EXPERIMENTAL RESULTS OF GUIDED WAVE TRAVEL TIME TOMOGRAPHY

A. W. F. Volker, J. G. P. Bloom
TNO Science & Industry, Stieltjes weg 1, 2600 AD, Delft, The Netherlands

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. Guided wave travel time tomography is a promising method to monitor the wall thickness quantitatively over large areas.

Obviously the robustness and reliability of such a monitoring system is of paramount importance. Laboratory experiments have been carried out on a 10” pipe with a nominal wall thickness of 8 mm. Multiple, inline defects have been created with a realistic morphology. The depth of the defects was increased stepwise from 0.5 mm to 2 mm. Additionally, the influences of the presence of liquid inside the pipe and surface roughness have been evaluated as well. Experimental results show that this method is capable of providing quantitative wall thickness information over a distance of 4 meter, with an accuracy better than 1 mm. The method has no problems imaging multiple defects.

1. Introduction

Corrosion is the main cause of integral degradation in the pipelines and it comes in many forms. To guarantee a specific life span, the wall thickness of the pipeline is often designed with a safety margin and this excess material can guarantee the life span of the design if the rate of corrosion is known and sufficiently low. An important element here is the predictability of the rate of corrosion. However, there are many factors – such as for example insulation or a changed production process – that cause the assumed rate of corrosion to alter over time. This prompts the need to conduct inspections on a regular basis to collect information necessary to determine the maintenance strategy as well as the activity and investment plans. In order to control inspection and maintenance costs, the interval between two inspections is as large as possible, while seeking an optimum balance between reliability and inspection costs.

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. An essential aspect of the reliability of the permanent monitoring system is the coverage. To reduce the chance of unexpected failures, the sensors must monitor the complete pipe wall and not just the part where corrosion is most expected. Furthermore the costs associated with the installation of permanent monitoring systems can be quite large. Therefore the area covered in relation to the installation costs is a very important aspect of a monitoring system.

Ultrasonic guided waves can be very suitable for such monitoring systems, because these waves can propagate over very long distances. Furthermore, they follow the curvature of the structure which makes it easier to cover the complete object. This paper discusses a technology which makes use of the tomographic inversion of the travel time of guided waves to measure the wall thickness of pipelines over long distances and with full coverage.

2. Guided wave corrosion mapping

We describe a method to monitor the wall thickness of an arbitrary object using guided waves. It uses the fact that the phase velocity of certain ultrasonic guided wave modes depends on the thickness of the wave. 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, these include the low attenuation and the fact that this is the fastest mode, which makes it easier to distinguish this wave mode from other possible modes. Similar wave modes exist in a pipe.

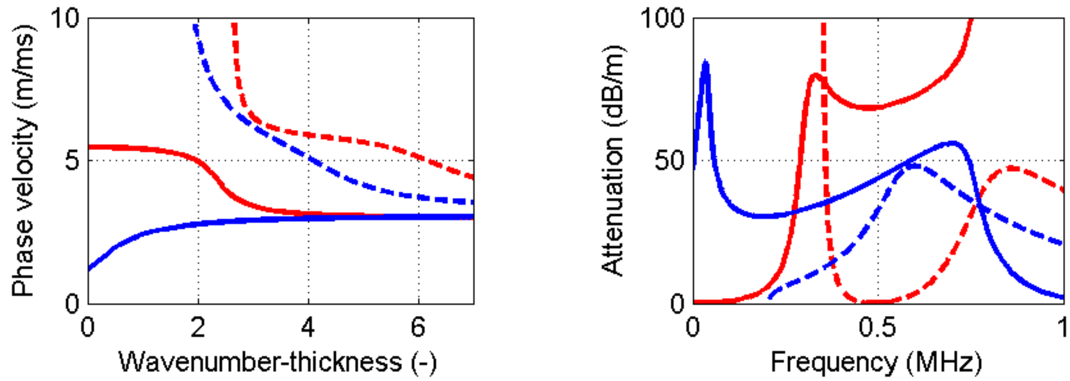

Figure 1 The left graph shows the dispersion curves for a steel plate. The shown modes are the fundamental and first order symmetric and asymmetric Lamb wave modes. The right graph shows the attenuation due to leakage of the same modes for a steel plate of 8 mm thick water loaded on one side.

