Ultrasonic Monitoring of Corrosion with Permanently Installed Sensors (PIMS)

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Abstract Ultrasonic wall thickness monitoring using permanently installed sensors has become a tool to monitor pipe wall thicknesses online and during plant operation. This talk aims to give a short introduction to the benefits and drivers of the technology as well as the technical challenges that had to be overcome during the development of the waveguide sensor that is Permasense Ltd.'s flagship product. The presentation will present the underlying measurement principle and then give some more detail on key parameters that influence the measurement, such as temperature and surface morphology. It will also be shown how these effects can be managed. Some example data of application used in industry will be presented and the paper will end with a look into the near future and describe technology that will become available soon.

Keywords Ultrasonics · Corrosion · Structural health monitoring SHM

1 Introduction

Ultrasonic wall thickness measurements or ultrasonic thickness gauging is one of the most commonly employed tools to check that corrosion or erosion has not degraded metal work in industrial plant. The methods are well documented and there are industrial standards that describe how to carry out the measurements [1, 2]. Traditionally, all measurements were carried out manually. This means that an operator goes out to the location of the plant where the measurements are required; he gains access to the component (removing insulation, building scaffolding, or

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rope access can be required) and then carries out the actual measurement. Because of the restricted access to some components, this procedure is not carried out frequently. Furthermore, because of coupling and positioning errors on repeat manual measurements, there is a rather large uncertainty on these measurements. Therefore, over the last decade, permanently installable, wireless thickness gauging sensors have been developed. Once installed, these sensors remain fixed in the same location and send back data at regular pre-configurable intervals. Several systems are on the market. The information relayed here will be kept as general as possible; however, the author has been deeply involved in the creation of the Permasense Ltd. wireless ultrasonic monitoring system, and therefore some information that is displayed might be biased toward this particular system [3].

It is of utmost importance that permanently installed sensors are as rugged as possible and therefore their coupling and attachment mechanisms are key. Furthermore, it needs to be ensured that the sensor can withstand the operating conditions (e.g., temperature) at the location where the transducer is to be installed. In the Permasense system, both these problems were solved by means of the use of a robust waveguide that isolates the fragile transducers and electronics from the measurement error. The waveguide is thin and slender so that it can isolate large temperature differences over short distances. The transducer is attached to the sample under test by means of two welded studs which apply load onto the contact patches and enable dry coupling of the waveguide to the pipe surface. This has proven to be much more reliable than bonding of the transducer.

This paper is organized as follows: Sect. 2 describes the key features of the fully wireless ultrasonic corrosion monitoring system as it is deployed in an industrial plant and shows some example long-term wall thickness trends. Section 3 is concerned with the effects of temperature on the monitored wall thickness and Sect. 4 is concerned with the effects of changes in surface morphology. Finally, conclusions are drawn from the presented information.

2 A Complete Industrial Ultrasonic Monitoring System

2.1 Overview of Components

Figure 1 shows an overview of the Permasense Ltd. wireless ultrasonic corrosion monitoring system. Sensors are installed at monitoring locations in the industrial plant, and they communicate wirelessly with each other (forming a mesh network) and relay data to a gateway that is connected to the general business IT network of the plant. Via the network the gateway communicates with a database server on which all the information is stored and users can visualize the data in the database from any office PC that has network access.

Fig. 1 Overview and pictures of the Permasense Ltd. wireless ultrasonic corrosion monitoring system

2.2 *A Typical Thickness Measurement*

Figure 2 shows the geometry of the waveguide sensor on a metal sample of thickness T. The measurement is a pitch-catch measurement from the transmitting transducer Tx to the receiving transducer Rx. The ultrasonic signal travels via different wave paths resulting in the arrival of distinct wave packets as can be seen in the ultrasonic signal of Fig. 2b. The arrival time difference between echoes is directly linked to the component thickness via the ultrasonic shear velocity in the material that is being tested. To estimate the component thickness, the arrival time difference is established and turned into a distance by multiplication with the wave velocity. The final result is a thickness value.

