OCTOPUS-A MID RANGE ULTRASONIC CORROSION-EROSION MONITOR

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ABSTRACT

Octopus is a corrosion-erosion monitor (CEM) that uses a main transducer and up to eight secondary transducers, up to one metre away, to monitor an area of structure. By transmitting a carefully constructed signal from every transducer to every other transducer, and analysing the received waveforms, it is possible to monitor the average thickness in each transmission path. This provides quantitative permanent monitoring of an extended area, and so is suitable for many remote surveillance situations. This paper describes the operation and use of the system.

INTRODUCTION

Corrosion and erosion detection and monitoring is essential to the integrity of process equipment and structures in a wide range of industries. The oil and gas industry suffers significant losses every year as a result of corrosion and erosion of structures, especially the consequence of failure in pressure systems, with pipe-work being a major contributor. The general areas of common corrosion and erosion are known, from experience and from use of RBI analysis. Scheduled NDT accounts for major manpower resources spent making spot thickness measurements, often in areas that are difficult, and so costly, to access. In addition the periodicity of the spot measurements is usually determined by the “worst-case plus safety factor”, as a result many areas are over-inspected, however, should the corrosion rate increase for some reason then a risk to integrity may rapidly result. Corrosion or erosion reduces the thickness of the metal, Octopus CEM provides permanent monitoring of corrosion rates by measuring the average remaining thickness, and so is able to flag the need for a visit by inspection personnel before corrosion or erosion becomes a major threat to integrity. Since the transducers are fixed, the measurement is highly repeatable. Each measurement takes a few minutes to acquire and analyse, a fully automated process, so in terms of corrosion rate it can provide real-time monitoring. The method employs lamb-wave transmission to measure average thickness on each path between transducers, and in addition can make spot measurements through thickness at the actual transducer locations.

HOW IT WORKS

The use of lamb or guided waves for defect detection in plate type structures has been investigated extensively; both in research and industry, guided wave pipe screening systems are in widespread use worldwide. These systems send out a wave packet over long distances and measure reflections resulting from significant changes in total pipe cross-sectional area, they do not measure wall thickness, and are not particularly quantitative. Octopus CEM uses three separate measurements to get the best information possible from its deployment, two based on a pitch-catch system, and one on spot thickness ultrasonic measurement.

The most straightforward measurement is the spot thickness measurement, each sensor makes a spot thickness measurement at its location by using the through-thickness longitudinal resonance, and a robust mathematical algorithm to estimate the periodicity of these resonances. This provides the first order initial estimate for the pipe thickness and is also be used as an input to the two following steps.

The second step of the measurement involves using the ‘Low Group Velocity’ (LGV) measurements between each pair of sensors, and analyzing the family of longitudinal and shear waves that travel at these lower regime group velocities. These can be quickly analyzed to get an estimate of general wall thickness condition in that path. These LGV measurements are very sensitive to variations in wall thickness along their path of propagation. This can be exploited to flag paths where such a variation is detected. This technique is very accurate in monitoring more or less uniform loss of wall thickness over fairly large distances, for example erosion, but breaks down when the resonances are lost as a result of significant thickness variations between the probes. This method can therefore be used only over a limited range of wall thicknesses (wall thickness variations of less than 10% between probes).

These variations have to occupy a minimum width in the circumferential direction to be detected. In laboratory tests and theoretical analyses, the LGV based assessment has been seen to break down when there are local thickness variations of the order of 10-15% of absolute wall thickness, and when these defects occupy a reasonable percentage of the line-of-sight between the transducers. The LGV method thus can provide an overall assessment of the 'well being' of a pipe section, and is an absolute measurement. As mentioned before, a drawback of this technique is that a path will be flagged irrespective of the phenomenon that causes the change in wall thickness. For example, an inherent variation in pipe wall thickness of the order of 10% will also cause that path to be flagged. This happens because the system cannot distinguish between changes in wall thickness caused by erosion or corrosion and those caused by natural imperfections of the same magnitude. Thus, there are conceivable situations where the LGV method may not be useful, when inherent variations already exceed system sensitivity. In such cases, where the system cannot calculate the wall thickness based on these LGV modes, it is just the third, and most robust, thickness assessment technique that provides the wall thickness estimate.

