Application of Guided Wave Technology to Tube Inspection

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Abstract. The inspection of industrial tubes such as those present in heat exchangers or boilers for defects using established methods generally requires careful cleaning of the tubes. This is time consuming and as a result cost-intensive. A fast screening tool based on ultrasonic guided wave technology, which minimizes the need for cleaning, is presented. A specially designed ultrasonic probe to excite guided waves is inserted into the tube and positioned within about a meter from one end. The ultrasonic guided waves propagate along the tube and are reflected from features such as defects. The echoes are then detected by the same ultrasonic probe and are processed to give an Ascan type signature of the tube, from which defects can be identified. The major advantage of this approach is to quickly identify the tubes that are non-defective and, if required, concentrate on the defective tubes only with a more accurate defect sizing method. The paper discusses advantages and limitations of the technique, and example results are presented.

1. Introduction

The current and widely used set of techniques for tube inspection include ultrasonic Internal Rotating Inspection Systems (IRIS), Magnetic Flux Leakage (MFL), Eddy Current (EC) and Remote Field Eddy Current Technique (RFEC or RFET) [1].

Each of these techniques has advantages, but also limitations. This is in most parts due to the varied conditions encountered in the petro-chemical industry. There is a great variety of tube materials, both ferro-magnetic and non-ferro-magnetic. Moreover, different types of service conditions produce different defect mechanisms. This ranges from mechanical fatigue caused by non-uniform stress distribution in the material and mechanical defects caused by vibrations in service to chemical attack caused by the fluids involved, or any combinations of those. This variety of mechanisms in turn results in different types of defects: pin-hole defects, pitting, uniform or non-uniform thinning of the tube wall, general corrosion, axial or circumferential cracking are most commonly encountered. Fouling is also a major issue, and again, the type of fouling depends on the service and the materials involved (both fluids and tube material) [2]. Deposits may reduce heattransfer over the tube walls, and may reduce or even block the flow of the fluids.

All of the inspection techniques listed above suffer from the fact that extensive cleaning has to precede any inspection. The techniques require a probe-head to travel along the entire length of the tube, either by pushing and subsequent pulling by hand or through the use of a propelling-system, so that obstructed tubes cannot be tested. The quality of results for IRIS in particular is badly affected by deposits on the inside of the tube and so extensive cleaning is required. Both MFL and EC need certain fill factors in order to deliver reliable results.

An ultrasonic guided wave (GW) tool however only needs to be inserted within the first meter of the tube, and remains in one position during the duration of the test. No push-pulling units are required, and for a successful test the tube may have internal scale, deposits or even dents.

Before considering further advantages and limitations, it is important to understand the testing philosophy behind the GW screening approach. An ultrasonic GW tool is sensitive to changes in the cross-sectional area of the tube wall. While an estimate can be given by means of establishing the circumferential extent of the feature corresponding to that cross-sectional change, it cannot be used to measure wall loss accurately. In this sense the authors stress that a tube screening system basedon ultrasonic guided waves is not meant as a replacement to the testing methods that give an accurate measurement of wall loss (such as IRIS).

The main idea is to use the GW tool in order to quickly screen a number of tubes before extensive cleaning has to be carried out, which is required by all other techniques. In certain applications, the bundles even need not be moved from their in-service location. This can save a considerable amount of cost by reducing overall cleaning and shut-down time. The GW tool should be used to concentrate resources to areas where it is most meaningful by assessing whether it is necessary to clean certain tubes for further inspection with an accurate wall loss measurement tool or not – which may be the case for the majority tubes.

This screening can be carried in most applications, because the GW tool can be used with any tube material and, as is outlined in the examples in this paper, is very tolerant regarding the tube geometry. In some instances, the GW tool may even provide the only currently available testing method when the geometry of the tubes prevents the use of conventional techniques (for example twisted tubes).

As with any non-destructive testing method, there are limitations, which may be resolved with the further development of the technique. The remainder of this paper will outline these in detail, as they are important in assessing the overall benefit of GW screening.

