that it eliminates the need for traversing tubes with a probe. These properties are important advantages over currently more widespread methods.

In this paper we reviewed the physical principles behind two modalities of pulse reflectometry, APR and UPR. We have shown that neither of these methods on its own offers a sufficiently comprehensive solution to heat exchanger tube inspection, however, their capabilities are largely complementary. Therefore a system combining both technologies can detect all the defects found in heat exchanger tubing, while retaining the above advantages and suffering from fewer limitations than electromagnetic or conventional ultrasonic systems.

References