The third, and most robust, step of the thickness assessment procedure involves a comprehensive analysis of the phase and group velocity dispersion characteristics of appropriate modes of the dispersion curves. The choice of modes for the analysis constitutes an important part of the design, as not all modes are equally sensitive to variations in wall thickness. Also, complications arising owing to mode overlapping and distortion have to be tackled and overcome. Long term monitoring has to necessarily face the fact that there might exist local thickness variations that are a significant percentage of the average wall thickness, and most lamb wave modes do not display the robustness required to smoothly integrate these changes into a quantitative (rather than qualitative) thickness assessment. The third step of the CEM system algorithm incorporates the use of modes (Constant Group Velocity modes, or CGV modes) that provide maximum sensitivity to changes in wall thickness within the constraints imposed by the necessary robustness which the technique needs. In other words, the presence of highly localized damage and defects will be quantitatively incorporated into a robust 'average thickness' measurement, with the use of an effective spectral and temporal dispersive analysis of the generated and received waveform. The selection of the mode(s) for this analysis was crucial for the development of the system, taking into account ease of mode isolation, sensitivity of the mode to thickness changes, and unambiguous mode identification for a large range of thickness values. Several laboratory tests conducted on this dispersion based method indicate a sensitivity of better than 1% to changes in the value of average wall thickness, in the presence of an order of magnitude larger local thickness changes. Clearly, spurious effects, such as losses due to fluid loading, apparent reduction in sensitivity due to surface roughness, the presence of epoxy coatings, and temperature swings are all important factors that affect the system, but these have all been fully investigated and accounted for. For erosion and corrosion monitoring purposes, the measuring time is not crucial, in the sense that the phenomenon being monitored (erosion/corrosion) occurs over extended periods of time, so there is no constraint of finishing a measurement in just a few seconds. Therefore, extensive time averaging has been applied to recover weak signals from the surrounding electrical, and possibly mechanical and acoustical, noise. The robustness of the dispersion based method developed turns out to be crucial in reducing the otherwise critical effects of these phenomena, and the net error is thereby considerably reduced. This CGV measurement is a relative measurement, meaning that the system needs an initial thickness value (measured during/prior to system installation), which it uses as a baseline reading, and calculates changes in average thickness from this initial value.

The effect of fluid loading on the LGV modes is very strong, resulting in drops in signal amplitude. We also found that adhesive coating on the outside of the pipe exerts but a negligible effect on the propagation of the mode selected for quantitative thickness assessment. Even gross variations in coating thickness, including complete removal of the coating, will cause only less than 1% error in the wall thickness estimate, therefore variations in the coating thickness and epoxy properties can be neglected during CGV mode based guided wave corrosion/erosion monitoring of pipes.

Numerical simulations were conducted to study the adverse effect of surface roughness on CGV guided wave propagation. These simulations showed that even in the case of rather rough surfaces the average wall thickness can be sufficiently accurately determined by the proposed guided wave inspection method. For example, in the presence of moderate levels of surface roughness, the resulting amplitude variation of the CGV mode(s) is only $\approx$2 dB, and the error in the measured parameter produces a 1% error in wall thickness measurement. The relative insensitivity of the CGV mode(s) to surface roughness is due to its intrinsically good averaging property, which was the original reason why this robust method was selected over potentially more sensitive modes in the first place.

The adverse effects of pipe curvature on the CGV based inspection technique were found to be limited. Two types of pipe curvature were investigated, namely the intrinsic cylindrical curvature of the pipe characterized by the finite wall-thickness-to-average-pipe-diameter (d/D) ratio and the additional bending curvature characterized by the ratio between the average wall thickness and the radius of curvature of the bend (d/R). Generally, the effect of bending curvature on the CGV inspection method was found to be negligible except for excessively sharp corners. For the cylindrical curvature, the decreasing sensitivity to wall thickness variation has been corrected for in order to maintain sufficient accuracy. Both of these aspects were studied with the use of numerical simulations. The combination of the three thickness assessment approaches described in the preceding paragraphs is expected to provide a comprehensive approach to generating a reliable picture of the condition of the pipe wall between any given pair of transducers. While the LGV method can potentially indicate paths where drastic local variations exist, the third dispersion based method can smoothly integrate their effect into a very reliable assessment of average wall loss.