2. Tube Screening System

The Guided Ultrasonics Ltd T-SCAN transducer probe-head assembly and software is compatible with the Wavemaker G3 instrument and hence benefits from the improvements from the earlier version of the Wavemaker SE16. The G3 system including a 3/4 inch probe-head is shown in Figure 1.

Figure 1. Wavemaker G3 and 3/4 inch probe-head.

For the test, the probe-head is inserted up to a meter into the tube, or less depending on the application (see Figure 2). The transducers, which can move freely in the radial direction with respect to the axis of the probe-head and the tube, are pneumatically pressed against the inner wall of the tube. No coupling fluid is needed for the transfer of ultrasonic energy into the tube. When the transducers are excited, a guided wave propagates simultaneously in both directions along the tube as depicted in Figure 3. The guided wave is then reflected by any change in cross-sectional area. The amplitude of the reflection depends on the magnitude of this change in cross-section. These reflections are recorded by the transducers array and processed to give an A-scan type image of the tube where the amplitude of the reflections is plotted against the distance with respect to the probe-head position. The guided wave is reflected from both ends of the tube. These reflections serve as a calibration reference as they represent a 100% reflection. If there is another feature such as a defect, a signal appears at the corresponding position with an amplitude corresponding to the cross-sectional area change.

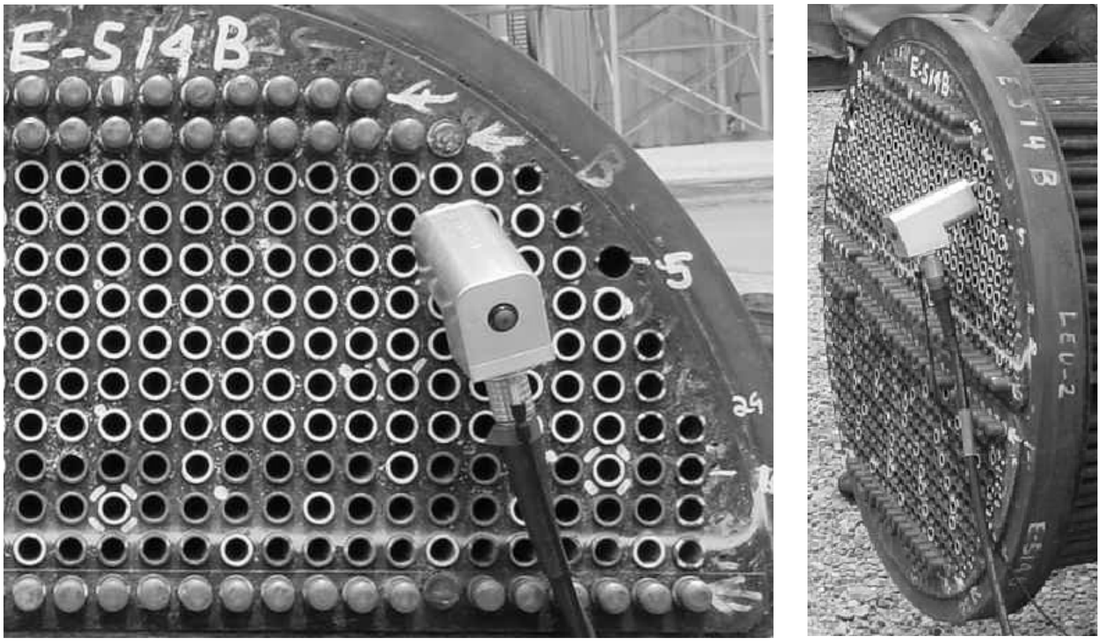

Figure 2. Tube screening system with probe-head inserted the tube, only handle is visible.

