EXPERIMENTAL RESULTS OF GUIDED WAVE TRAVEL TIME TOMOGRAPHY

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Abstract.
Corrosion is one of the industries major issues regarding the integrity of assets. Currently inspections are conducted at regular intervals to ensure a sufficient integrity level of these assets. Cost reduction while maintaining a high level of reliability and safety of installations is a major challenge. The concept of predictive maintenance using permanent sensors that monitor the integrity of an installation matches very well with the objective to reduce cost while maintaining a high safety level.
Guided waves are very attractive for permanent monitoring systems because it provides a wall thickness map in between two sensor rings. The wall thickness map provides quantitative information about the remaining wall thickness, location and extent of the corrosion. The performance of guided wave tomography has been evaluated experimentally assessing the sizing accuracy and the smallest corrosion spots that can be detected with this technology. The results show accurate sizing, with a sizing accuracy better than 10% of the nominal wall thickness. Additionally, the maximum distance between the transmitter and receiver rings and the presence of different coatings have been evaluated. The results demonstrate the robustness of the technology under a range of practical conditions.

Keywords: Ultrasonic, Tomography, Inversion, Guided wave, Corrosion monitoring, Travel time, Parameterization, Dispersion

1. Introduction

Corrosion is one of the most important mechanisms of structural damage. There are various reasons why corrosion is such an issue. First of all, its behavior strongly depends on operating and environmental conditions. Also, it can occur in many forms from the formation of clusters of small cracks to large patches of wall thickness loss. Finally, the parameters driving the corrosion growth and appearance are not well understood and are often based on expert opinion. This way corrosion can strike unexpectedly and due to possible high grow rates it can lead to incidents before regular inspections are carried out.
Therefore periodic inspections can never be a cost effective solution for corrosion monitoring. More promising are permanent monitoring systems that can measure the integrity of the installation at any moment in time. The ideal permanent monitoring system for corrosion management should have the following properties. First of all, the coverage of the system should be 100% of the inside as well as the outside surface of the object. It should also be able to measure the corrosion rate, in order for optimal replacement or repair planning. Finally, the system should be able to work without interference with the production process.

2. Guided wave tomography

We developed a method to monitor the wall thickness of an arbitrary object using guided waves [1]. It uses the effect that the phase velocity of most ultrasonic guided wave modes depends on the thickness of the wave guide. In a plate symmetrical and anti-symmetrical modes exist. The zero-order modes (S0/A0) are attractive to use, since these modes always exist. There are several reasons for using the symmetrical zero-order mode S0 instead of A0, these include the
low attenuation and the fact that this mode has the highest velocity. The latter makes it easier to distinguish this wave mode from other possible modes. Similar wave modes exist in a pipe. The geometry consists of two sensor rings, each consisting of 32 piezo electric elements. The distance between the rings can be several meters. The main limiting factor of this distance is the resolution with which a defect can be imaged. Additionally, since we use travel time tomography, the direct waves and higher order helical path should not interfere too much to have sufficient travel time information.

![Diagram](image)

**Figure 1** The top image shows a schematic depiction of the setup used to measure the wall-thickness loss of the area between the single source and receiver. The bottom image shows the schematic depiction of the setup used the measure the absolute wall thickness of the pipe using two linear arrays around the circumference.

3. Processing scheme

A non-linear inversion scheme is used to invert the travel times. The dispersion curve scales with the shear wave velocity, before starting the actual tomographic reconstruction, the shear wave velocity is estimated from the data. The tomographic inversion starts by performing a dispersion correction on the raw data and extracting the travel time of a specific Lamb wave arrival for several higher orders of circumferential waves. In the dispersion correction refraction effects are also included, i.e., no straight rays are used. A reference frequency is defined and after dispersion correction the event will have an arrival time that corresponds to the phase velocity for the reference frequency. Based on an initial guess of the thickness profile the travel times are forward modeled using a ray tracing algorithm using the velocity profile that corresponds to the reference frequency. Normally this initial guess is simply the nominal wall thickness of the pipe. After one or a few iterations a new dispersion correction is performed on the measured data. A locally changing velocity causes changes in travel time and refraction effects. When the travel time difference between the measurements and the forward model data is sufficiently small the inversion process is complete. Normally this occurs within a few iterations.
4. Experimental evaluation using machined defects

The technology outlined in the previous paragraphs is tested in the laboratory. As an example the results on a steel pipe with a nominal wall thickness of 8 mm and a diameter of 10” are shown. The pipe has a total length of 10 m, where three transducer rings are mounted 4 m apart. The outer rings are 1 m from the ends of pipe. Each ring of 32 sources is permanently bonded to the pipe wall. The sources and receivers are small piezoelectric transducers. Mechanical defects are machined to systematically test the detection and sizing performance of our method. The depth, diameter and shape of the machined defects were varied, which in total yields 33 datasets, which have all been processed. A selection of these results is shown here. Figure 2 shows the tomographic inversion of small and shallow defects. Defect depths were 1 mm and 2 mm. The surface area of the defects is increased. The depth and surface area of a defect determines the change in travel time compared to the defect free case. This essentially determines the likelihood of detection. Global variations in the wall thickness exist. Manual pulse-echo measurements confirm that the area between 0 and 0.4 m in the circumferential direction is slightly thicker. The results indicate that the defect shown in Figure 2a is not visible. In all other results, the defect is detected. When a defect is only 1 mm deep, other indication are of similar depth.

