Proceedings of POWER2009
ASME Power 2009
July 21-23, 2009, Albuquerque, New Mexico, USA

POWER2009-81018

INSPECTING U-TUBE BUNDLES USING ACOUSTIC PULSE REFLECTOMETRY

Noam Amir	**Oded Barzelay**	**Amir Yefet**	**Tal Pechter**
AcousticEye Ltd.	AcousticEye Ltd.	AcousticEye Ltd.	AcousticEye Ltd.
Tel Aviv, Israel	Tel Aviv, Israel	Tel Aviv, Israel	Tel Aviv, Israel

ABSTRACT

Acoustic Pulse Reflectometry (APR) has recently been gaining acceptance for a variety of tube inspection applications, as a viable alternative to more entrenched technologies such as eddy current. In this paper we present a case study demonstrating how APR can be used successfully for inspecting U-tube bundles. This type of heat exchanger poses a great challenge to technologies which require traversal with a probe, due to the presence of tight bends in the tubes. These are usually not traversable by probes. APR, on the other hand, uses an acoustic pulse as a “virtual probe”, with the ability to navigate bends, elbows, fittings etc. with no difficulty. In this paper we show how the various typical faults are revealed in the acoustic measurements and demonstrate how the analysis software recognizes these faults and generates the report. In one case presented here we inspected 62 heat exchangers used to heat natural gas, containing 39 U-tubes each, totaling 2379 tubes. Each tube had an internal diameter of 11mm, wall thickness of 2.5mm, and a length of approximately 6 meters, though there was some variability in length due to different lengths of the U bends. An added difficulty in inspecting these tubes was that the tube sheet was about 80 centimeters in distance from the inspection port-hole. The average inspection time in the field was 25 seconds per tube. All measurements were logged to computer files, and automated fault detection software generated a full report showing the condition of the tubes, indicating degradations in wall thickness, full and partial blockages, and holes. In the second case study we examine the variability in u-tubes in a single bundle and discuss the effect this has on the results.

INTRODUCTION

Currently, the most commonly used techniques for inspecting tubes found in heat exchangers are based on invasive testing. Eddy current, magnetic flux leakage, Iris and ultrasound based methods all require a probe to be traversed throughout the entire length of each tube being examined. Though these technologies are at a mature stage and considered to be reliable, they still suffer from several drawbacks. Under ideal conditions, inspection times of about 1 minute per tube are often cited, though this rate is very difficult to maintain over an entire shift. Probes are prone to becoming stuck in cases where the tubes have not been cleaned properly, which is difficult to ascertain a-priori. Finally, probes are difficult to negotiate through bends in u-tubes. Though some flexible probes are currently available, some bends are too tight for such probes. When bends are non-negotiable using such technologies, both sides of the u-tube must be measured separately, requiring two measurements per tub, and the region of the bend itself remains untested.

Acoustic Pulse Reflectometry (APR) is a technology that has matured in academic research labs for several decades, though it has only recently been commercialized as a viable alternative for tube inspection. APR involves sending an acoustic pulse down the air inside the tube and measuring the reflections caused by various defects. In the case of u-tubes it is especially appealing, as it is non-invasive, and the acoustic pulse can traverse bends and constrictions with no difficulty.

In this paper we present a condensed introduction to APR, since a paper dedicated to this subject was presented at a previous ASME conference [1]. We then discuss the particularities of inspecting u-tubes, and end with two case studies.

Basics of APR

An acoustic pulse injected into a semi-infinite straight walled tube will propagate down the tube without generating any reflections. This pulse can be measured by mounting a small microphone with its front surface flush with the internal tube wall. When the pulse encounters a discontinuity in cross section, a reflection is created. The amplitude and form of the reflection is determined by the characteristics of the discontinuity: a constriction will create a positive reflection, whereas dilation (increase in cross section) will create a negative reflection. Neither of these discontinuities will change the shape of the pulse in their vicinity, but the reflection measured by the microphone will be an attenuated and smeared replica of the impinging pulse, due to propagation losses [2]. A hole in the tube wall, on the other hand, will create a reflection having a more complicated shape, affected by the size of the hole and the radiation of acoustic energy to the space outside the tube [3]. Schematic examples of these cases are presented in Figure 1.

