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Permanent corrosion monitoring using guided waves

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Abstract

Corrosion is one of the industries major issues. Currently inspections are conducted at regular intervals to ensure a sufficient integrity level of assets. Both economical and social requirements are pushing the industry to even higher levels of availability, reliability and safety of installations. The concept of predictive maintenance using permanent sensors that monitor the integrity of an installation is an interesting addition to the current method of periodic inspections. Coverage is obviously very important when it comes to permanent monitoring since the exact location of corrosion is difficult to predict. Sufficient coverage is required to achieve a certain level of reliability of a permanent monitoring system.
The application of guided wave tomography is a very promising tool for permanent corrosion monitoring. This method is capable of determining the wall thickness of large area's with only a limited number of ultrasonic transducers. The wall thickness is determined between two transducer arrays, where each transducer in the transmit array is excited separately and all transducers in the receive array record the signals.
These transducers excite specific guided wave modes that are highly dispersive, i.e., their wave speed depends on the wall thickness. Measuring the travel time requires dispersion correction and accurate time picking of the recorded signals. The measured travel times are then used in an inversion algorithm that inverts the measured travel times to a wall thickness map.
Experimental results on pipes and plates show the potential of the method.

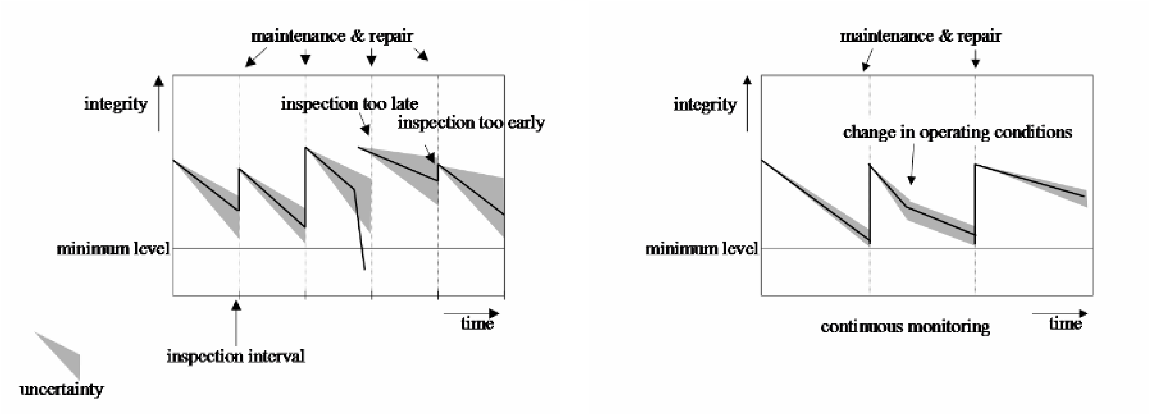
Keywords : corrosion monitoring, predictive maintenance, guided wave, tomography.

1. Introduction

Corrosion is a major cost factor in the industry. Inspection and repair programs are set-up to deal with corrosion issues. The efficiency of such a strategy depends strongly on the predictability of the corrosion process. Some corrosion processes behave very predictable and can be well controlled using corrosion inhibitors. Unfortunately there are also corrosion processes, which behave very unpredictable. Main reason for the unpredictable behavior is usually lack of accurate knowledge of the environmental conditions at which an object is exposed. A good example is corrosion under insulation. Such forms of corrosion are difficult to deal with efficiently in a maintenance strategy.

Inspection intervals are maximized to increases the availability of an installation. On the other hand installations in Europe and North America are aging and require more attention. The reliability and maintenance cost basically determines whether these installations can operate economically.

The use of permanent sensors that monitor the progress of corrosion quantitatively is an interesting new option to improve reliability, especially for unpredictable and rapidly progressing corrosion processes.
Obviously coverage is then an important issue, because spot measurements do not provide sufficient information. Ideally a permanent corrosion monitoring system should provide quantitative wall thickness information of the complete asset. Since such a system provides ‘real time’ information, the accuracy is less important then traditional pulse-echo wall thickness measurements and is basically determined by the growth rate of the corrosion. For example, if the accuracy of the permanent monitoring system is 0.5 mm and the growth rate of the corrosion equals 3 mm/year, this means a response time for maintenance of 2 months.
Figure 1 gives a conceptual sketch of the current and a possible future situation using permanent monitoring systems of asset maintenance. On the left hand side the current situation is sketched, periodic inspection intervals are based on a minimum required integrity level. Due to uncertainty and lack of knowledge about the actual conditions, inspection and maintenance intervals will sometimes turnout to be too long, resulting into failures and sometimes they are too short resulting in unnecessary inspections.
With permanent monitoring systems the uncertainty of the actual integrity level is significantly reduced. Moreover changes in conditions that affect the growth rate of corrosion are detected and maintenance intervals can be adjusted safely.



a) b)

Figure 1 Illustration of current inspection approach (a) and a future approach based on permanently installed integrity monitoring systems (b). Inspection intervals can be increased and uncertainty regarding the structural integrity is reduced.