So if a source and a receiver are placed at a known distance from each other, the time it takes a guided wave mode to travel from the source to the receiver is a direct measure of the integral thickness of the waveguide. However, the wave only contains information of the part of the waveguide it traversed and the travel time only measures the integral wall thickness. Therefore, the local properties of the thickness profile can not be retrieved from a single travel time measurement. To obtain this information, it is needed to measure the travel time along different paths over the object. Non-linear inversion of all the different travel times then yields the wall thickness map.

Different approaches to guided wave tomography were discussed in by other authors papers [1]-[3]. In most cases a back-projection approach is used, which essentially requires an enclosed area to avoid a lot of artifacts. Leonard and Hinders [4] describe a method for pipes, using a dense parameterization of the pipe surface to reconstruct the velocity profile

The method described in this paper could for example be applied to monitor the wall thickness in pipes, bends or plates but uses an adaptive parameterizations and hence requires much less transducers.. For a schematic depiction of the sensor setup on a pipe see Figure 2. One ring array of sources is placed on the pipe. At a certain distance L further along the pipe a ring array of receivers is placed. This way a large number of travel times can be measured using direct arrivals and higher order circumferential paths. The time window in which higher order modes can be used is limited by the arrival of other (slower) wave modes. Typically three to four orders of circumferential passes can be used. The number of orders that can be used determines the spatial resolution that can be achieved in the axial direction.

The larger the distance between the two arrays the larger the area covered and the more useful the method is in practice. The goal is to maximize this distance, while maintaining sufficient resolution for the detection of corrosion defects.

For tomographic inversion the resolution of the wall thickness map and sensitivity to defects not only depends on the sensitivity to wall thickness variations, but also on the ray coverage of the object by the guided waves. For a high resolution and uniform sensitivity as many paths as possible through the pipe wall should be used for the inversion. Therefore multiple sources arranged in a ring around the circumference are used. The sources are fired sequentially and the wave field is recorded at all receivers. The travel time of the direct path from source to receiver of the S0-mode is determined for each source-receiver combination. To further increase the resolution also the travel time of paths of the S0-mode that travel around the circumference more than one time are used for the inversion. This is schematically drawn in Figure 2. Practically the number of usable paths will be limited by the arrival of other modes, reflections and attenuation.

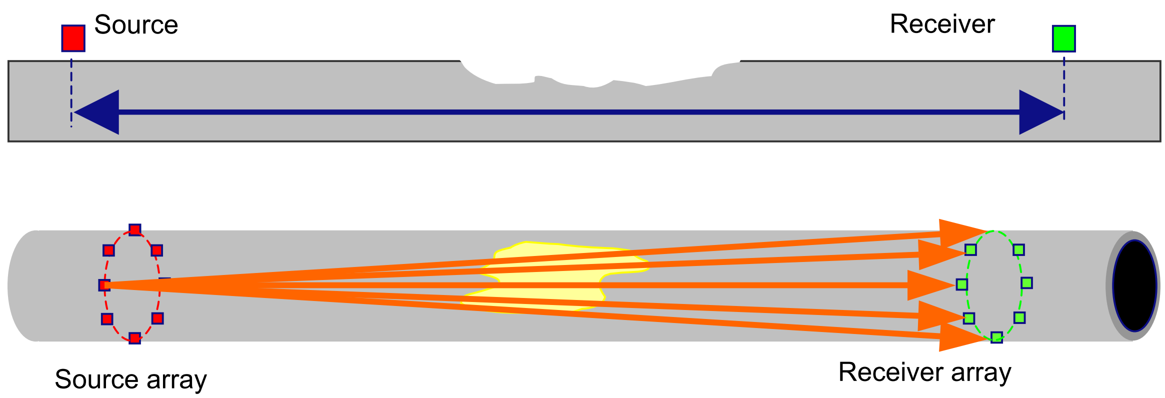

Figure 2 The top image shows a schematic depiction of the setup used to measure the wall-thickness loss of the area between the single source and receiver. The bottom image shows the schematic depiction of the setup used the measure the absolute wall thickness of the pipe using two linear arrays around the circumference.

