# COMBATTING CORROSION

### AUDUN OPPEDAL PEDERSEN, CLAMPON, NORWAY, EXPLORES THE BENEFITS OF MONITORING STRUCTURAL HEALTH WITH GUIDED WAVES.

Ultrasound has been a technology of choice for decades due to its combination of applicability and inherent safety. Not least in the oil and gas industry, ultrasonic waves have enabled detection, measurement, and monitoring where other technologies have fallen short. ClampOn AS develops instrumentation for sand monitoring, valve leak detection, vibration monitoring, and wall thickness monitoring on pipes. One of the most significant developments in the last few years has been the CEM® Corrosion-Erosion Monitor, a permanently installed system for measuring wall thickness loss across a continuous area of pipe or bend. Versions have been delivered for topside and subsea installation in a variety of configurations, spanning from fully integrated solutions for real time monitoring, to stand-alone systems with battery operation and internal data logging including possibilities for manual or subsea wireless data harvesting.

## Continuous coverage by guided waves

Point sensors have been the predominant solution for ultrasonic wall thickness monitoring. Handheld, scanning, and fixed alternatives, all provide finite resolution depending on the extent of the monitored area and the grid resolution of fixed sensors, or on the time and effort an operator is willing to spend on mechanical or manual scanning. Each sensor transmits an ultrasound wave into the wall in its through-thickness direction, to achieve either back-wall echoes or local thickness resonance under the ultrasound transducer. Detection of a wall thickness loss, and measurement of its depth, then depends upon whether a point sensor is situated at the location of maximum wall thickness loss. Assessment of defect area size becomes possible only if the defect is large enough to cover multiple sensor locations. In light of the shortcomings of conventional technology, ClampOn sought fundamentally different solutions to the challenge of non-invasive, topside and subsea wall thickness monitoring. It became important

**Figure 1.** *CEM on 24 in. gas pipeline, with ultrasound transducers under two circumferential protection covers. Signal paths set up to monitor generalised corrosion on top, bottom, and sides.*

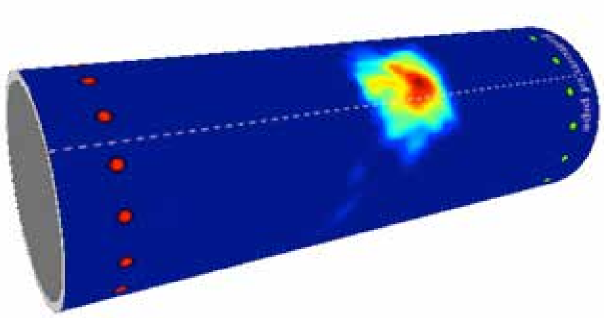


**Figure 2.** *Tomography monitoring data from CorrPRINT showing a localised damage on a straight pipe.*

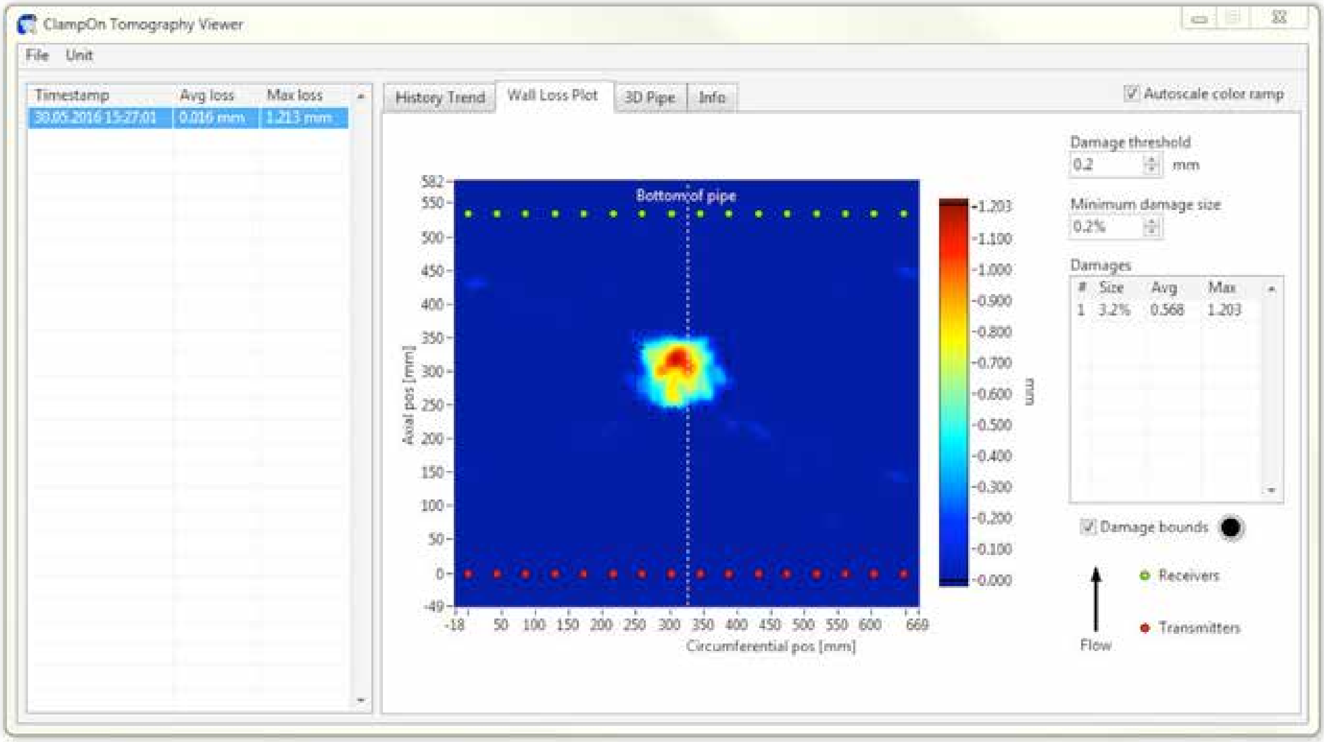
to find a solution that could monitor a continuous area, not only discrete points scattered across it.