As pointed out earlier, coverage is an important issue. A technology that provides a large coverage and quantitative wall thickness information is ultrasonic guided wave tomography.

2. Theory

Ultrasonic waves in solids can roughly be divided into two groups, the bulk waves and guided waves. The majority of ultrasonic inspections are carried out with bulk waves. In this case the wavelength of the waves is small compared to the dimensions of the object under inspection. Relatively localized information is obtained with this type of waves.
The second group are the so called guided waves. In this case the wavelength is typically in the order of the wall thickness or even larger. These guided waves may propagate over very long distances and hence may provide global information[2].
There exists a whole variety of guided wave modes in plates and pipes. By far the majority of these wave modes are dispersive. This means that their phase velocity depends on the frequency and wall thickness. This is an interesting property that can be used to monitor the wall thickness. This is the basic idea behind guided wave tomography[1,4].
In a plate there exists a family of symmetrical and asymmetrical wave modes. The zero order modes exist for all frequencies. The zero order asymmetrical mode is denoted by A0 and the zero order symmetrical mode is denoted by S0.
The propagation velocity of these guided waves is determined by the dimensionless number ‘ $k_t d$ ’, where k_t is the wavenumber for transversal (shear) waves and d equals half the wall thickness.
The higher order modes appear above a certain $k_t d$ value. The dispersion curves for the first few modes in a plate are shown in Figure 2.

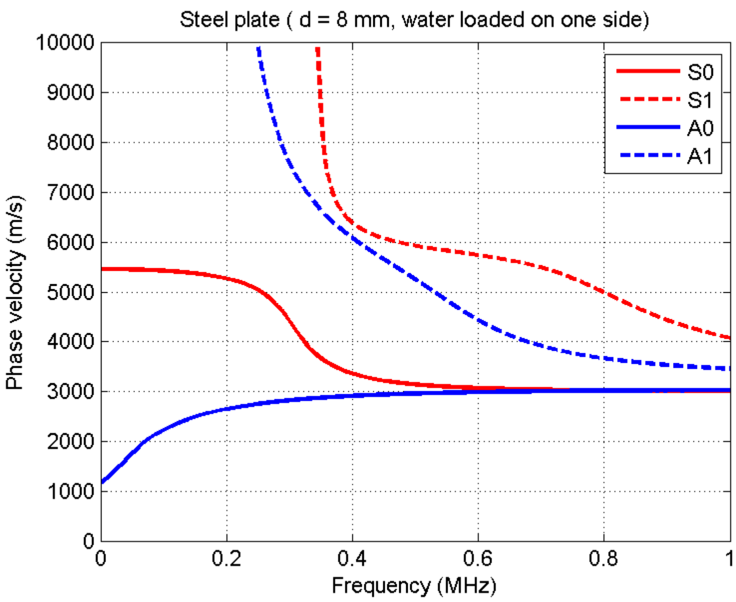


Figure 2 Dispersion curves for the first few orders of symmetric and asymmetric guided wave modes in a plate.

In principle both the A0 and S0 modes could be used for wall thickness monitoring. However due to the vibration motion of the A0 mode, mainly in the thickness direction, this wave mode couples efficiently with a liquid which may be present on one side of the plate or inside a pipe. This causes strong attenuation of this mode, see Figure 3.
The motion of the S0 at low frequencies is mainly in plane and therefore this mode does not couple with a liquid. Hence this mode has a low attenuation. At higher frequencies the S0 mode also gets particle motion in the thickness direction and it becomes more dispersive. This region is of particular interest for wall thickness monitoring of liquid loaded objects.
So far we discussed guided waves in plates, the same concept can be applied to pipes. The dispersive behavior of these waves is essentially the same as for plates. In fact, as long as the curvature of the pipe wall is large compared to the wavelength the same dispersion curves apply.