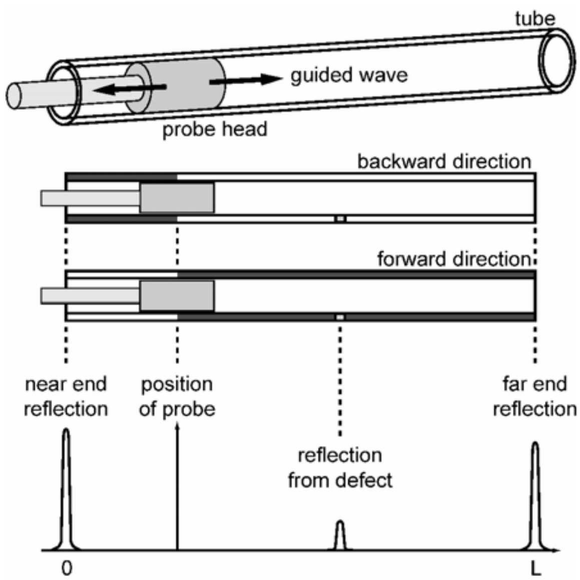

Figure 3. Schematic of the principle of test in a tube with defect.

As the transducers need to have a certain mass in order to function properly in the test frequency range, fitting the required number of transducers into the restricted space is a considerable engineering problem. At the moment, the smallest tube size that can be accommodated for is 3/4 inch 12 gauge tube (0.109 inch wall thickness). Any larger tube sizes pose no problem, as there is no theoretical limitation as long as a sufficient number of transducers can be included in the array.

For a particular tube size, a certain minimum number of transducers is required for the GW test depending on the number of propagating GW modes present in the frequency range of the test. Axially symmetric modes in tubes are used for the tests, but additionally detecting and processing for mode converted non-axially symmetric modes is important. Axi-symmetric features can be distinguished in this way from non-axi-symmetric features. This is the main reason why piezo-electric transduction has been chosen instead of a magnetostrictive transduction system.

It should also be noted that the GW system does not require calibration using known machined defects. Apart from IRIS, all other tube inspection techniques depend on this calibration prior to testing. While this practice is commonly accepted, it should be viewed with caution as the sensitivity of these techniques is evaluated on these defects. However, their response to naturally occurring defects in the tube under test may be different.

The GW tube screening system is controlled via a laptop computer and the software TubePro (see Figure 4 for a screen-shot). The software is based on the Wavemaker WavePro software. A tube sheet program was implemented into the software for ease of use and reporting. Once the tube sheet layout is specified, a test can be initiated by selecting the tube of interest. The test result is presented on the left hand side, and tubes can be colored and classified to user defined thresholds. For example, all tubes above 30% cross-sectional change could be classified as fail for further examination, and colored in red.