Years of maturing possible technology choices with the foremost academic groups within ultrasonic non-destructive evaluation (NDE) led to the discovery of an accurate and robust alternative to the conventional point measurement technology. Guided Lamb waves are utilised in a pitch-catch mode between pairs of non-intrusive ultrasound transducers. Using the pipe wall as their waveguide, this family of ultrasonic waves spread cylindrically from an ultrasound source, analogous to the surface ripples from throwing a stone in a pond. Guided Lamb waves follow the curvatures of mechanical structures such as pipes, elbows, container walls, or hulls. Receiving transducers pick up the signal after a suitable propagation distance, typically 0.5 m to 1 m depending on the pipe geometry and purpose of monitoring. Guided wave technology enables continuous coverage across a wall area, using relatively few non-invasive ultrasound transducers, rather than the discrete point-by-point coverage obtained by other means. CEM systems can also offer an unprecedented degree of redundancy because multiple signal paths can be set up to cover an area of concern.

Lamb waves are dispersive with respect to wall thickness, meaning that the thickness of the monitored wall affects their velocity of propagation. Changes in wall thickness along a distance travelled affect the local propagation velocity of the signal, and thus contribute to a change in its time of flight. Baseline time-of-flight measurements are acquired upon system installation and associated with nominal or measured wall thickness profiles. All subsequent measurements are compared against these baseline data, leading to accurate trends of wall thickness loss over time based on a well-defined anchor point. This approach is particularly suited for corrosion and erosion monitoring, where change over time is the measurement result of greatest interest.

## The ultrasound transducer revisited

Accurate monitoring of the corrosion and erosion processes requires highly repeatable data. A critical component in any



| Timestamp | Avg loss | Max loss |
|---|---|---|
| 30.05.2016 15:27:01 | 0.016 mm | 1.213 mm |

☑ Autoscale color ramp

Damage threshold: 0.2 mm

Minimum damage size: 0.2%

Damages

| # | Size | Avg | Max |
|---|---|---|---|
| 1 | 3.2% | 0.568 | 1.203 |

☑ Damage bounds

**Figure 3.** *Interactive browser and analysis tool for tomographic wall thickness maps. Automatic detection and tracking of localised damages.*

ultrasound measurement system is the electroacoustic transducer. A transmitting transducer converts an electrical signal into a mechanical disturbance in the wall upon signal transmission. At the receiving end, another or the same transducer converts minute ultrasonic disturbances in the wall into electrical signals that can be recorded and analysed. In conventional point measurement systems, fixed grids of transducers solve the question of repeatability with regard to sensor positioning, but more challenges remain. Conventional ultrasound transducers generate and detect mechanical motion within their interior, typically using a piezoelectric element. For this principle of operation, it is of utmost importance that ultrasound signals travel in a repeatable way between the wall structure and the interior of each transducer. Acoustic coupling is typically obtained through firm metal surface contact in combination with a wet or dry coupling medium such as gel, grease or glue on the face of the transducer. It has proven challenging to make such an acoustical interface robust and stable over time. In many cases, periodic maintenance is required involving operations that can affect the baseline used for data sets that typically run across several years. The performance of piezoelectric transducers also depends on other internal components than the piezoelectric element itself, and these affect characteristics such as bandwidth and sensitivity. Such internal coupling and damping components need to be stable over time to maintain signal repeatability, but are generally prone to ageing effects.