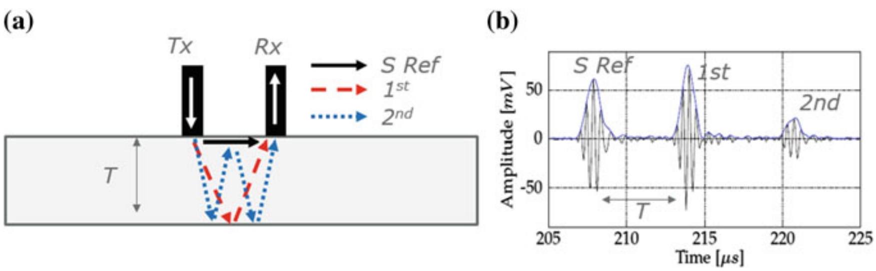

Fig. 2 **a** Illustration of ultrasonic signal path and **b** typical ultrasonic signal that is received by a sensor

2.3 Example Wall Thickness Measurement Trends

Figure 3 shows thicknesses that were monitored over the period of about 3.5 years in a plant component where the wall thickness remained constant. The plot demonstrates the very good repeatability and measurement frequency that can be obtained with a permanently installed monitoring system.

Figure 4 shows the wall thickness trend measured on another component in a plant. Here, it is clearly visible that wall loss is taking place. The wall loss rate is roughly 1 mm/year; however, there is also a period where no wall loss/corrosion is taking place. The measurement frequency and precision of the automated measurements make it possible to gather information on wall thickness changes that would not be obtained with conventional manual ultrasonic measurements. Conventional measurements would have much higher error bars (i.e., measurement uncertainty) and would record data much less frequently. This is indicated by the box plot on the right of Fig. 4 which illustrates ± 1 standard deviation of the measurement uncertainty (indicated by the extent of the box; ± 2 standard deviations for the whiskers) that has been quoted for manual UT measurements [4]. The additional information can be used to take decisions about corrosion mitigation strategies, the effect of operating conditions on the plant, or if component retirement should be considered in the near future.

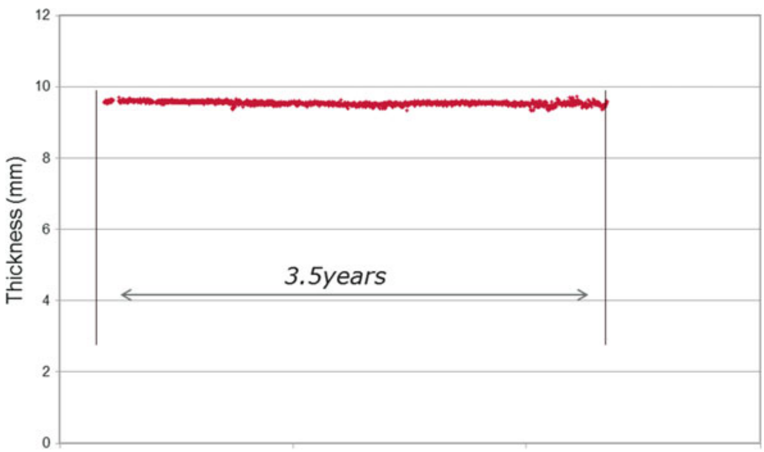

Fig. 3 Constant wall thickness monitored over the period of $\sim$3.5 years

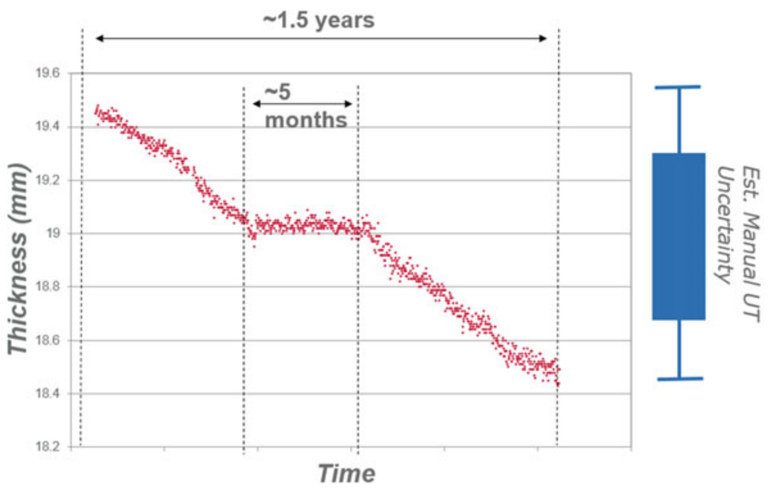

Fig. 4 Wall thickness trend showing wall loss due to corrosion and intermittent period of no corrosion, also indicated on the right is the uncertainty that is expected to result from manual ultrasonic measurements