SELECTED RESULTS

Many tests have been performed to test the effectiveness of the CEM system in assessing loss in average wall thickness. Figure 1 shows the tests performed on a large (1 meter by 1 meter) plate, where two transducers were placed 400 mm apart and a power grinder was used to erode the area between the transducers to simulate the effect of localized material loss phenomena. In the figure, the horizontal axis represents different runs with the grinder, each resulting in a random loss in average wall thickness. The acoustic data was numerically inverted to obtain the relevant thickness information, and a statistical spot measurement technique was employed to estimate the two dimensional average loss in wall thickness. The robustness of the technique is demonstrated by the very similar results obtained from using four different frequencies (differing by as much as 30%) of pulsing, and the approximately 10% loss in average wall thickness is starkly evident. The much larger local thickness variation that caused this change in average thickness did not adversely affect system performance. The maximum error between estimated and calculated thickness was approximately 2%. The difference between the acoustically inverted and manually estimated thickness measurement can be partially attributed to the inherent complexity and error associated with a statistical spot measurement method (the average wall thickness loss is not readily measurable) and partially to the relatively lower order inversion procedure employed here, as these measurements were taken towards the earlier stages of system development. A higher order inversion procedure has been developed since, which improves the sensitivity and dynamic range of the system.

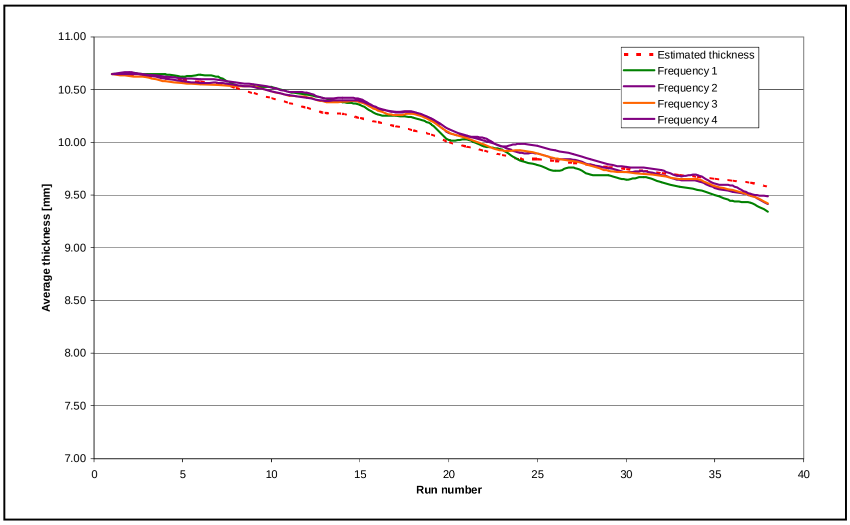

Figure 1: Plot of acoustically and manually estimated change in average thickness.