For the reasons above, piezoelectric transducers may be considered unlikely to provide the stability and repeatability desired for the design life of a wall thickness monitoring system such as the CEM®. A particularly well suited alternative has been found, based on EMAT (electromagnetic acoustic transducer) technology. EMAT is a non-contact ultrasound transducer, utilising static and dynamic electromagnetic fields to generate and detect ultrasound signals within the pipe wall itself. Since no ultrasonic signal is required to enter the transducer, there is no need for acoustic coupling between the transducer and the monitored wall. Most EMAT designs are also insensitive to ageing effects in their internal components. The transducer typically comprises one or more magnets producing a permanent magnetic field in the transducer's vicinity, and a network of electrical conductors producing a variable magnetic field at the wall surface. Three mechanisms contribute to the transduction between electrical signal and mechanical disturbance (acoustical signal); the Lorentz force is often the most important, while magnetisation and magnetostriction forces contribute in ferromagnetic materials. The tranducers require electrically conductive specimens (walls). Surface coatings under the transducers are allowed up to

**Figure 4.** *Subsea CEM with transducers installed under insulation. The sensor electronics are located in a ROV retrievable canister.*

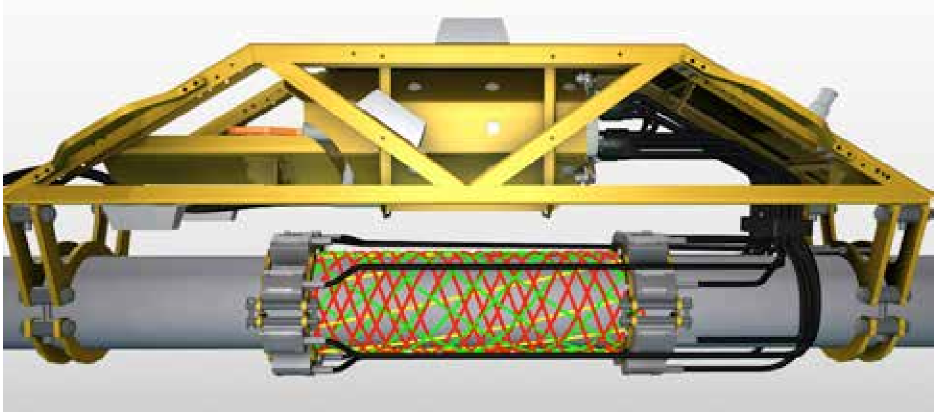


**Figure 5.** *Illustration of a Subsea CEM with 16 transducers, with the artist's impression of the helical signal paths. Since each path provides a broad area of wall thickness sensitivity, any point on the monitored pipe section is covered by one or several paths.*

**Figure 6.** *Topside CEM being installed for field testing on a 6 in. pipe. Transducers under protection covers, to be covered by insulation.*

a certain thickness. Pipe coatings do not affect signal stability in the case of EMATs, but cause a hold-off distance between wall and transducer that weakens the signal without harmful effects in terms of time-of-flight monitoring.

The omnidirectional EMAT was an important step in the development of the CEM and a door opener for tomographic wall thickness monitoring, with its ability to suppress spurious signal propagation modes and enhance the particular guided Lamb wave mode used for wall thickness monitoring.

## Tomographic imaging for greater detail

In many cases it can be possible to expand a CEM installation with CorrPRINT tomographic wall thickness mapping technology. Tomographic imaging methods are well known from a host of applications, for example ultrasound and x-rays for medicine and industry. Tomographic images can be qualitative in nature, for detection or visual assessment of a sample. Quantitative elements, such as sizing of defects and other internal features is a further step in complexity and also well known. A main motivation for ClampOn to develop tomographic wall thickness mapping was to enable detection and measurement of localised damage anywhere within a monitored area, without being limited by the positioning of point sensors. In addition to the existing ability to monitor average wall thicknesses across broad signal paths, tomography makes it possible to pinpoint areas with the greatest wall thickness loss and to track the development of those particular areas.