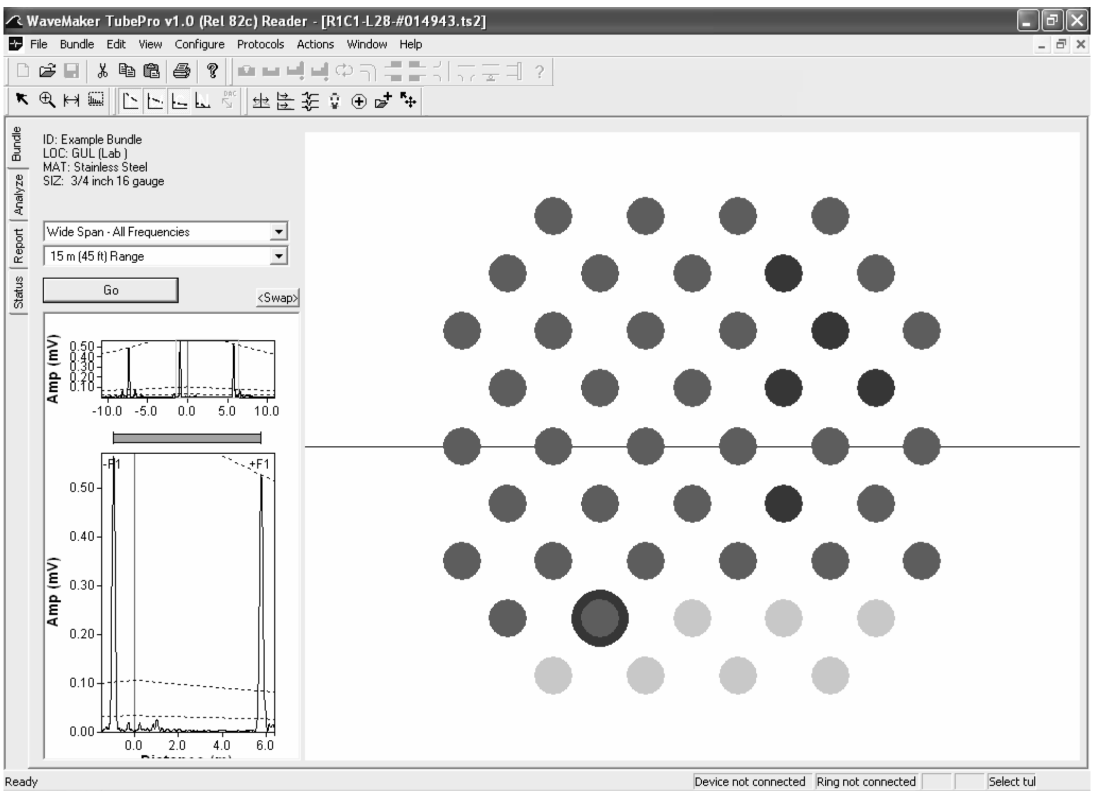

Figure 4. Screenshot of the software TubePro with implemented tube sheet diagram.

3. Application areas and limitations

3.1 Heat Exchanger Tubes

Guided waves are extremely accurate and reliable in identifying tubes with no defects. All that can be seen in the result of a clean tube are the two reflections from the far and the near end. Because an end reflection is a 0 dB reflector, the software can automatically compute the DAC levels from the result. As an example, Figure 5 shows the result from a new heat exchanger tube. For comparison, Figure 6 shows the result from a new heat-exchanger tube with one machined defect of 7% and a second of approximately 10% cross-sectional area. The call DAC level, which can be set by the operator depending on his application, was set to -14 dB (corresponding to 20%), which shows that the amplitude of the reflection is consistent with the size of the defect.

Note that there is a dead-zone and a near field, the size of which depends on the frequency of the test. Generally, there is a dead-zone of about 250mm. In the dead-zone, no data can be obtained, and in the near-field, the amplitude of the reflections is affected.