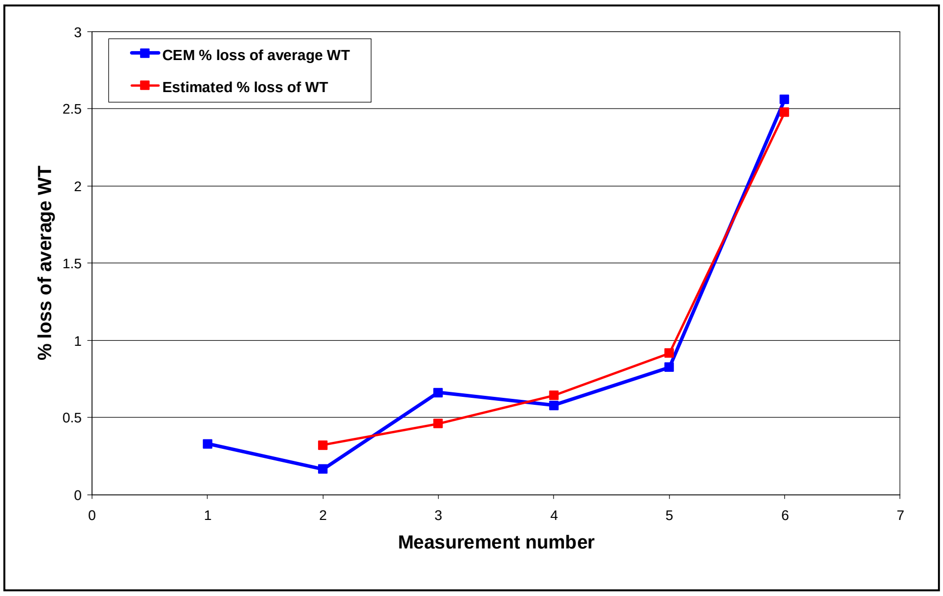

Figure 2: Plot showing a thickness change of 2.5% on a test that was independently monitored

Figure 2 shows the results obtained from a CEM test that was independently monitored by several attendees. In this case, a large 12 mm thick plate was eroded with a power grinder, but the drop in average wall thickness was measured and calculated independently later on by the attendees, while the CEM produced immediate results. The figure shows the excellent correlation between the two sets of readings, testifying to the system's accuracy.

Figure 3 shows the total thickness change recorded on a 12 mm thick plate that was subjected to artificially induced wall loss over a period of time, as a trend of average thickness against time. The essentially uncontrolled nature of the induced erosion extent is evident from the measurement.

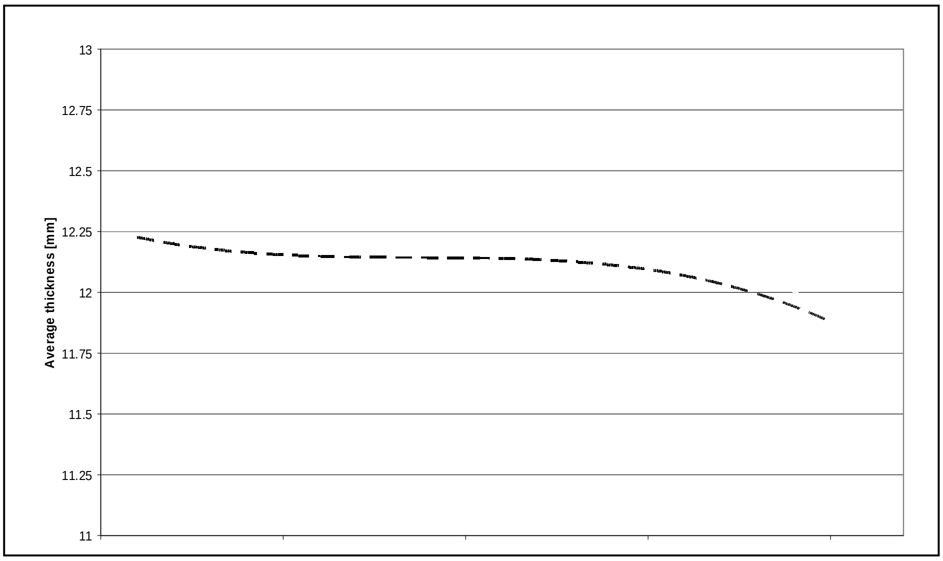

Figure 3: Total thickness change trend measured on a 12 mm thick plate that was subjected to artificially induced wall loss

Figure 4 shows the results obtained from using the LGV based method to detect the thickness variation as a 20 mm thick plate was progressively milled down to 10 mm, in uniform steps of 0.5 mm each. The figure shows the readings taken with two different pairs of transducers, separated by 400 mm and 500 mm respectively, along with readings of the plate thickness taken with a set of callipers. As can be seen, even in this case, there is remarkable agreement between estimated and actual thickness. The error in this case was calculated to be less than 1%. As stated before, the LGV technique is very useful in quantifying uniform drops in wall thickness.