3 Effects of Temperature on the Ultrasonically Monitored Wall Thickness

The ultrasonic wave velocity in steels is a function of temperature. This can introduce changes into wall thickness measurements, if these measurements are not made at the same temperature. Figure 5 shows the velocity temperature behavior of

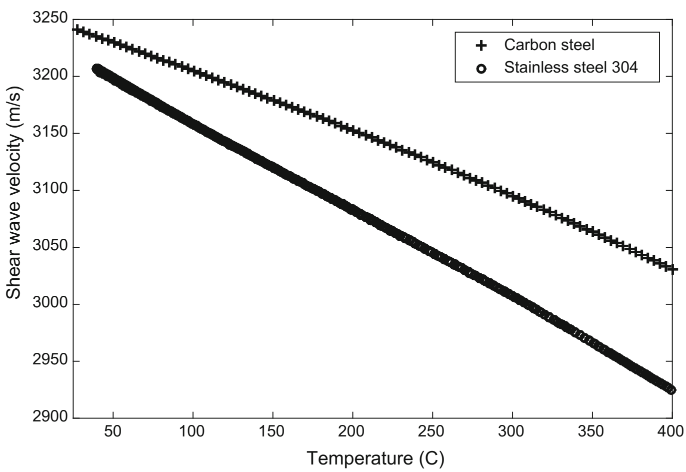

Fig. 5 Shear wave velocity as a function of temperature for carbon steel and stainless steel 304

a 10-mm-thick carbon steel plate and that of a 10-mm-thick stainless steel 304 plate that was measured in the laboratory. While overall the velocities are within 1% and both steels behave similarly, there are subtle differences in slope which can cause errors in the temperature compensation if large temperature swings are encountered or if a very good measurement precision is required. Based on the carbon steel measurements the ultrasonic velocity reduced as 0.56 m/s per °C or 0.017% per °C. This would cause a thickness error of ~0.17% or 17 μm in 10 mm wall thickness for a 10 °C temperature change. For the stainless steel, the results are slightly different and the velocity reduced as 0.78 m/s per °C or 0.024% per °C. Here, a thickness error of 24 μm in 10 mm wall thickness for a 10 °C temperature change would result. If the wrong calibration curve for carbon or stainless steel were used, an error of ~7 μm in 10 mm wall thickness for a 10 °C temperature change could result. Therefore, for very precise measurements, both temperature compensation and choice of the correct calibration data becomes important.

Gajdacsi [5] also analyzed the performance of temperature compensation of ultrasonic signals with a thermocouple that is attached to the outside of a fluid carrying pipe wall if the pipe wall is heated by the internal fluid. He showed that under steady temperature conditions there is little error in the temperature compensation when data from the external thermocouple is used. Under these conditions, sub-μm changes in wall thickness can be tracked [6]. However, if there is unsteady heating or cooling of the pipewall, then larger errors can result due to the nonuniform temperature distribution within the pipe wall. Depending on the rate of change of temperature, errors in the order of μm could result. It can be concluded that very advanced temperature compensation methods would be required to reliably track thickness changes below the μm mark using ultrasonic techniques.

4 Effects of Corrosion-Induced Surface Morphology Changes

In this section, we are interested in the effect that uneven surface morphology changes have on ultrasonically monitored thicknesses. Corrosion is a complicated phenomenon and is a large field of study. It is a degradation mechanism that can result in thickness loss of many forms. The loss can be spatially uniform as in etching or spatially nonuniform as in pitting corrosion and any combination of the two depending on the material and environmental conditions. It is therefore important to note that every component will have spatial variation of its thickness due to the nature of the corrosion process. Furthermore, it is very simplistic to condense the resulting surface condition into a single thickness value that results from an ultrasonic thickness gauging measurement. It is the end user of the information who needs to decide what metric is important to him, does he/she require the mean, max, or minimum thickness?

