1-D Profiling Using Highly Dispersive Guided Waves

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\textbf{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. There are many situations where the actual defect location is not easily accessible, e.g., a pipe support or a partially buried pipe. Guided wave tomography has been developed to reconstruct the wall thickness of steel pipes. In case of bottom of the line corrosion, i.e., a single corrosion pit, a simpler approach may be followed. This method is intended for rapid, semi-quantitative screening of pipes.

Data is collected in a pitch-catch configuration at the 12 o’clock position using highly dispersive guided waves. We invert for the wall thickness profile in the circumferential direction, assuming a simple defect profile. The approach is evaluated on numerically simulated data and on measured data.

\textbf{Keywords:} ultrasound, inspection of pipelines, tomography, guided wave

\section{1. Introduction}

Corrosion is one of the major problems of the industry and it often occurs at difficult accessible locations. This has been one of the motivations for our development of guided wave tomography\cite{1}. With tomography, we can make a wall thickness map of the pipe wall in between two transducer arrays. The technology can be used for permanent monitoring as well as inspection. With the current technology, we can inspect/monitor pipe sections up to 10 m, with an accuracy similar to manual ultrasonic inspection. An example of the output of the tomography is shown in Figure\textsuperscript{1}. This shows the corrosion at a pipe support of an 8 bar gas pipe. In this case the remaining wall thickness is less than 20\% (80\% wall thickness loss).

![Example of tomogram of heavy corrosion on a pipe support, the data indicates a remaining wall thickness of about 2 mm.](image)

\textbf{Figure 1} Example of tomogram of heavy corrosion on a pipe support, the data indicates a remaining wall thickness of about 2 mm.
This pipe support example shows the case for inspection using guided wave tomography. In this paper we show the results of a first exploratory exercise to develop a semi-quantitative screening method with highly dispersive guided waves. This is complementary to guided wave tomography in the sense that is can be deployed rapidly and provides virtually real-time, (semi) quantitative results.

The main idea is to deploy a transmitter/receiver transducer (EMAT) at the 12 o’clock position of a pipe and perform a scan in the axial direction. A highly dispersive guided wave (S0 or A0) mode is transmitted in the circumferential direction. Based on the phase change due to corrosion, we will evaluate whether it is possible to invert for the wall thickness loss, using assumptions about the defect shape.

2. Model of the data

The principle behind the method is explained in Figure 2; a transducer is used at the accessible surface of a pipe, which is usually around the 12 o’clock position. A dispersive guided wave is generated that travels in the circumferential direction. Along its travel path it collects information about the wall thickness. The phase of the measured signal can be expressed as:

\[
\phi(f) = 2\pi \int_0^L \frac{dx}{\omega \tilde{v}(\omega \rho)}
\]

where \( \tilde{v}(\omega \rho) \) is the phase velocity as function of the spatially varying wall thickness \( \rho(x) \) and frequency \( f \). The integral is over the circumference of the pipe \( \Omega \). This is graphically illustrated in Figure 2.

![Figure 2 Graphical illustration of the measurement concept.](image)

In order to reconstruct the wall thickness loss, we have to assume a simple defect shape. In this case we assume a Gaussian shape, which is characterized by two parameters. Other shapes may be possible as well, as long as the number of parameters that describe the shape remain limited. Additionally we need to emphasize that it is principally not possible determine the location of the corrosion, because we use only a single transmission measurement.

The Gaussian function to describe the wall profile to fit the data has only two parameters, the maximum corrosion depth and the width. The location is always positioned at the centre (6 o’clock position), but this is purely for visualization purpose. In the fitting process, we minimize the phase difference compared to a reference measurement, i.e., a location without corrosion. The objective function that is minimized is given by:
\[ |\varphi_{\text{meas}}(\delta) - \varphi_{\text{ref}}(\delta) - 2\pi \int_0^{\delta} \frac{1}{\sqrt{(\sigma^2(x))^2 - (\omega - \omega_0)^2}} dx|^{1}, \]

where \( \varphi_{\text{meas}}(\delta) \) and \( \varphi_{\text{ref}}(\delta) \) are the phases of the reference measurement and the current measurement, for which the wall thickness profile is determined. The parameters are indicated by \( \mathbf{p} \).

In order to obtain a good convergence in the inversion, it is important to use sufficiently dispersive waves.

In this approach, we make a number of assumptions; firstly, we assume that we can model the shape of the corrosion with a Gaussian profile. Secondly, we ignore refraction effects, meaning that we assume a one-dimensional defect. This is quite important and in the next few examples we investigate the sensitivity to this second assumption.