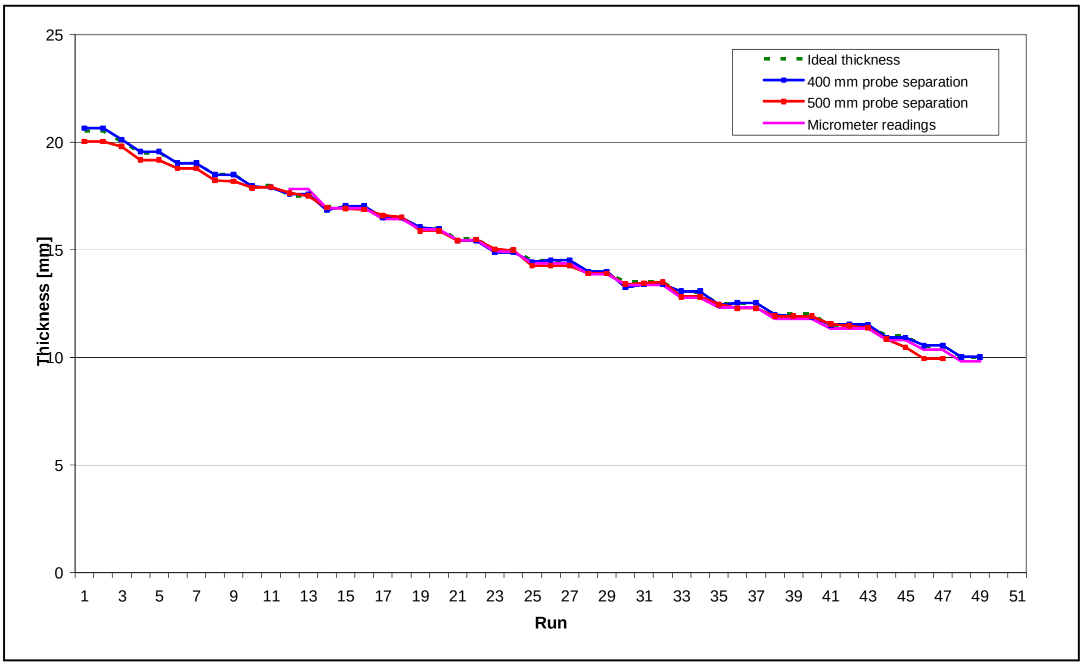

Figure 4: Plot showing a thickness change of 10 mm on a plate that was tracked by the LGV method.

Figure 5 shows the loss in wall thickness recorded from measurements from a 5mm thick heavily corroded steel pipe. A file was used to manually inflict the damage in random amounts. Figure 6 shows a picture of the pipe, and two transducers attached on either side of the damaged region.

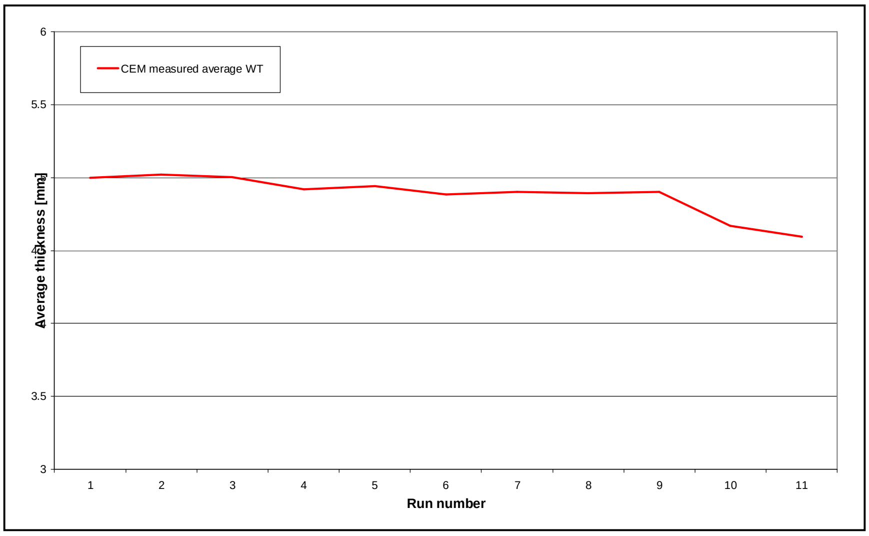

Figure 5: Plot showing a thickness change of 0.4 mm on a 5 mm thick steel pipe.