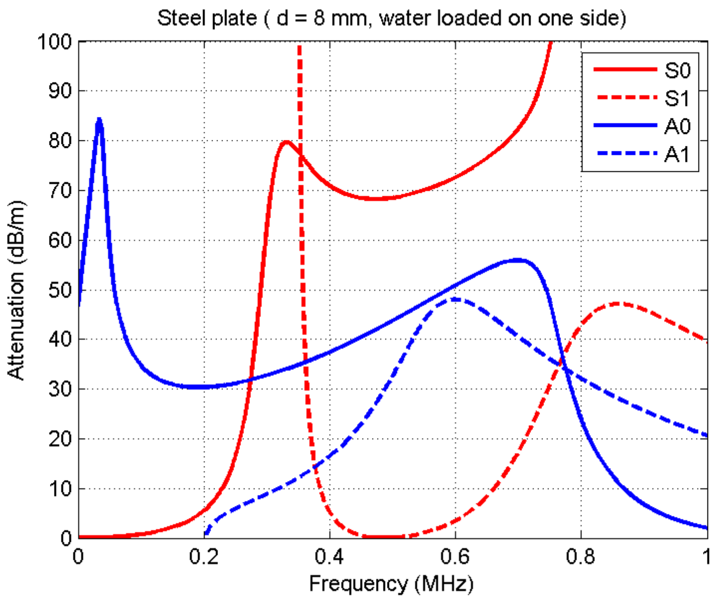


Figure 3 Attenuation curves for the first few orders of symmetric and asymmetric guided wave modes for one-sided liquid loaded plate.

To obtain quantitative wall thickness information, two arrays of ultrasonic transducers are applied. One array generates a specific guided wave mode and the other array records the wave field. Each element in the transmit array is excited separately. During propagation the guided wave gathers information about the wall thickness. In order to translate that information into wall thickness a tomographic inversion is required.
The tomographic inversion basically consists of two steps, a forward modeling step to correct for dispersion effects taking into account the presence of one or more defects and an inversion step that maps the observed travel times after inversion into a wall thickness profile. In order to do a perfect dispersion correction, the exact wall thickness profile is required. Obviously at the start of the tomographic inversion process the wall thickness is unknown.

We apply an iterative approach, starting with a dispersion correction for a defect free wall and with each iteration, the wall thickness profile is updated and a new dispersion correction is applied. This process rapidly converges as long as the dispersion effects are not too strong. This basically relates to selecting the appropriate frequency range in the dispersion curve for a specific case[1].
The dispersion correction requires a forward modeling step to calculate the phase rotation for each frequency component. There are several modeling codes, ranging from relatively simple ones like ray-tracing or eikonal equation solvers. In case of ray tracing, rays are traced through a velocity model, basically taking into account Snell's law. Defects may cause focusing effects, which result in caustics. This is particularly the case using the zero order anti-symmetric mode. The phase velocity decreases for this mode in case of a defect. This yields strong focusing effects, which can be observed in strong spatial amplitude variations of the detected guided waves. Similar effects may occur using the symmetrical mode, particularly near the edges of the defects.

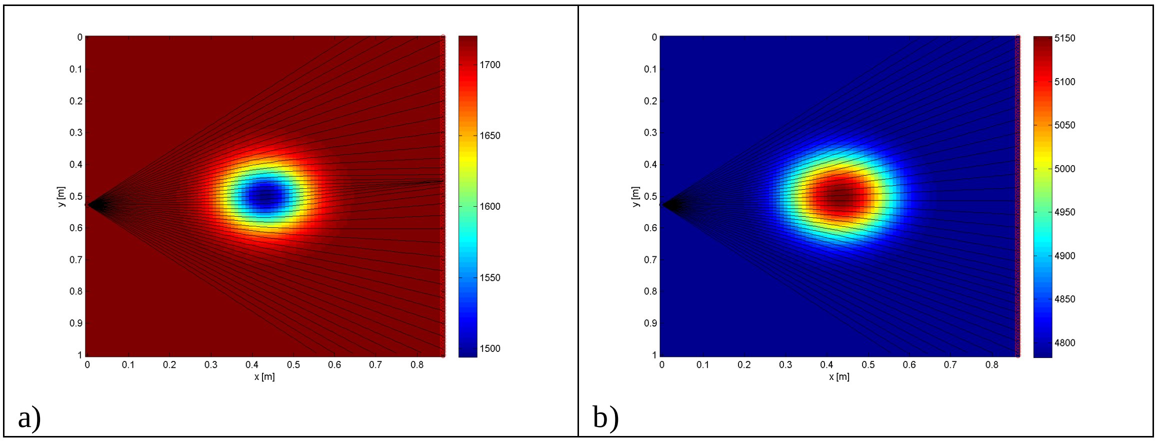


Figure 4 Ray tracing of A0 (a) and S0 (b) modes through a Gaussian defect. In case of the A0 mode, the phase velocity (color-coded) decreases which causes focusing effects. This complicates the interpretation of A0-mode arrivals.

More advanced methods use phase shift operators[2,3]. These methods are better in handling strong refraction effects and multi-valued arrivals in case of significant corrosion. A further discussion about this modeling approach is beyond the scope of the current paper.

3. Example

We will illustrate our approach on an artificial defect in an aluminum plate of 1 by 1.3 m. The defect has a smooth gaussian shape, with a maximum depth of 30% of the wall thickness. The width of the defect at half depth equals 15 cm. Figure 5 shows the measured wall thickness using a fine grid of pulse echo measurements. Two arrays consisting of 16 ultrasonic transducers are used to generate and detect ultrasonic guided waves. With this set-up, mainly the anti-symmetric zero order mode is excited.

