The state of the art in structural health monitoring of steel structures

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1. ABSTRACT

The majority of the crucial deterioration mechanisms of structural integrity and adequacy of metallic materials and structures due to operation have an "exponential" development. For example, corrosion (chemical and mechanical) and fatigue cracks if untreated, may lead to sudden catastrophic failure with severe consequences. Especially in critical / dangerous structures, there is a clear need for continuous monitoring depending on the failure mechanism. Modern, advanced and non-destructive testing techniques allow the monitoring of healthy operation of metal structures, aiming towards timely detection and warning of evolving phenomena, at an early stage, before they become dangerous / critical. In this paper, state-of-the-art technologies are presented, such as the CALIPERAY™ ultrasonic system for continuous local measurement of general corrosion, the GUL PIMS system for continuous corrosion screening of long piping and Acoustic Emission systems for crack detection. Such systems are applied in critical but inaccessible constructions, wherein periodic monitoring would be uneconomic and/or insufficient, such as piping and pressure vessels in refineries and in oil extracting platforms e.g. for fatigue cracking in conjunction with strain measurements and on steel bridges.

2. INTRODUCTION

Advanced NDT systems and techniques have been developed during the past years, targeting to early detection of dangerous flaws inside an operating structure. Structural health monitoring may warn for critical failure mechanisms, such as chemical/mechanical corrosion or fatigue cracks, at the very early stages. Depending on the technique, both manufacturing (e.g. weld l.o.f.) and operational flaws (e.g. hydrogen attack) may be detected. Depending on the structure type and failure mechanism to be detected, latest technologies in ultrasonic (UT) and acoustic emission (AE) testing can be used for continuous or long-term monitoring.

3. STRUCTURAL HEALTH MONITORING

Main advantage of remote and continuous structural health monitoring (screening) is getting early warnings of impending failure, minimizing manual inspections and avoiding multiple hazardous on-site visits. Depending on the monitoring method, restrictions may apply, such as periodical checks and maintenance to ensure functionality. Various techniques may be less sensitive than traditional NDT methods but may provide large area coverage in low cost.

Pass/Fail criteria can be carefully set and applied on received data, providing early notification. Monitoring may be combined with periodical follow-up inspections by other NDT methods for verification purposes.

For specific structures, considerations should be given, regarding the application of a suitable technique. Combinations of screening and traditional NDT methods can also be made, so that health monitoring may be a part of a risk based inspection program, either by covering a structure globally or only its high risk areas.

4. CORROSION MONITORING

High-temperature, hard-to-reach locations are hard to be tested as often as they should be. Without adequate testing, plant operators have little-to-no warning of developing problems arising from corrosion and erosion – a costly surprise. Traditional ultrasonic thickness testing (UTT) methods for determining corrosion and erosion on piping and vessel walls can be challenging to execute at times. It can often be difficult for technicians to access assets in potentially hazardous locations, while manual measurements have to adapt to changes in surface conditions, technology and equipment.

The ability to acquire information remotely and continuously even on difficult to access areas provides significant advantage in detecting problem areas before they become failures.

A remote thickness tracking system such as the CALIPERAY™ makes it easy for operators to stay on top of their asset integrity and maintenance by utilizing permanently installed ultrasonic sensors to remotely, quickly and accurately monitor corrosion and erosion.

The thickness transducers are installed on the monitoring locations and make up a wireless mesh network (see Fig. 1). As they collect data from the piping or vessel walls, they both receive and transmit information through the rest of the network until it reaches the Smart

Wireless Gateway, where it is then transferred to a host computer. The wireless mesh allows CALIPERAY™ to seamlessly merge with on-site and remote network equipment.
The system allows the user to configure settings, store readings, view thickness trends and waveforms, and monitor the status of all the installed UT nodes from anywhere using a web-connected device.

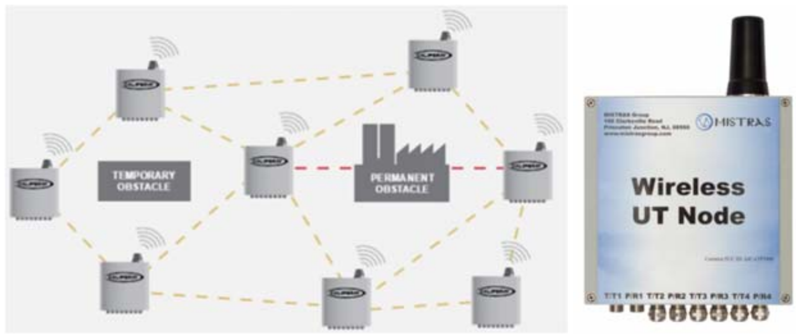

Fig. 1: Wireless Mesh (left) and wireless UT node (right).