Tomographic methods in general base themselves on travel time and/or attenuation data from multiple sections, or signal paths, through a sample. Such sections are usually wave propagation paths, being optical, x-ray, radio, or ultrasound. In the case of guided-wave wall thickness mapping, the sample is the wall of a pipe or elbow, and the sectioning modality is the ultrasonic guided Lamb wave.

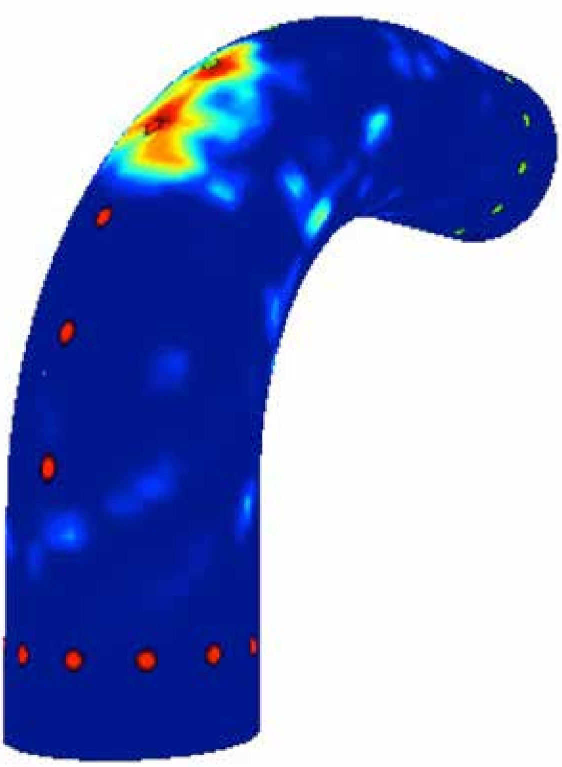


***Figure 7.*** *Tomographic wall thickness map of a bend with erosion damage on the extrados.*

A CEM system set up for tomography will typically include two circumferential rings of eight to 16 evenly spaced transducers. Counting only the direct signal paths from a ring of transmitting transducers to a ring of receivers, one would suffer from a lack of sections to build tomographic image resolution in the axial direction. In the case of pipe monitoring, this so-called limited view problem is readily overcome by including multiple signal paths between each pair of transducers. In addition to the shortest path, there are multiple clockwise and counter-clockwise helical paths, spiralling around the pipe. First-order helical paths wrap once around the pipe's circumference before reaching the receiver, second-order helical paths wrap twice, and so on. Inclusion of two to three orders of helical paths has been shown to result in excellent resolution and ray coverage in both the axial and circumferential directions, providing true two-dimensional maps of measured changes in wall thickness.

## Flexible system integration

A guided wave monitoring system can acquire a large quantity of data every time a measurement is run. A 32-channel CEM records up to 256 series of ultrasound data, which are processed into a wall thickness map before further analysis and reporting to the operator's control system. The operator can choose a minimum of data reported in real time, such as average and minimum wall thickness, or greater levels of detail as desired. One may for example require real time comparison between the top and bottom lines of a pipe, or between a straight leg and an elbow that is exposed to erosion. A combination of data redundancy and available system health indicators facilitates condition based maintenance of not only the monitored pipe, but also the measurement system itself.

Regardless of control system integration choices, full details of the monitoring data are available at any time through CEM client software that interfaces directly with the CEM controller over Ethernet or a serial connection.

Integration with other sensors can provide added value. Combination of passive acoustic sand monitoring and wall thickness monitoring has proven particularly useful for high-velocity gas wells where a sand burst can lead to significant wall thickness loss within minutes. Immediate shut-down of a well may be triggered by a particle monitor alarm, while subsequent wall thickness readings may confirm pipe integrity before re-opening production. In other cases, the CEM provides continuous time-stable monitoring of corrosion processes over months and years, either online with a control system, or in stand-alone configurations with battery operation, data logging, and, for example, a subsea acoustic modem for data harvesting.

Subsea CEM versions have been deployed for several applications and levels of system integration. Most installation jobs have been carried out topside, both on new structures and on modules that have been topside for maintenance. The complete set of sensor electronics is contained in an atmospheric chamber, available as an ROV-retrievable canister where desired. The non-intrusive EMAT transducers are installed permanently on the pipe wall, under insulation if applicable. A fully ROV-installed system has also been installed subsea.

Depending on the measurement interval, a battery can last from several months to a year before needing to be recharged. The battery canister will in most cases include data storage so that all available data is collected as part of the battery replacement operation. ▫