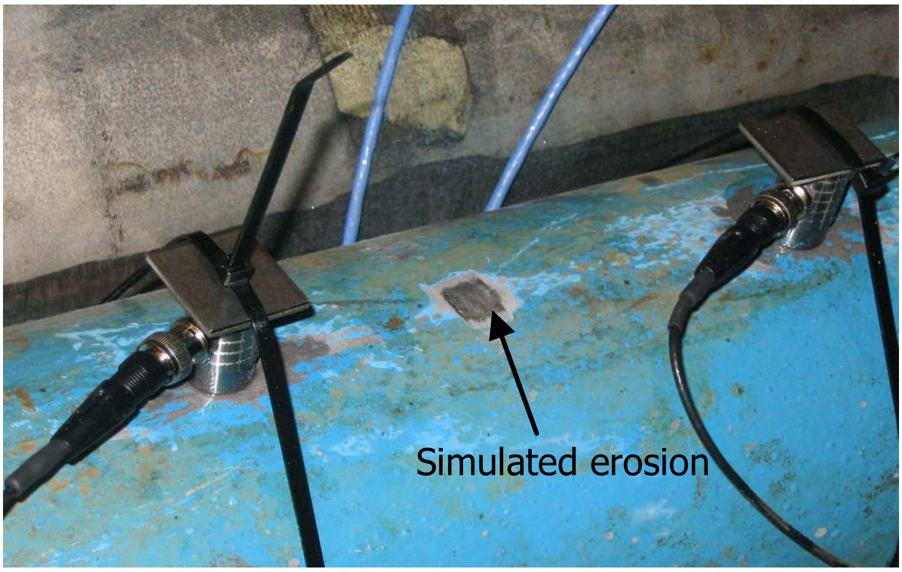

Figure 6: Photograph of the steel pipe showing the damage and transducers

FIELD INSTALLATIONS

The Octopus CEM consists of up to eight sensors that can be mounted on to the pipe surface. Requirements imposed by important factors such as mode separation and spurious arrivals place limits on the maximum and minimum distance between transducers. These limits are functions of pipe thickness and diameter, and need to be decided for each installation in order to be able to maximise 'coverage area'. At the time of this writing, coverage area for a given pair of transducers is defined as the distance between the transducers times the physical diameter of the transducer. Once this value has been calculated for all relevant transducer pairs, the coverage area can be obtained with respect to the area defined by the perimeter sensors in the deployment. Clearly, with the reduction in complexity achieved by having permanently installed transducers, the coverage area of the system will be a certain fraction of the area over which the system is deployed. Typically, this fraction will be greater than 0.6, or 60%. Also, the main unit and transducers need direct metal-metal contact with the pipe surface, implying that any coating will have to be temporarily removed, and then reapplied once the system has been fixed in place. This metal-metal contact requirement arises from the need to have good earthing for the system, and to ensure adequate ultrasonic coupling (epoxy) with the pipe wall. As far as possible, the system needs to be installed at locations that are a sufficient distance away from abrupt edges such as flanges. The presence of welds is not expected to influence the working of the CGV assessment technique, and the variation in thickness caused by the weld will be incorporated in the measurement. The CEM ultrasonic technique, coupled with the inherent limitations imposed by transducer sensitivity limits, indicates that the system will perform as expected on thicknesses varying from 5 mm to 40 mm.

CONCLUSIONS

The Octopus CEM, has been designed to provide a cost-effective alternative to other ultrasonic-based systems and undesirable intrusive systems to estimate and trend the extent of corrosion and erosion damage in a structure. The system relies primarily on lamb wave dispersion based analysis, and the attempt has been to optimize the compromise between high accuracy and high stability of the measurement. Acoustically important spurious effects have been taken into account in the design of the method, including temperature, fluid loading, etc, and several tests have been performed in-house to verify system functionality and effectiveness. A permanently installed, real time monitoring system with a sensitivity of 1% to changing average wall thickness, coupled with its robustness of operation is expected to provide the oil and gas industry an economic, efficient and reliable alternative to existing non-destructive pipeline evaluation methods.