Especially on pipes, the CALIPERAY™ system can be combined with a permanently installed guided UT wave monitoring system (GUL PIMS). Guided waves are increasingly being used for pipe inspection. One of their main advantages is their ability to inspect large lengths of inaccessible pipe from a single location (see Fig. 2). However, it is still necessary to gain access to the pipe in at least one location in order to perform the inspection. In many cases, gaining this access accounts for the majority of the inspection cost.

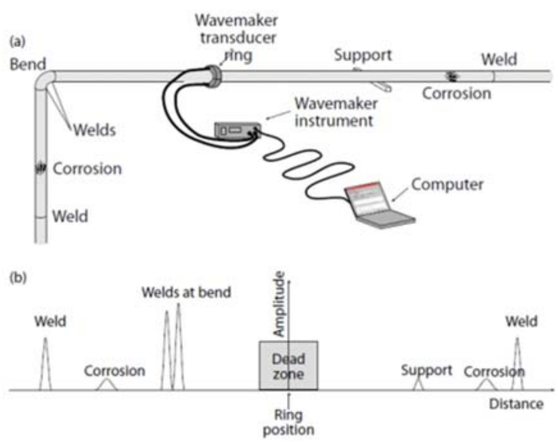

Fig. 2: (a) Schematic diagram of the GUL ring operating on a typical pipe that contains an assortment of features around the test location. (b) A schematic of the corresponding results.

Where regular inspection is needed, leaving a transducer in place on the pipe and exposing a connector in a convenient to access location can provide a substantial cost savings. The use of a permanently installed monitoring system implies that the pipe being inspected is difficult to access and usually difficult to inspect with other techniques. In order to effectively manage such pipes, it is essential that the guided wave inspection provides as much quantitative information as possible about any changes that are detected.
In addition to the CALIPERAY™ system, the permanent GUL PIMS system provides information on inaccessible areas (e.g. under railways) and detects manufacturing defects

(e.g. lack of weld root penetration). Welds, supports, defects, and other features generate echoes from which their locations and severities (in the case of a defect) can be measured.
A transducer system that can be permanently installed offers the full benefits that are offered in the normal removable transducer system, but it remains stable over long time periods in harsh environments.
Very attractive applications for a permanently installed GUL system include offshore risers, sub-sea pipes, buried or sleeved pipes and any safety critical or difficult to access section of pipe. Attaching the transducers when the pipe is first installed usually provides the most cost effective deployment. However, the system can also be retrofitted on existing pipes.

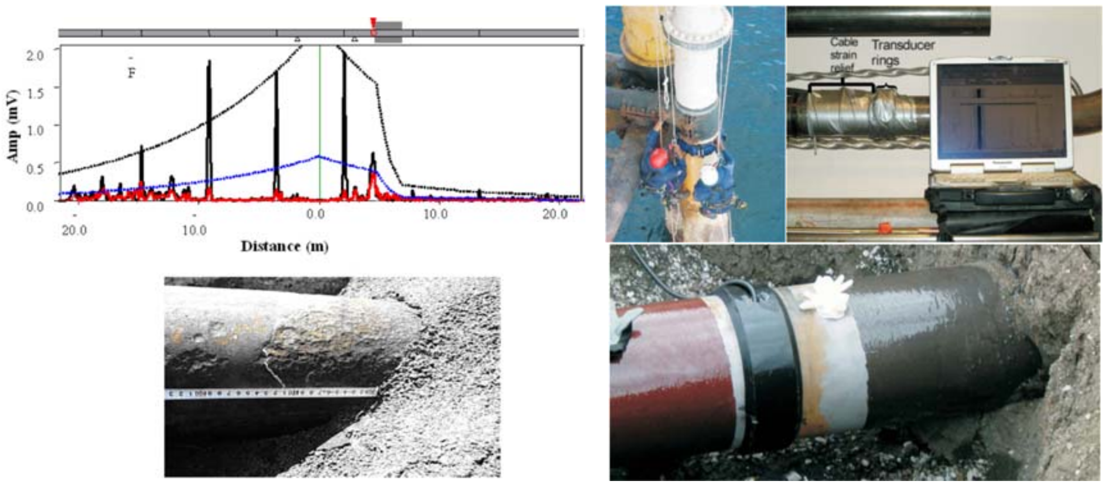

Fig. 3: (Left) Inspection results from a screen capture showing preferential corrosion as identified between 0 & 10m mark. (Right) Transducer ring can be placed on an easy accessible part of the pipe. No need to access the buried part of the pipe or the part under roads or railways.