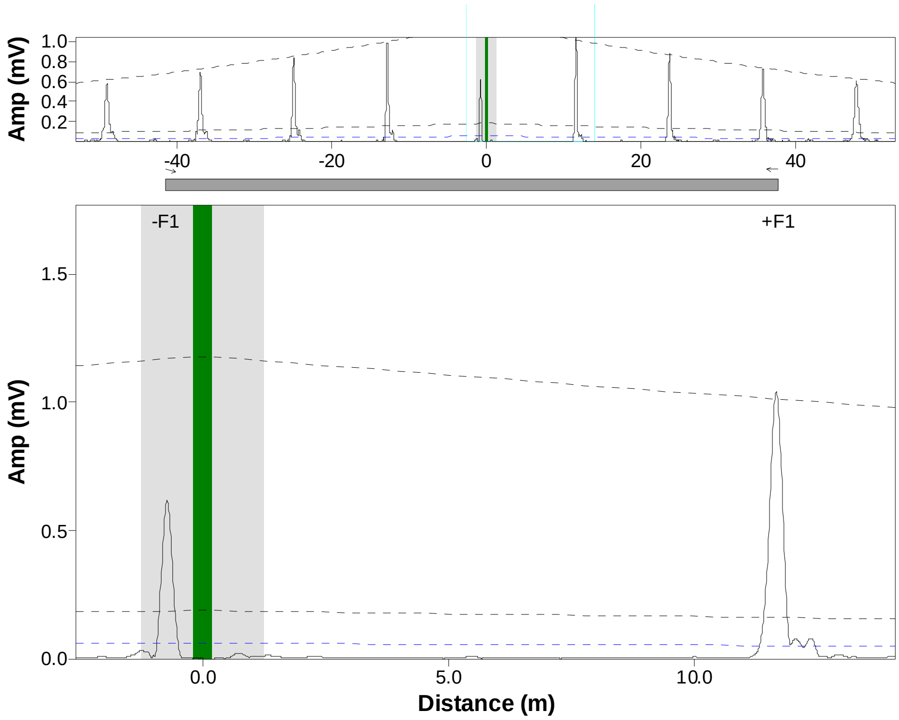

Figure 5. Example result from a tube with no defect.

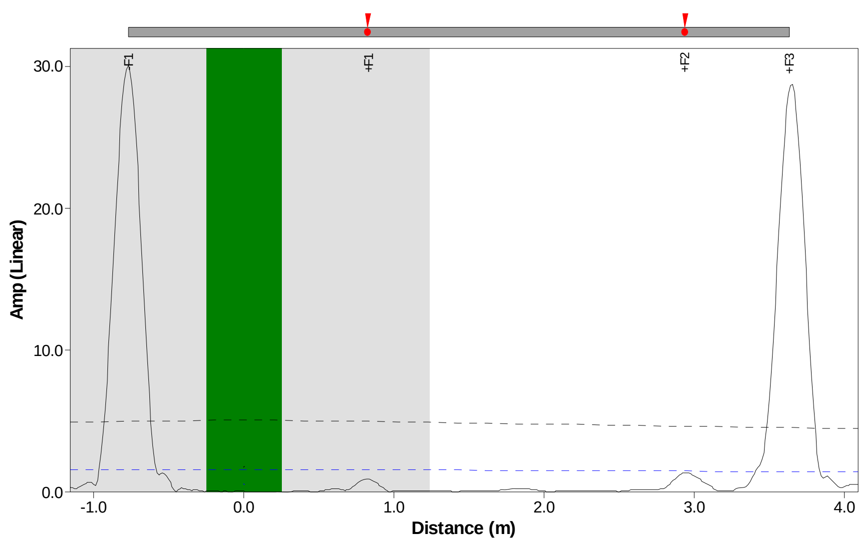

Figure 6. Example result from a tube with two defects (+F1 approximately 8%, +F2 approximately 10% cross-section loss).

3.2 U-Bends

Some heat-exchangers have tubes arranged in a U-shape. Guided waves propagate through bends, and if the tube is in good condition, both legs of the U-tube including the bend can be screened in one test. This can potentially halve the inspection effort. Because a U-bend represents a change in geometry, the guided wave is partially reflected both from the start and the end of the bend. The amplitude of this reflection depends on the bend radius. Generally, the tighter the bend, the larger is the reflection. This is the case for tubes closer to the line of symmetry in the centre of the bundle. However, the amplitude of this reflection decreases strongly with increasing bend radius. Reflections from tight bends may potentially mask defects in the bend, however, mode converted signals and the properties of the reflection help identifying defects in this area.

3.3 Baffle Plates

The explanations so far have only concentrated on simple tubes, but a complete heat-exchanger system also contains a number of support plates (see schematic of Figure 7). These baffle plates are usually staggered and control the flow of the fluid on the shell-side of an exchanger.

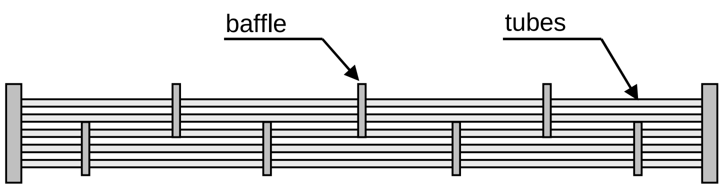

Figure 7. Schematic of a heat exchanger (side view).