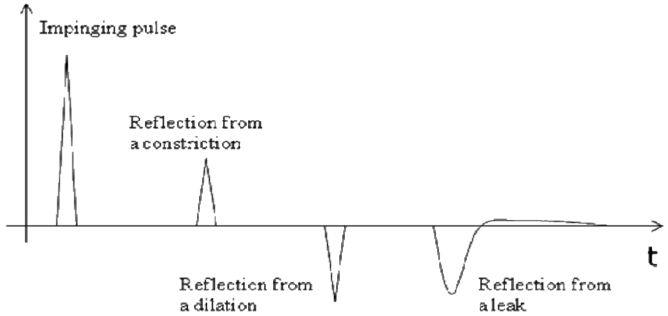

Figure 1: Schematic examples of reflections from discontinuities

Though some of the acoustic energy present in the original pulse is reflected at discontinuities, the rest of the acoustic energy continues to propagate down the tube. Any further discontinuities will once again create reflections.

APPLYING APR TO FAULT DETECTION

Diagnosing the internal condition of the tube is a matter of correctly interpreting the reflections as they arrive back to the microphone. One aspect of the interpretation is straightforward: the time of arrival of a reflection can be used to calculate the precise location of the discontinuity, since such reflections propagate at the speed of sound. The second aspect of interpretation is more complicated, as it involves inferring the exact nature of the discontinuity from the detailed shape of the reflection. In a practical system the pulse shape is constrained by the capabilities of the transducer, therefore it is more complicated than the pulse shown in the schematic example in Figure 1.

Several factors determine whether the APR system can identify faults correctly: the level of background noise, the distance of the fault down the tube (since the pulse decays over distance, due to friction with the tube walls), and the accuracy and sophistication of the detection algorithms.

A complicating factor is the fact that early reflections may overlap with the excitation pulse itself, which is usually a much stronger signal than the reflections themselves. This stems from the fact mentioned above, that transducers are far from ideal and cannot really create an extremely localized pulse as the one in figure 1. Sample measurements from two tubes are presented in figure 2, one from a blank tube and one from a tube with a dent at 0.96m, creating a localized blockage in this tube. At first glance the measurements look nearly identical, though zooming in on the region of the fault shows a clear difference between them. Subtracting the two measurements, as presented in figure 3, shows a signal that resembles the idealized reflection created by a blockage, as presented in figure 1: a constriction followed by a dilation. The need to subtract the measurements from a reference measurement on a blank tube is in fact the price that must be paid for using a small handheld system. In academic APR systems, tubes are long enough so that by the time reflections arrive, the excitation pulse has died out, thus the early reflections do not pose a problem.

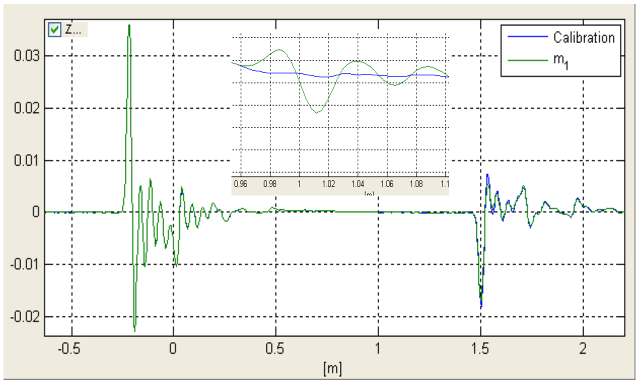

Figure 2: measurements from a blank tube (calibration) and a tube with a dent (m1). Zoomed insert shows where they differ.

The measurement of a pristine tube is referred to as the calibration process. It is important to perform this calibration measurement on site, since it is affected by factors such as temperature, humidity, ambient pressure, and various adaptors fitted to the probe for measuring different tube diameters. Of course a pristine tube is not always available on site, and it is not always feasible to carry one around, since heat exchanger tubes can reach lengths of 60' or more. We have found that two simple approaches work very well in the field: either selecting post-priori the best measurement from a large number of measurements taken on a tube bundle, or even better – creating a calibration by combining measurements of a large number of tubes, using statistical methods.

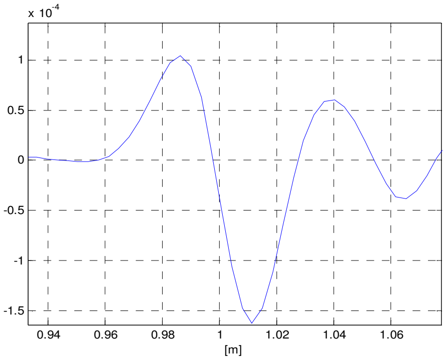

Figure 3: Subtraction of the two signals in figure 2.