A ± 5 Volt sweep signal is used for the excitation of the transducers. Low power excitation has several advantages; it is much simpler to comply with ATEX regulations and usage of battery power supply.
Transmission measurements were carried out between the two arrays of 16 transducers, which yields a total of 256 signals. After dispersion correction the travel time was measured and shown in Figure 6. In this case the A0 mode was used, a defect causes a longer travel time and this is clearly observed in the data.

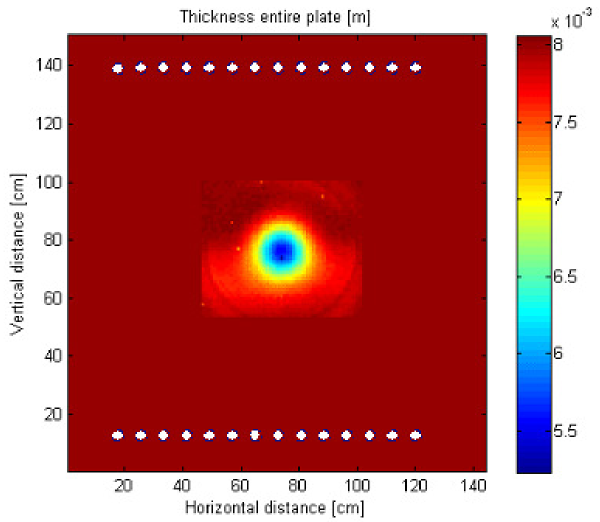


Figure 5 Pulse-echo wall thickness profile using pulse-echo measurements on a dense grid.

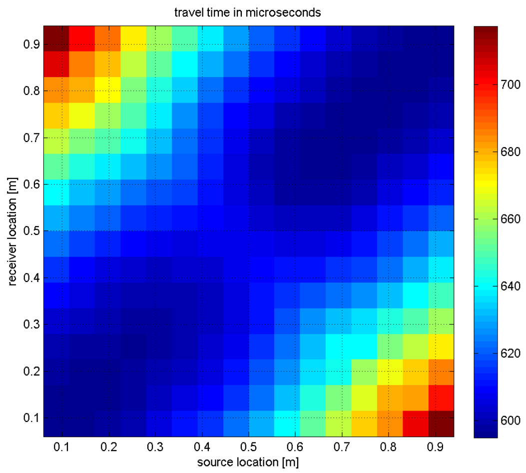


Figure 6 Travel time matrix obtain from the data

The measured travel times are used as input of an iterative tomographic inversion algorithm to produce a wall thickness map. The depth of the corrosion spot is correctly recovered in the inversion; there are some irrelevant differences in the shape of the defect. These differences are due to the selected parameterization in the inversion. We are

currently working on an adaptive parameterization in order to obtain more detailed information about the shape of the defect.
For our specific application, the permanent monitoring of corrosion, the accuracy requirements are not as demanding as for common pulse-echo measurements.
With this approach, it is possible to produce wall thickness maps at any desired moment in time. We aim to achieve an accuracy of ± 0.5 mm in depth. Given a rapidly progressing form of corrosion, with for example a corrosion rate of 3 mm/year, this should be sufficient.

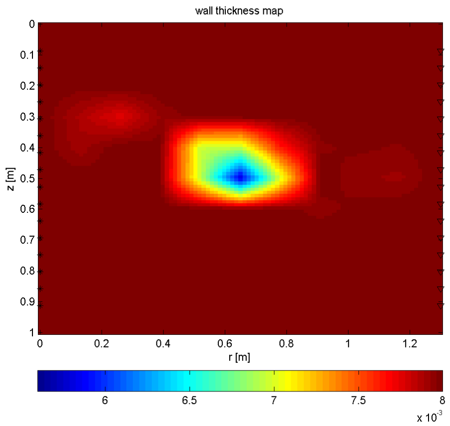


Figure 7 Tomographic inversion result, clearly showing the artificial corrosion spot.

4. Conclusion

Corrosion is major cost factor in the industry. Inspection and repair programs are set-up to deal with corrosion issues. The efficiency of such a strategy depends strongly on the predictability of the corrosion process. The use of permanent sensors that monitor the progress of corrosion quantitatively is an interesting new option in these cases. Coverage is an important issue, spot measurement do not provide sufficient information. Guided wave tomography provides a method of quantitative wall thickness measurements with a limited amount of ultrasonic transducers. We have demonstrated this approach on measured data on an aluminum plate with an artificial defect. The depth of the corrosion spot is correctly recovered using two arrays of only 16 transducers per array.

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