If the plates are lose and do not make contact with the tube, they have no influence on the guided wave. However, if they make contact with the tube wall, a reflection occurs at this position. The tightness of the contact between the tube wall and the baffle plate determines the size of this reflection – the tighter the contact, the higher the reflection. There should normally be a certain clearance between the plate and the tube to enable the assembly of the exchanger. However, product as well as corrosion may build up in the space, or the tube may subsequently be expanded with a special tool to avoid vibrations in service. In some cases, the baffle plates may be so tight that the reflections cause the guided wave to be almost entirely reflected. At other times, the reflections may be low, but they mask fretting defects, which is a common wall loss caused by vibration of the tube against the baffle plate. Figure 8 shows an example result from a tube with tight baffle plates, with large reflections occurring at the baffle locations. Therefore, GW testing of heat exchangers should currently be limited to those where the tubes are not severely clamped by the baffle plates.

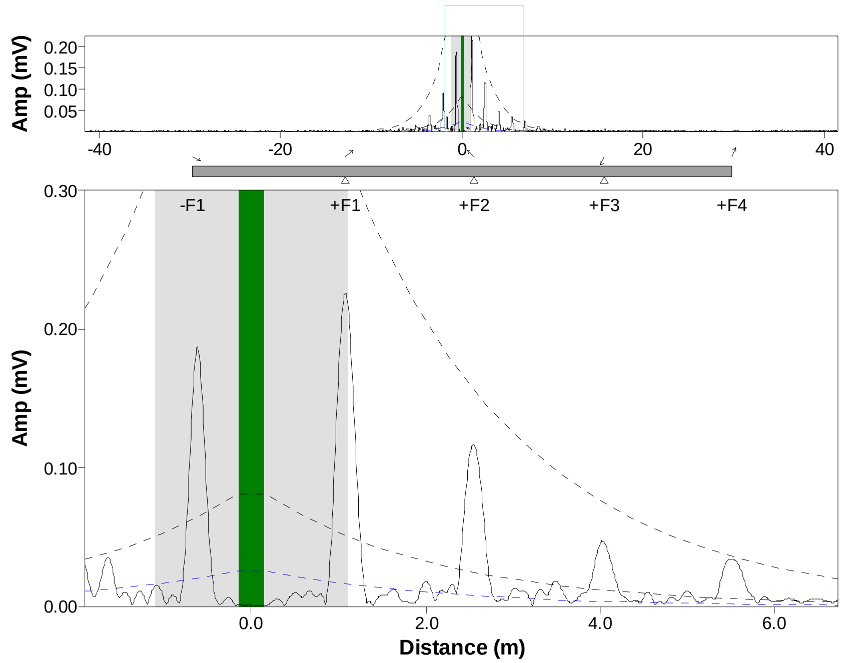

Figure 8. Heat exchanger tube with tight baffle plates.

3.4 Specialty Tubing

Further main applications include the screening of tubes with special geometries. The screening of integral fin tubes, where grooves perpendicular to the tube axis are machined into the tube wall, has been carried out with success. Moreover, the numerical modeling for the calculation of the dispersion curves for the guided wave propagating in this particular guided wave system is computationally straightforward. Figure 9 shows a picture and an example result from an integral fin bundle. The smaller, evenly spaced reflections stem from the areas where the baffle plates are located, however, the cause of the reflections is not the baffle plates but the fact that these areas are not grooved. Guided waves will reflect from any change in the main tube geometry. The result in Figure 9 suggests that defects with a cross-sectional loss of 15% or greater can be detected with confidence. Smaller defects may be detected using advanced interpretation techniques. Note that the inspection was carried out without previous cleaning.