.

A detailed analysis of these issues, with numerous examples, was presented in [1]. In the rest of this paper we'll focus on the particularities of performing APR in u-tubes.

Measuring u-tubes with APR

Applying APR to u-tubes raises two questions: 1) how will defects in the u-bend itself show up; 2) how will the u-bend affect reflections from the straight part of the tube beyond the bend. The answers to these questions depend to some extent on the internal structure of the tube at the bend.

Theoretically it is possible to construct u-bends which have nearly no effect at all on the internal cross section of the tube. Figure 4 shows a measurement taken from a 1" tube with a bend having a radius of curvature of approximately 12 cm.

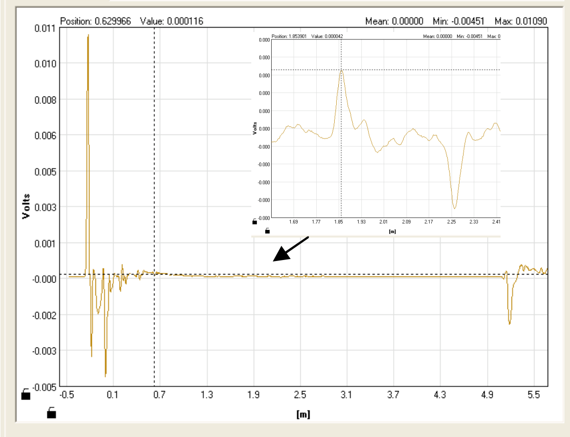

Figure 4: Measurement of a relatively smooth u-tube. Insert is a zoomed view of the reflections from the bend.

Only when zooming in considerably on the region of the bend do the reflections become visible. In this case we observe a small positive reflection at the beginning of the bend followed by a small negative reflection at the end of the bend. The positive reflection indicates a reduction in cross section that lasts until the negative reflection – in other words these reflections indicate that the cross section of the tube throughout the tube is slightly smaller than its nominal value in the straight parts. No other effects of the bend are found in the rest of the signal – the reflection from the far end of the tube is clearly visible in figure 4.

U-tube manufacturers do not generally impose tight tolerances on the internal cross section at u-bends. U-tubes commonly found in heat exchangers vary to a great extent in the manner in which the bend affects this cross section, depending on tube radius, radius of curvature of the bend, tube material, and other factors specific to various manufacturing processes. This has been borne out by the extensive experience we have accumulated by now in inspecting such tubes.

Fault detection in u-tubes

In order to demonstrate how faults can be detected in u-tubes using the same methodology for detecting them in straight tubes, we created artificial faults in two such tubes: one with a hole in the u-bend itself, and one with a dent in a straight segment of the tube on the far side of the bend.

Figure 5 shows two measurements: one from a blank u-tube with no faults, and one from a u-tube with a hole in the middle of the bend. Both tubes have 1" Outer diameter with a wall thickness of 2mm. hole diameter was 1.5mm.

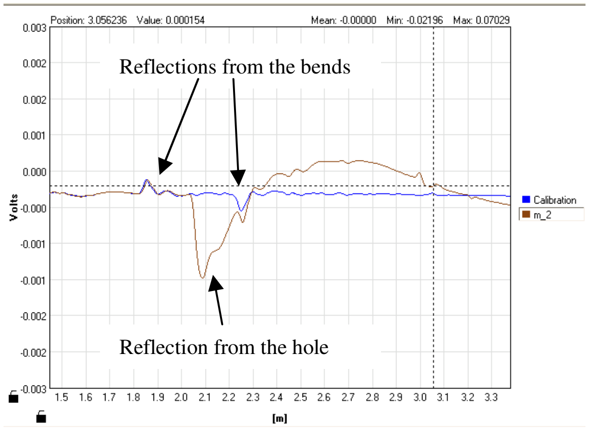

Figure 5: Measurement of u-tube with a hole in the middle of the bend, on top of a measurement from a blank tube.

The reflection from the hole stands out clearly and is easily distinguishable from the small reflections pointed out earlier, created at the beginning and the end of the bend. In fact the reflection from the hole is simply superimposed on these.