Figure 2 Demonstration of detection performance for a small defect, the depth and size (surface area) are gradually increased. The measured depth and in-plane dimensions are indicated below the result

Depth sizing accuracy is the most important feature of our guided wave tomography. A defect was machined with a surface area of 15 x 22 cm, the depth was increased from 1 mm to 6 mm. The sizing performance is shown in Figure 3. As reference a laser scanner was used, the measurement uncertainty is indicated by the horizontal error bars. The comparison with reference measurements shows a linear trend over the complete depth range. The difference between the tomographic result and the laser reference measurement is 0.5 mm.
Figure 3 Tomographic inversion with a systematically increasing depth, a) tomographic result of a 3 mm deep defect, b) tomographic result of a 4 mm deep defect, c) tomographic result of a 6 mm deep defect, d) measured depth versus actual depth for all datasets ranging from 1 to 6 mm. The horizontal error bars indicate the depth sizing uncertainty of the laser reference measurement.

Apart from circular/elliptical defects, axial grooves were machined. A groove is also a frequently occurring corrosion profile, e.g. bottom of the line corrosion. The width of the groove is increased from 2 cm to 12 cm. The depth is fixed at 4 mm (i.e., 50% wall loss) and the length is 1 m. The results are shown in Figure 4.
Figure 4 Tomographic inversion in case of an axial groove, the width of the groove is increase, the length is 1 m and the depth is 4 mm. a) width = 2 cm, b) width = 4 cm, c) width = 8 cm, d) width = 12 cm. The color scale is the same in all figures.

Even the smallest groove gives an indication in the tomographic inversion result, even though the smallest groove is smaller than the wave length of the guided waves. Obviously in these cases the shape of the groove is not properly recovered. A groove with a width of 12 cm is more or less properly recovered. The depth of this indication is 3.1 mm, while the actual depth equals 4 mm.

More in depth analysis shows that the ray approximation, which is currently used in the tomographic reconstruction kernel, does not accurately describe the wave propagation. This explains why the reconstruction is less perfect than for circular/elliptical defects.

5. Coating

Coatings are frequently applied in the industry to prevent corrosion. Within the scope of this project we evaluated an epoxy coating and Stopaq wrapping. Here we present the results with the Stopaq wrapping which is visco-elastic coating with a thickness of several millimeters. A pipe was coated with Stopaq, the length that was covered was gradually increased up to a length of 3.5 m. The signal spectra were recorded and used to assess the amount of attenuation (see Figure 5). Although the attenuation is significant the signal quality remains good as can be seen in Figure 6.
The data without a coating (Figure 6a) looks more noisy. This is due to the higher frequency content in the data. Because guided wave tomography is performed using transmission measurements, a huge amount of attenuation can be accepted, while for reflection measurements the dynamic range if normally the limiting factor.

Figure 6 Recorded wave fields, a) without a coating, b) with a coating. The data with a coating looks more noisy due to the higher frequency content present in the data.
6. Accelerated corrosion test

Apart from mechanically machined defects, an accelerated corrosion experiment has been performed. Salt was sprayed intermittently at a hot pipe to accelerate corrosion. Three nozzles were used to spray the pipe at three closely spaced locations. Guided wave transmission measurements have been performed on a regular basis and laser scans were used as reference. The shear wave velocity was determined for each measurement separately to compensate for temperature effects. The data were processed using the first dataset as baseline. The baseline is subtracted from the obtained time picks, such that only changes due to wall thickness loss remain. The inversion results are shown in Figure 7. Guided wave travel time tomography is much more sensitive using baseline subtraction. Already after 16 days, a wall thickness loss of 0.3 mm could be detected. After 57 days the three corrosion spots are clearly visible. The currently designed piezo transducers are not sufficiently robust to withstand the test conditions. No special measures were taken to improve the lifetime, consequently the result after 78 days suffers from aging effects.

![Image a)

![Image b)

![Image c)

![Image d)
Figure 7 Tomographic inversion results as function of time. Already after 16 day the first indications of corrosion is visible.

The comparison with the laser scans is summarized in Figure 8. Similar as with the mechanically machined defects, the difference between the measurements is less than 0.5 mm.

Figure 8 Comparison of laser reference measurement with the corrosion depth determined from guided wave tomographic results. After 120 days, no tomographic inversion result was obtained due to sensor deterioration.

7. Performance overview

The objective was to establish the current performance of guided wave tomography. This can be expressed in terms of depth sizing and defect detection capabilities. The sizing performance was determined from mechanically machined defects and accelerated corrosion experiments. Provided that the corrosion patch is sufficiently large, typically a diameter of 15 cm, the sizing accuracy is typically 0.5 mm. It should be emphasized that in case of small diameter pitting (~1-5 cm), the sizing error is larger.
Small defects may not be detected. The detection capability can be expressed in terms of defect length times the defect depth. This product is proportional to the change in travel time compared to a defect-free case. For the mechanically machined defects, an overview is shown in Figure 9. The results indicate that defects with a size of 3 cm$^2$ can be detected reliably.

Using a baseline, as in the accelerated corrosion experiment, the system is much more sensitive. Based on the accelerated corrosion test, the detection capability improves to 0.6 cm$^2$.

Guided wave tomography is quite insensitive to coatings. The presence of a coating affects the phase velocity, but this is compensated by the velocity estimation procedure as part of the data processing. The attenuation losses in case of thick visco-elastic coatings, are likely to reduce the sensitivity due to loss of high frequencies. This can (partially) be compensated by controlled electrical excitation.

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References