A similar, but nevertheless different class of tubing is represented by those where the tube features have helical symmetry. Fin-fan tubing, mostly used in air-cooling units, comes in many different forms. Some common fin-fan tubes have a helical groove running along the outside of the tube, with thin Aluminum fins attached. MFL is usually used because it is not sensitive to Aluminum fins, has fast inspection speeds and is sensitive to pitting. However, it is a volumetric method and cannot measure wall loss accurately. Also, it cannot measure defects close to the header box, where thinning of the tube often occurs. A GW tool does not measure wall loss accurately either, but can potentially pick up defects close to the headers, and does not require push-pulling units and the extensive cleaning of the tubes.

Another application for which there is currently no other form of inspection method has attracted increased attention. Twisted tubes have an elliptical cross-section shape, and helical symmetry along the tube main axis. For example, a pulled rotating ultrasonic tool can always only inspect at normal incidence to the tube wall and so only at four points. A GW tool however screens 100% of the tube.

The main challenge behind the applications where the tube has a helical geometry is the calculation of the modes and their propagation constants of the guided waves as they differ considerably from the constants in plain tubes. This development work is planned in the near future.

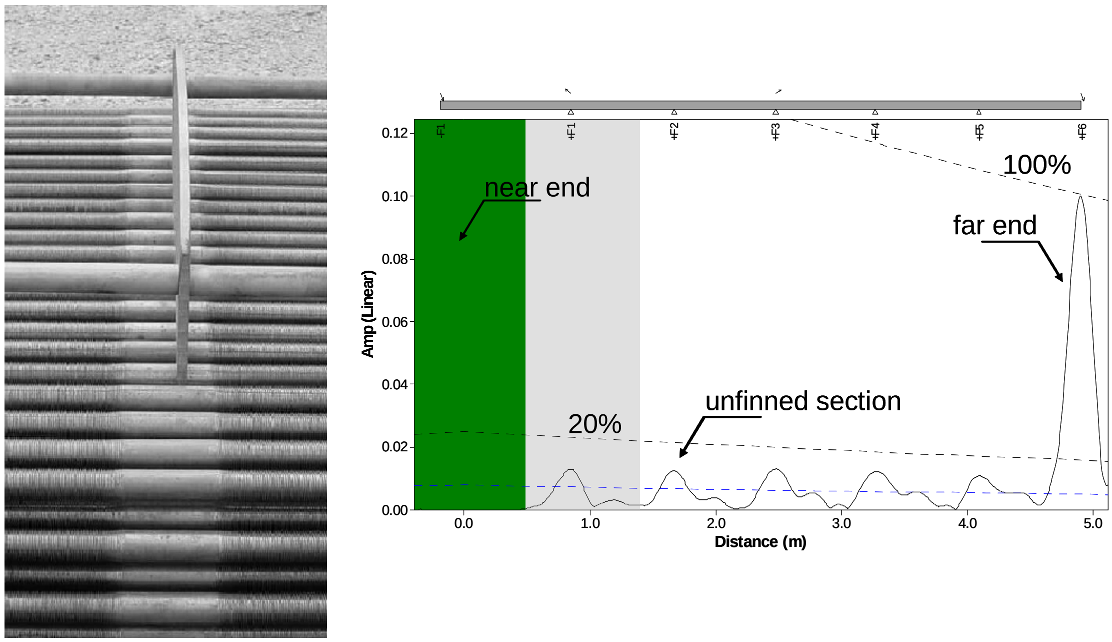

Figure 9. Integral fin tubing (left) and example result (right).

4. Conclusions

A guided wave tool for the screening of tubes in general has been presented. The most important advantage is that it requires minimal cleaning only and therefore saves cleaning cost and reduces down-time. The application areas are widespread as it can be used with any tube material and is very tolerant of the tube geometry. Screening can be carried out through bends, and it can be applied to finned and twisted tubing. The application is currently limited to tubes with loose baffle plates as reflections may occur from tight baffles.

References

[1] Birring, A. S., "Selection of NDT Techniques for Inspection of Heat Exchanger Tubing", ASNT International Conference on Inspection in the Petro-Chemical Industry, Houston, 2001.
[2] Hewitt, G. F., "Heat Exchanger Design Handbook", Begell House, 2002.