3. Tomographic inversion

The non-linear inversion scheme is shown in Figure 3. We start 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 arrival 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.

Then a cost function is defined based on the difference between the modeled and measured travel time and a sparseness constraint [7] to improve the resolution and avoid oscillations in the solution. This cost function is minimized in an iterative way by updating the initial guessed wall thickness, refining the mesh and redoing the dispersion correction.

Figure **4** illustrates the mesh refinement; only at the nodes of the mesh a parameter is defined that describes the local wall thickness. During the interactive inversion nodes can be added or removed from the grid automatically, such that only a fine mesh is obtained where needed. The final number of used support point is 100, whereas 6240 support points would have been needed on a uniform grid with the same resolution.

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 effect. This means that a straight ray-path approach cannot be used. This is illustrated very clearly in Figure **5** for the A0-mode in a plate. Due to the presence of a defect a local low velocity area exists. The low velocity zone will focus the rays, clearly illustrating that a straight ray approach is not valid. This behavior is characteristic for the A0-mode. A wall thickness loss increases the phase velocity for S0-mode and no focusing effects occur.

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 ten iterations.

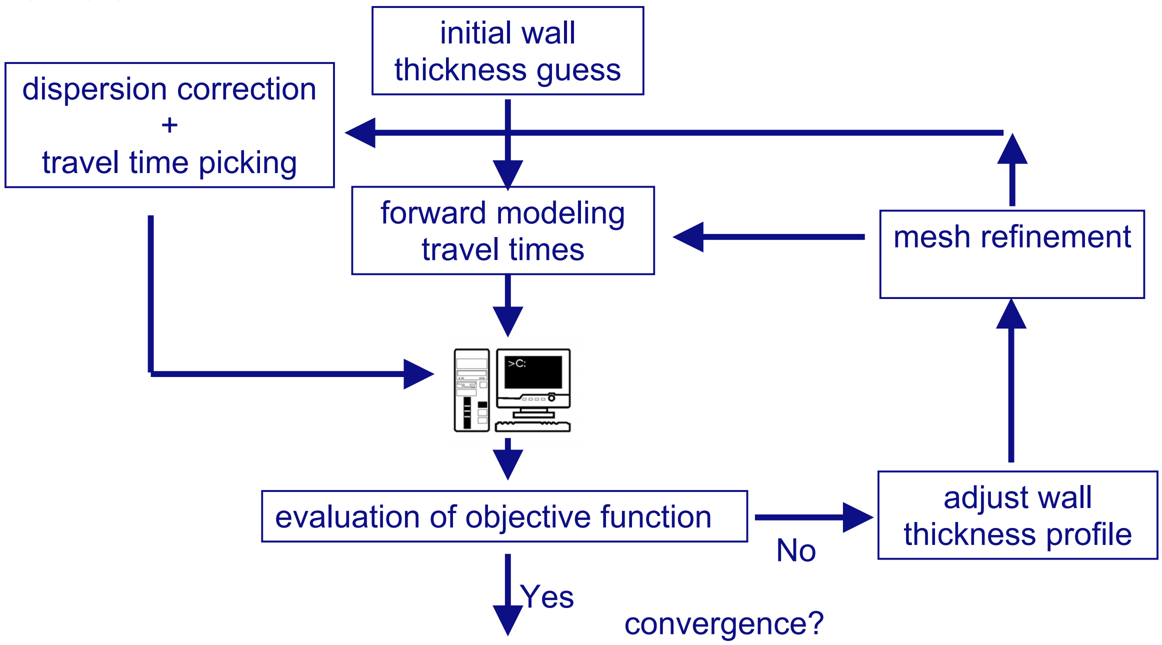

Figure 3 Inversion scheme of the travel times to obtain the wall thickness image.