Figure 6 shows two measurements also on tubes of similar dimensions. One measurement was taken from a blank tube, and the second was taken from a tube with a very small dent on the leg beyond the u-bend.

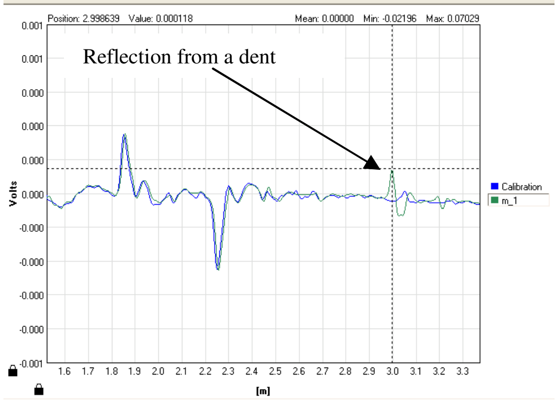

Figure 6: Measurement of u-tube with a dent on the leg beyond the bend, on top of a measurement from a blank tube.

The reflections from the bends coincide in both tubes, whereas the dent stands out clearly in the faulty tube. These two examples demonstrate that the u-bend presents no obstacle to detection of faults, in the bend itself or beyond it.

CASE STUDY 1

In September of 2008, AcousticEye's APR equipment was employed to inspect an entire site, composed of 31 heat exchangers, each of them containing two bundles of 39 u-tubes. Each tube was about 6.2 meters in length, with some variation due to different lengths of u-bends. One challenge in inspecting these bundles was that the tube sheet was deeply recessed with respect to the access port, requiring an extension of approximately 80cm to be fitted to the probe. A photo of the setup is shown in figure 7. A horizontal plate separating the upper and lower half of the bundle can also be seen in the photo. The map of a single bundle is show in figure 8 – the rows in this bundle contain 5, 6, 9, 10 and 9 tubes, respectively.

Figure 7 – the probe with the extension tube, inserted into one of the bundles.

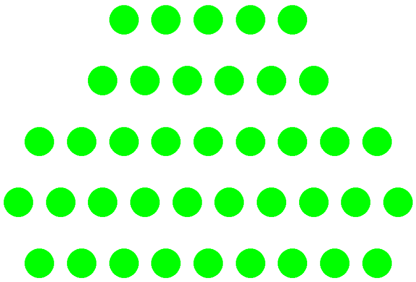

Figure 8 – layout of tubes in a single bundle

All tubes found in a single row were identical in these bundles. Examining five representative measurements from the five different rows demonstrates the different lengths of tubes found in each row. In figure 9 we show a zoomed view on the reflections from the ends of the tubes. These occur at 6 meters in the shortest row (bottom row in figure 8) and 6.3 meters in the longest row (top row in figure 8).

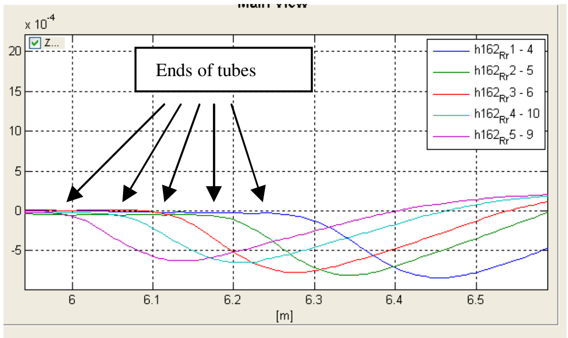

Figure 9 – reflections from the end of five tubes from five different rows.

The main difficulty at this site was in obtaining a good seal between the probe extension tube and the tube being inspected. Maneuvering the end of long extension tube and holding it properly against the tube sheet proved to be challenging, especially since some of the tube ends suffered from severe corrosion, which make a good seal more difficult to obtain. Lack of a good seal causes a certain amount of drift in the measurements, which is analyzed and removed using signal processing techniques. This makes it somewhat difficult to present a direct graphical comparison between the signals at the u-bends. Looking at the same measurements as in figure 9, but in the vicinity of the bend, in figure 10, reveals some such drift but no major change in signal shape:

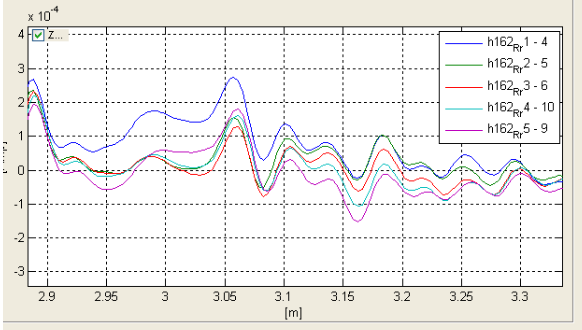

Figure 10 – signals near the centers of the same five tubes as in figure 9

Our conclusion from observing these measurements and many more from this site was that there was a minimal effect of the u-bend on the internal cross section. Thus we were able to analyze the entire set of measurements without the need to take any special steps to take these bends into account. A full account of holes, pitting and erosions was given to the operator.