In corrosion engineering, it is common to use the weight loss of coupons or electrochemical potential or current measurements to infer a corrosion rate. When doing these measurements, one inherently averages over the area of the component, and this effectively results in a mean wall thickness loss evaluation. In the field, it is therefore accepted that some form of mean or average is reported when quoting a corrosion rate. For the purpose of this work, it was therefore decided to compare ultrasonic wall loss trend measurements on rough surfaces to the mean wall thickness change.

Gajdacsi et al. [5, 7] investigated the effect of surfaces morphology changes on the error in ultrasonically evaluated corrosion rate compared to the actual underlying corrosion rate by means of simulation. They simulated the evolution of many hundreds of random rough surfaces with the same statistical properties, simulated ultrasonic signals reflected from these surfaces, and used different signal processing algorithms to estimate the wall loss trend/corrosion rate from the ultrasonic data. They concluded that standard signal processing algorithms resulted in rather large corrosion rate error estimates and developed a new signal processing algorithm that they termed adaptive cross-correlation (AXC). This new algorithm performed much better and was able to monitor corrosion rates (90% of simulated population) to within −10 to +25% of the actual trend of the mean wall loss for spatially random and evolving thickness loss (Gaussian rough surfaces of RMS 100–300 µm and correlation length 1 mm). This means that if the actual underlying mean wall loss of the rough surface was 1 mm/year, in 90% of cases, the algorithm would report a rate in between 0.75 and 1.1 mm/year. These figures were quoted for the worst-case surface conditions and the algorithm did perform better on flat surface morphologies and evolutions. Figure 6 summarizes the trend error results for the different algorithms (first arrival [FA], peak-to-peak [P2P], cross-correlation [XC] and

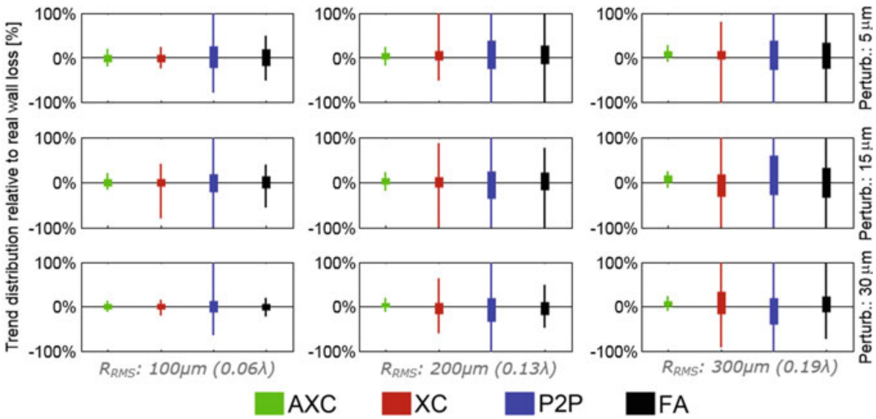

Fig. 6 Trend error distributions as computed by Gajdacsi [5, 7] on simulated ultrasonic monitoring data from rough evolving surfaces. The results show the performance of different signal processing algorithms

adaptive cross-correlation [AXC]) and surface morphology evolutions. The interested reader is referred to [7] for more detail.

5 Conclusions

This paper summarized current knowledge of the performance of a state-of-the-art wireless ultrasonic corrosion monitoring system. These new systems make it possible to collect ultrasonic wall thickness data with unprecedented frequency and precision. It was discussed that temperature compensation and accurate material data is required to make very precise wall thickness measurements. However, it was also discussed that temperature compensation with independent thermocouple measurement data to sub-μm precision will be very difficult in the field because of the existence of temperature gradients within pipe walls during heating and cooling processes. The topic of corrosion-induced surface morphology changes on ultrasonically monitored data was also introduced. The work by Gajdacsi et al. on advanced signal processing algorithms (AXC) to mitigate the uncertainties that are introduced by the changes in surface morphology was recalled. Gajdacsi et al. concluded that corrosion rates on spatially uniform corroding surfaces could be track to within −10 to +25%.

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