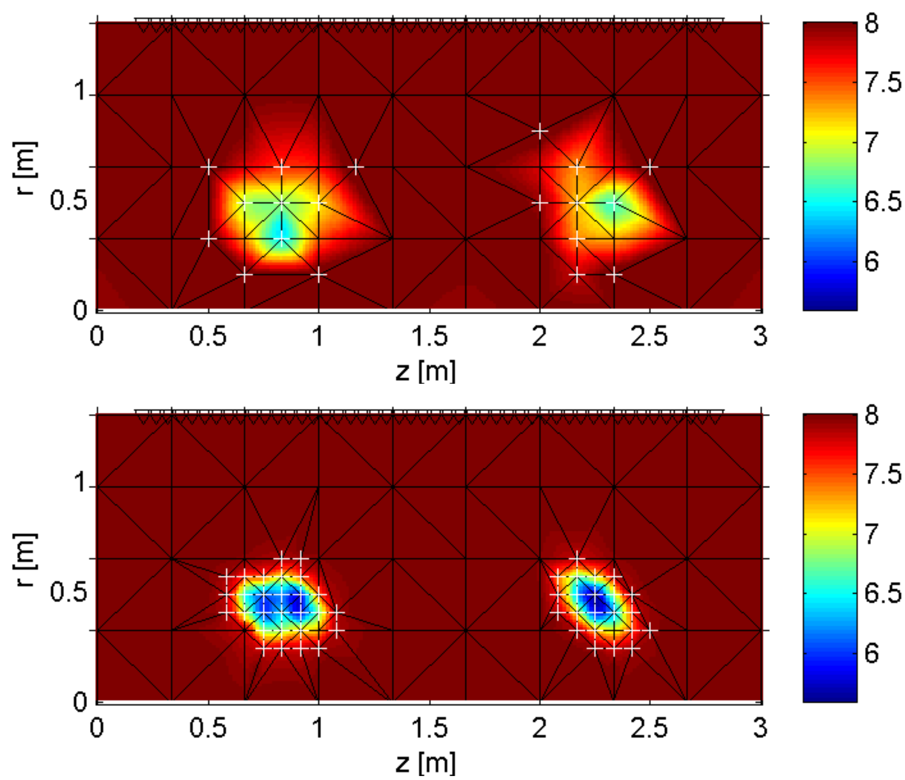

Figure 4 The top image shows the progress of the inversion process after two more iterations. Newly added support points are again denoted by white crosses. The bottom image shows the final result of 10 iterations. Many support points are used to describe the defects with high resolution and a limited number of support points is used to describe the rest of the surface.

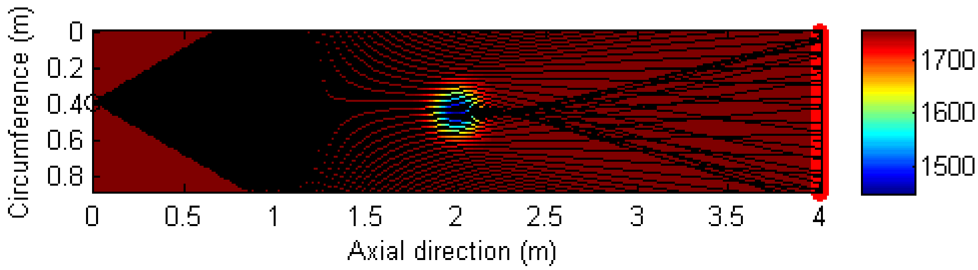

Figure 5 The image shows the phase velocity profile of a pipe wall with a large Gaussian shape defect in the middle. The black lines indicate the ray-traced paths from the source on the left. The formation of caustics can be clearly seen

4. Experimental results

The technology outlined in the previous paragraphs is tested in the laboratory. As an example here 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 6 m. At 1 m from the end of pipe a ring of 32 sources is glued to the pipe wall. The sources are small piezoelectric transducers. At 4 m from this ring (and 1 m from the other end) a second ring consisting of 32 receivers is glued to the pipe. The second ring is aligned to the first ring and contains the same number of transducers

This setup is shown in Figure 6.