5. CRACK PROPAGATION MONITORING

Especially applied on large metal structures, such as atmospheric tanks, pressure vessels, refinery columns etc., acoustic emission can be used for permanent or long-term structural health monitoring. Acoustic emission monitoring has been performed on various structures, where crack propagation is the main issue.
A short-duration in-service monitoring (about 2-3 days) on Pressure Swing Adsorption (PSA) vessels (see Fig. 4), where pressure is circling and fatigue conditions are present, may reveal significant AE sources, as result of failure mechanisms (e.g. fatigue cracks).
Long-term in-service monitoring (about 4-5 months) of steel vessels (see Fig. 5), where operating conditions (pressure, temperature, product flow etc.) are continuously changing, may determine crack growth as a result of in-service propagation (e.g. hydrogen induced cracks).
Cracks that are not growing will not emit AE and will not be located. On structures where the operating conditions are periodically repeated in cycles, existing fatigue cracks may grow and may emit AE at same periods of operating conditions, that can be early evaluated.

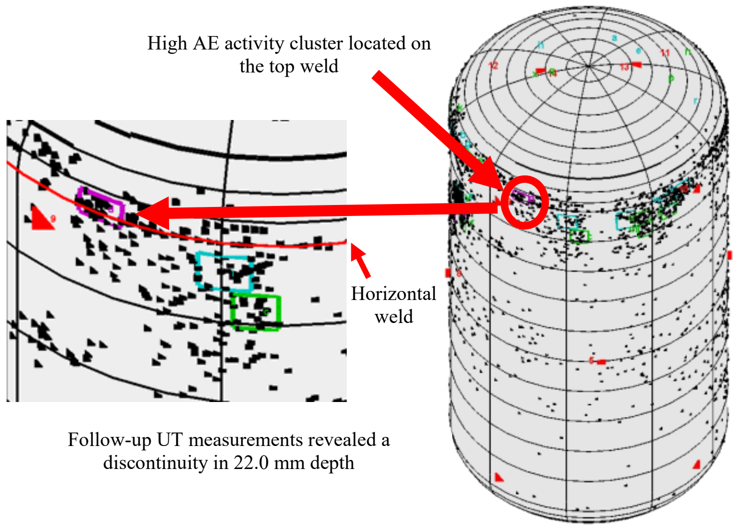

Fig. 4: Results of AE monitoring on PSA vessel. High located AE activity revealed discontinuities (as verified with other NDT methods)

On structures where operating conditions are not changing on a repeating rate, existing cracks growth/AE emission may depend on the combination of operating conditions (e.g. pressure vs. temperature). In this case, a longer duration monitoring is required for AE evaluation. Evidence of flaws inside the structures is usually verified by Ultrasonic Phased Array and their growth can be inspected by periodic measurements (see Fig. 5**Error! Reference source not found.**).

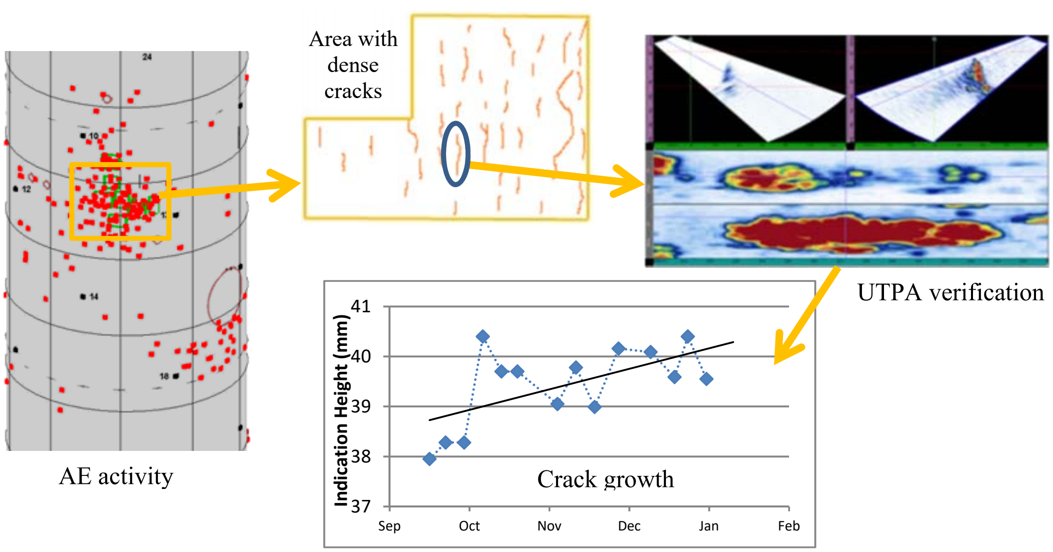

Fig. 5: Results of AE monitoring on steel vessel. High located AE activity revealed areas with high concentration of cracks (as verified by UT Phased Array)

Data acquisition and warning (in case of critical failure) can be achieved remotely via internet. The AE system is placed inside a protected room (e.g. site's control room or a container close to the monitored structure) and the operator can control it from his/her office, even at the same time with other AE monitored structures.