CASE STUDY 2

In December of 2008, AcousticEye's APR equipment was demonstrated at a large refinery. 24 tubes in a bundle of u-tubes were measured, all from a single row. Zooming in on the measurements at the end of the tubes, in figure 11, we observe that indeed all the tubes are of the same length.

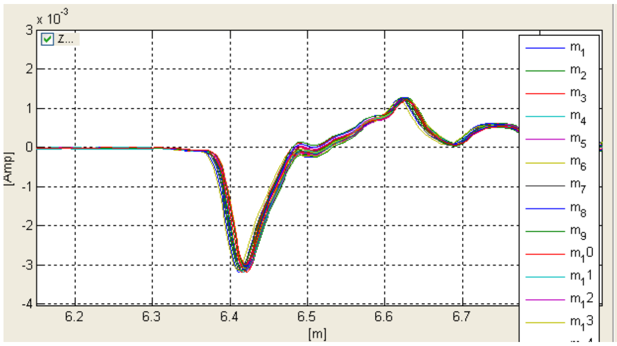

Figure 11 – reflections from the end of 24 tubes in case 2

A close look at the measurements near the bend, in figure 11, reveals that in these tubes reflections do occur there. This indicates that the cross section is not uniform throughout the bend. Furthermore, the measurements seem to group into 2 generic shapes. We might speculate that they belong to 2 manufacturing lots, though this was hard for us to verify on location.

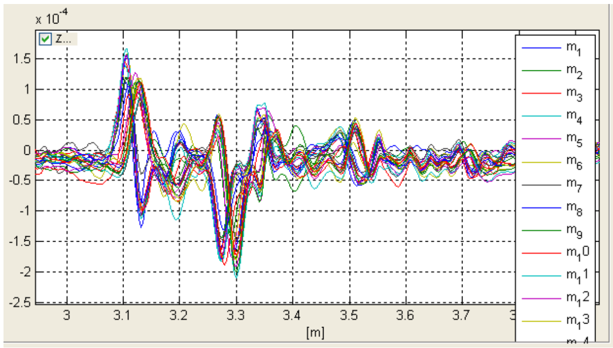

Figure 11 – reflections from the middle of 24 tubes in case 2

Obviously, using a measurement from one type of tube as a calibration measurement for the second type of tube would give many false alarms. Therefore, in a case like this, some observation of the signals is necessary in order to determine how many different types of tubes are present in the bundle. Calibration must then be performed for each type of tube separately.

CONCLUSIONS

APR is becoming an acknowledged NDT technique for straight tubes, whereas the question of measuring u-tubes and other configurations (serpentine, spiral, etc.) has been put to us many times. The experience we have accumulated so far suggests that APR is clearly applicable to u-tubes, saving considerable time, since it requires taking measurements from one side of the tubes only.

However, measurement of u-tubes must be carried out carefully, since it is not possible to know a-priori the internal structure of the tubes at the bends. Indeed – tubes may differ from each other even when they are present in the same row and have the same overall length. If a calibration can be measured, or derived statistically, from a batch of identical tubes, then faults can be reliably found in the bend itself. In any case, APR signals have no problem traversing the u-bend and giving clear indications of the tube condition beyond the bend.

REFERENCES

1. **ASME Power 2008** – *Condenser tube examination using acoustic pulse Reflectometry* – Noam Amir, Oded Barzelay, Amir Yefet, Tal Pechter.
2. **Acustica 82**, 1996 - *Losses in Tubular Acoustic Systems – Theory and Experiment in the Samples Time and Frequency Domains* - N. Amir, U. Shimony, G. Rosenhouse.
3. **Forum Acusticum 2005**, *Detection, location and sizing of multiple leaks in ducts* - Victor Chilekwa, David Sharp