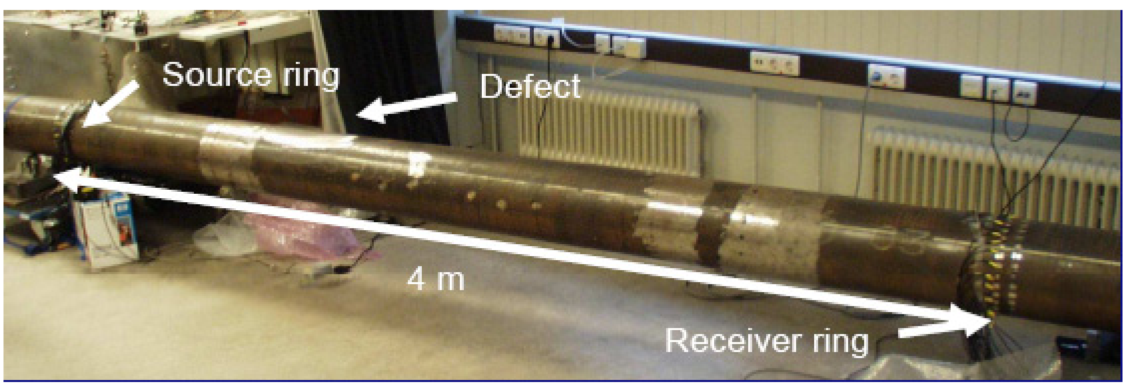

Figure 6 Picture of laboratory set-up, two rings consisting of 32 piezo-electric transducers are glued to the pipe surface at a distance of 4 m.

The transducers are excited by a sweep with a amplitude of 5 V in a frequency range from 50 to 350 kHz. In the applied frequency range the phase velocity of the S0-mode depends on thickness and the travel time of this mode will be used for the processing. The S0-mode as well as the A0-mode are excited, but because the A0-mode propagates significantly slower than the S0-mode separating these different modes in time is straightforward. The wave field caused by exciting each source is recorded by all receivers; data acquisition of the full dataset takes a few minutes since all source-receiver combinations are recorded separately using multiplexers. This full dataset is used for further processing, but a specific frequency band filter is used to limit the amount of dispersion. The data is sorted to common source gathers. One common source gather consist of 32 signals. This gather is copied seven time, such that a (super) source gather is created consisting of 224 signals. A dispersion correction is done for one specific arrival per trace as indicated in Figure 7.