6. ADVANTAGES – RESTRICTIONS

While traditional inspection methods provide value to plant operators, many owners have adopted condition-based inspection programs aimed at bolstering their mechanical integrity and preventive maintenance programs. As discussed above, to assess the condition and subsequently target the inspection where it's actually needed, condition monitoring systems have been developed and are currently in operation worldwide. The following paragraphs summarize the advantages of popular, state-of-the-art permanent monitoring systems.

6.1 CALIPERAY System

Advantages

- Continuous, repeatable and recordable thickness measurements from exact same position, easy comparable with previous measurements.
- Prevents multiple hazardous on-site visits.
- Fast on-site data analysis leading to immediately follow-up or complementary inspections if needed.

Restrictions

- Monitoring is local (on one point).

6.2 GUL-PIMS System

Advantages

- Rapid inspection of 100% of large piping sections with minimal insulation removal.
- Localized damage can be identified avoiding multiple hazardous on-site visits.
- Previously inaccessible areas can be inspected especially where consequences and likelihood of failure are high.
- Point of contact corrosion areas can be rapidly inspected for piping systems resting on supports, eliminating the need to "lift" pipes. The environmental impact and potential for further damaging suspect pipes during live "lifting" is eliminated.
- Automatic recall and comparison of previous test data to detect even very small changes.
- Quick installation and easy comparison with previous measurements with fast on-site data analysis leading to immediately follow-up or complementary inspections if needed.

Restrictions

- Applied only on pipes.

6.3 Acoustic Emission

Advantages

- Global monitoring of large structures., providing alarm/notifications at early stages.
- Recordable for future reference.

Restrictions

- Not repeatable method, affected by external noise (nearby operations, rain, wind etc.).
- Needs filtering of irrelative data (e.g. operational noise).
- Installation is not instant and requires on-site preparation measurements.

6. CONCLUSIONS

Latest technologies in ultrasonic (UT) and acoustic emission (AE) testing can be used for continuous or long-term monitoring of steel structures. These technologies provide safe, cost-effective, fast and productive monitoring. Depending on structure type and failure mechanism to be detected these technologies include:

- Permanent wireless ultrasonic thickness testing that can be applied in various structures and components inside a large installation, where it is difficult for technicians to access assets in potentially hazardous locations for manually UT measurements.
- Permanently installed monitoring system for guided wave ultrasonic long range inspection for assessment of long pipes, avoiding any access with buried parts or pipe parts under roads or railways.
- Short- or long-term Acoustic Emission monitoring of large structures, providing location of possible growing flaws, as fatigue cracks.

A combination of these technologies, depending on the needs, requirements, as well as on environmental and safety factors of an industrial installation, may provide an accurate structure health warning system.

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ΠΕΡΙΛΗΨΗ

Οι μηχανισμοί που μειώνουν τη δομική ακεραιότητα λόγω της λειτουργίας μιας κατασκευής παρουσιάζουν μια "εκθετική" ανάπτυξη. Για παράδειγμα, διάβρωση (χημική και μηχανική) και ρωγμές κόπωσης, εάν δεν επισκευαστούν, μπορεί να οδηγήσουν σε ξαφνική αστοχία με ολέθριες συνέπειες.
Νέες τεχνολογίες υπερήχων (UT) και ακουστικής εκπομπής (AE) εφαρμόζονται για συνεχή ή μακροπρόθεσμη παρακολούθηση μεταλλικών κατασκευών. Οι τεχνολογίες αυτές παρέχουν ασφαλή, οικονομικά αποδοτική, ταχύτατη και παραγωγική παρακολούθηση. Ανάλογα με την κατασκευή και τον μηχανισμό αστοχίας που πρέπει να ανιχνευθεί, αυτές οι τεχνολογίες περιλαμβάνουν συνεχή παρακολούθηση σημειακού πάχους ελασμάτων, σύστημα παρακολούθησης σωληνώσεων μεγάλης έκτασης, καθώς και συνεχή ή μακροπρόθεσμη παρακολούθηση μεγάλων κατασκευών.
Ανάλογα με τις ανάγκες, τις απαιτήσεις, τους περιβαλλοντικούς παράγοντες και τους παράγοντες ασφαλείας μιας βιομηχανικής εγκατάστασης, ένας συνδυασμός αυτών των τεχνολογιών, μπορεί να παρέχει ένα έγκυρο και γρήγορο σύστημα προειδοποίησης.