3. Experimental results

In order to experimentally validate the performance of the 1D profiling method artificial defects were machined in a 8 mm thick aluminum plate. EMATs were used in a pitch-catch configuration to scan over the defects. The main reason for using aluminum instead of steel is that the EMAT’s can be moved easily over an aluminum plate. The EMAT’s are mounted in a bracket to ensure a fixed distance of 80 cm. Each scan consists of 48 positions scanning completely over the defect.

Two defects with different diameters were produced, the smallest has a diameter of 130 mm and the largest has a diameter of 260 mm. The wall loss was increased in steps of 10% starting at 10% to 80% wall loss. Figure 3 provides an impression of the experiment, Figure 3a shows a machining tool mounted in a three-axial scanning system and Figure 3b shows the EMAT’s mounted in their bracket.

Figure 3 Impression of the machining of defects (a) and the measurements (b) using EMAT sensors.

Figure 4 shows a typical processed data example for a wall loss of 70%. A dispersion correction is applied and only the wave mode of interest is windowed out. The signals to the left and to the right of the defect are used for reference. The presence of the defect is visible in the form of residual dispersion, running in front of the wavelet.
Figure 4 Processed data example. The data is corrected for the dispersion assuming no wall loss. At locations where there is some wall loss, ringing will be visible at times before the arrival of the wave in area’s without wall loss.

In order to reconstruct the wall thickness a multi-trace inversion scheme is used, where we use a parametric description in both the scan direction and the length direction. The number of parameters is limited as much as possible. The reconstructions for the 130 mm diameter defects (10%, 30%, 50% and 70%) are shown in Figure 5 and for the 260 mm in Figure 6.

The Figure title indicates the actually measured wall loss. The frequency dependent phase rotation contains the information about the depth and the shape of the defect. The smaller or shallower the defect, the less pronounced phase rotation is measured. This explains the systematic under sizing of the small diameter defects. The under sizing is 10% of the wall thickness. Because the defect diameter is known from the inversion, it is potentially possible to apply a correction factor to compensate for the under sizing. There is one outlier; the 30% defect is sized to be 50% wall loss. There is no clear explanation why this has happened. The data does not show any indication of some form of noise in the measurement.

Increasing the frequency causes the A1 mode to be generated, which starts to interfere with the S0 mode. This limits the use of the S0 mode.
Figure 5: Inverted wall thickness maps for the defects with a diameter of 130 mm, a) 10% wall loss, b) 30% wall loss, c) 50% wall loss, d) 70% wall loss. The actually measured wall loss is shown in the title of each wall thickness map.

The wall thickness reconstructions for the larger defect are shown in Figure 6. The defect depth is reasonably well reconstructed; typical sizing errors are less than 10%. But for this dataset there is also one data point which is significantly off. The defect with a wall loss of 40% is sized as 25%. This indicates that sizing errors may occur both over and under estimating the real depth. This is more likely to occur for shallow defects than for very deep ones.

In Figure 7 the sizing performance is summarized for all datasets. For both datasets a fairly linear trend is obtained, the correlation coefficient for the 130 mm defect is 0.60 and it is 0.91 for the 260 mm defect. The slopes are respectively 0.91 and 1.04. The selection of a function that describes the shape of the defect is the main drawback of this approach. The quality of the shape description mainly affects the quality of the data fit. This prior knowledge is generally not available. Therefore we investigate the inversion performance when using a more flexible parameterization.
Figure 6: Inverted wall thickness maps for the defects with a diameter of 260 mm, a) 10% wall loss, b) 30% wall loss, c) 50% wall loss, d) 70% wall loss. The actually measured wall loss is shown in the title of each wall thickness map.
Figure 7 Sizing performance of 1D profiling method on artificially made defects

Figure 8 shows a comparison of an inversion result using a pre-described function (a) and a more general parameterization using a cubic interpolation between the parameters. The machined defect shape is shown in red (true profile). The parameterization is such that only symmetrical defects can be realized to limit the number of parameters. Obviously the shape of the defect is better recovered using an appropriate function, but on the other hand the depth sizing is quite similar. The actual depth of the deepest point is the key parameter for the end user.
4. Concluding remarks

We have illustrated the sizing potential using phase dispersion only. This can be used as a 1D semi-quantitative screening method providing a wall thickness map along the axial direction of the pipe. Several simplifications have been made, the most important ones being the presence of only one defect with a symmetrical profile in the circumferential direction. Obviously the location cannot be determined, but is based on prior knowledge about the corrosion mechanism. Furthermore, as this method is intended for screening, the circumferential position of the defect is not that important.

The parameterization is an important aspect; using a simple function which describes the shape of the defect reasonably well, provides good sizing. Depth sizing errors are in the order of 10% to 15% of the nominal wall thickness. In case of small defects, there is a tendency to systematically undersize the depth of the defects. Preliminary results on a more general parameterization show encouraging results.

Future work involves the development of an EMAT sensor which can be used on pipes.

References

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