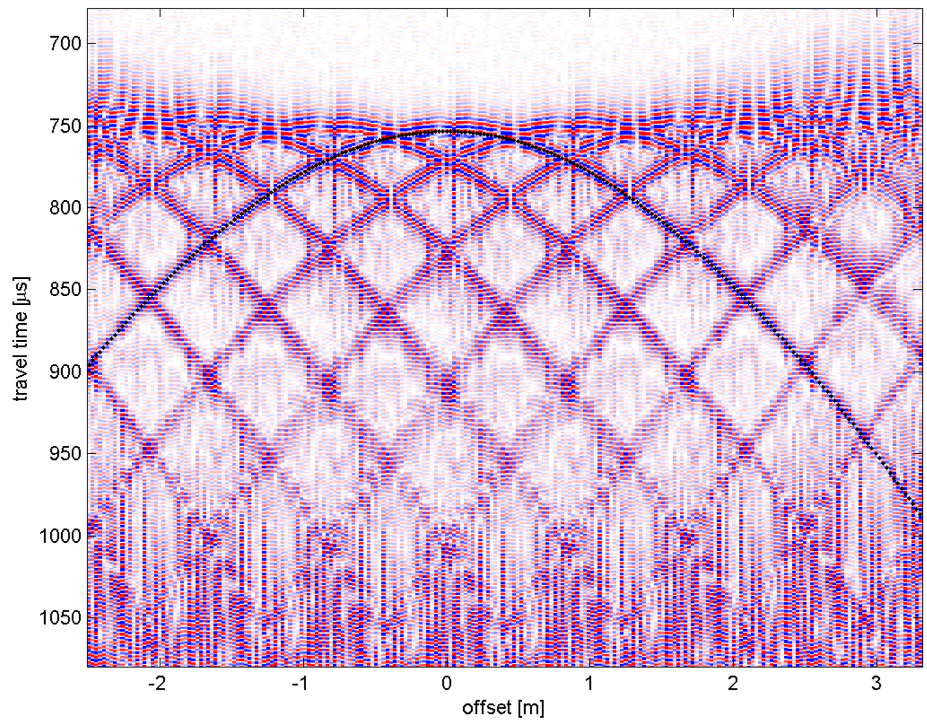

Figure 7 Dispersion corrected (super) source gather, this received signals are copied several times to perform a dispersion correction for higher order circumferential arrivals. The dispersion correction is done in the frequency domain for the indicated arrival only**.**

After the dispersion correction, a move-out correction is done to align the signals at zero-travel time. Due to the presence of defects a residual move-out is present. These travel time difference are picked and used in a tomographic inversion scheme as outline in Figure 3.To test the performance of the tomographic inversion several experiments have been performed: First a single defect with a full-width half-maximum (FWHM) size of 25 cm in the axial direction and FWHM of 13 cm in the circumferential direction. The depth of the defect is increased in a number of steps up to 2 mm. The detection threshold of the defect was 0.5 mm.

Figure 8 shows and example with a defect depth of 1 mm, as reference pulse-echo measurements are preformed. The results show that the defect is very well recovered; the shape and depth match quite well. The length of the defect is slightly overestimated leading to a bit too shallow defect. This is due to resolution limitations; the resolution in the circumferential direction is higher than in the axial direction. This depends on the ray-angles that delineate the extent of the defect.

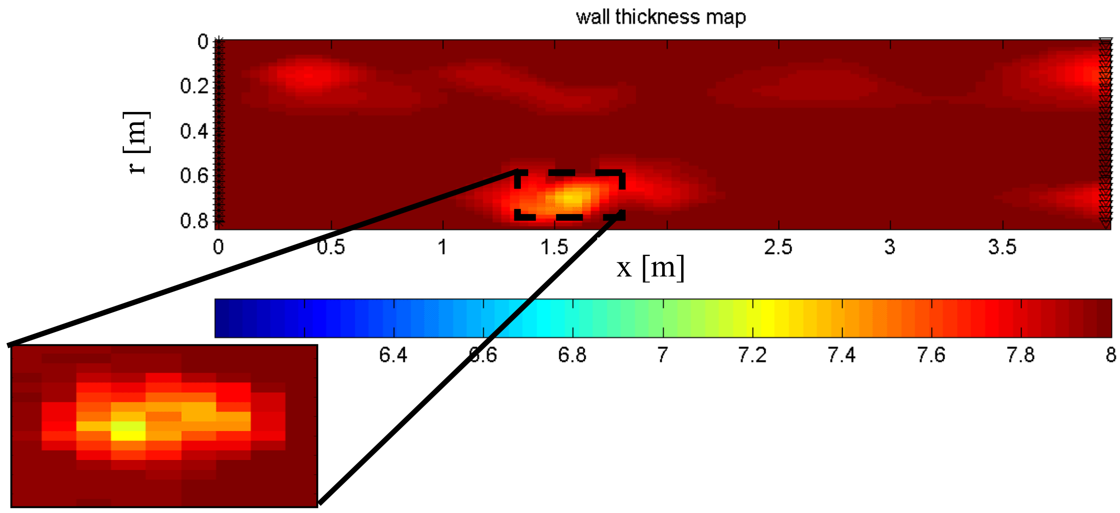

Figure 8 Tomographic inversion result on a 1 mm deep defect, a reference pulse echo measurements are preformed showing an accurate match with the inversion result**.**

A typical configuration for corrosion under insulation is the presence of multiple defects at the same circumferential location. With this configuration, we can evaluate whether the tomography is capable of recovering two defects located behind each other in the axial direction. The shape of the defects is different; one is more rounded, while the second one is more elongated. Both have the same depth of nearly 2 mm. The tomographic inversion result is shown in Figure 9. Both defects are recovered at the correct location, again slightly overestimating the defect length at the expense of the defect depth. Overall the sizing accuracy is typically better than 0.7 mm. Similar results where obtained with a liquid filled pipe.

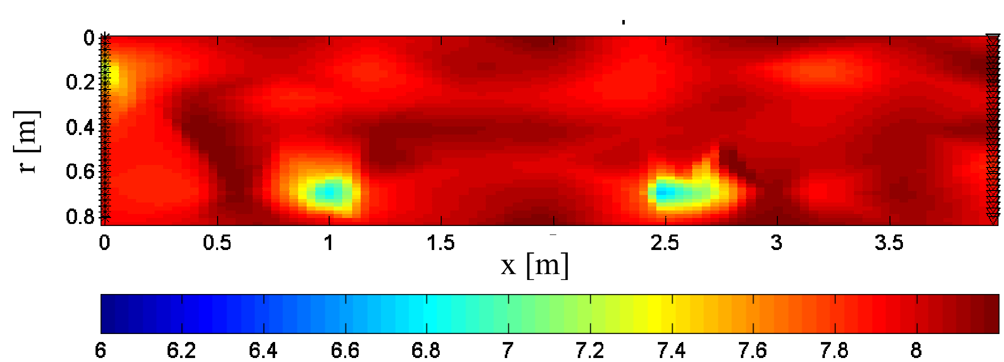

Figure 9 Tomographic inversion result of two defects behind each other in the circumferential direction

5. Conclusions and future plans

This paper demonstrated a new technique to determine the wall thickness of large structures such as plates, pipes and bends using the inversion of the travel times of dispersive guided waves. It is a promising technique for the monitoring of large area's using permanently attached sensors. The full area of the pipe can be covered, with no zones of reduced sensitivity by using several orders of waves that traveled around the circumference of the pipe. Key factors that determine the performance of the tomography are the objective function and the adaptive meshing.

By choosing the optimal wave mode this method also works on liquid filled pipes. Experimental results show that the tomographic inversion is capable in resolving multiple defects at the same circumferential location.

Future work will focus on improving the resolution, extending the distance between the transducer rings and handling more complex geometries like bends. Additionally field test will be carried out under operational conditions.

References

1. J.L. Rose, *J. Press. Ves. Techn. – Trans. ASME* **124**, 273-282 (2002)
2. M.J.S. Lowe, D.N. Alleyne, P. Cawley, *Ultrasonics* **36**, 147-154 (1998)
3. G. Instanes, M. Toppe, B. Lakshminarayan, P.B. Nagy, *Advanced Ultrasonic Methods for Material and Structure Inspection*, 115-157 (2006)
4. K. R. Leonard and M. K. Hinders, "Guided wave helical ultrasonic tomography of pipes", J. Acoust. Soc. Am. 114 (2), August 2003
5. J. Li and J.L. Rose, *Ultrasonics* **44**, 35-45 (2006)
6. P. Belanger, P. Cawley, Review of Progress in Quantitative NDE 27, 1290-1297 (2008)
7. P.M. Zwartjes, "*Fourier reconstruction with sparse inversion"*, Ph.D Thesis, Delft University of Technology, 2005.