

A Review of Ultrasonic Tomography for Monitoring the Corrosion of Steel Pipes

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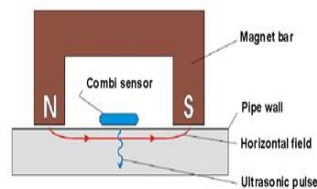
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Graphical abstract



Abstract

Infrastructure development is currently taking place rapidly. Designing a dwelling or premises is currently implemented quickly while controlling construction costs in addition to providing guidance on planned development. The architecture uses steel as a main part of the pile and drainage system is connected from sources to consumer. This study focuses on steel pipes that are exposed to corrosion. This problem is considered serious because steel pipes are used not only for the delivery of water supply but also for the delivery of gas and oil to the oil and gas sector, where the same problem occurs. Impacts of the problem of corrosion of steel pipes contribute to the risk of loss to the owner of the premises or industry. An overview of leakage problems, which cause a reduction in the volume of materials or hazards to the environment and consumers, is given, and the occurrence of corrosion in pipelines is evaluated. Monitoring methods use ultrasonic tomography as a major contribution to the implementation of monitoring and assessing the status of pipe durability and ability. This paper looks at the concept of diverse ultrasonic tomography inventions used to assist the process of monitoring of the level of pipeline capacity that will suffer corrosion.

Keywords: Steel pipe corrosion; cause and effect of corrosion; ultrasonic tomography monitoring

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1.0 INTRODUCTION

A building consists of a metal and non-metal structure. In addition to completing the facility of a building, and a bench mark for the strong structure depend the criteria used iron pile. Similarly, the construction of the water piping system is an essential element in the design of erected buildings. Water pipes are made of materials that rust easily, such as copper (Type L or M) [1], galvanized malleable iron, galvanized steel, Chlorinated Polyvinyl Chloride (CPVC), Cross-Linked Polyethylene, or other approved materials and must be in accordance with type of NSF 61 standard [2]. The problem of the corrosion process occurs in pipelines, and the corrosion of gas pipelines also occurs [3,4].

This phenomenon cannot be avoided even when the pipe is protected by insulation material such as cement, but corrosion can occur from the inside. The corrosion process occurs due to the reaction of iron and oxygen in the presence of water or humidity of the air [5]. Rust can also form as a result of the reaction between iron and chloride in an environment deprived of oxygen—rebar [6] used in underwater concrete columns is an example—which generates green rust. Some forms of corrosion are

distinguished by sight and by spectroscopy and form under different conditions. Rust consists of hydrated iron (III) oxides, $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$, and iron (III) oxide-hydroxide, $\text{FeO}(\text{OH}) \cdot \text{Fe}(\text{OH})_3$ [7]. Given sufficient time, oxygen, and water, any iron mass eventually completely rusts and disintegrates.

Surface rust is unstable and fragile, and does not provide protection to the basic iron, unlike the formation of patina on copper surfaces. Rusting is the common term for corrosion of iron and its alloys, such as steel. Many other metals undergo the same corrosion, but the resulting oxides are usually not called rust [8].

The impact of rust on pipes is very high; for instance over \$2.2 billion is lost to corrosion in the United States each year, according to government and industry studies. The cost of corrosion is equal to 3 or 4% of the Gross National Product [9]. Reinforced concrete structures have the potential to be extremely durable and able to withstand various adverse environmental conditions. However, the failure of structures still occurs due to premature corrosion of reinforcements [10, 11]. Maintenance and repair of bridges and buildings for their safety requires effective inspection and monitoring techniques to assess the corrosion of

reinforcements. Engineers need better techniques to assess the condition of the structure when maintenance or repair is required.

These methods need to be able to identify any possible security problems in the structure before it becomes serious. This paper examines all electrochemical techniques and nondestructive assessments from the viewpoint of corrosion and their application to bridges, buildings, and other civil engineering structures [12].

Corrosion problems exist in many industries [13, 10], and many inspection and monitoring techniques have been developed to assess the level of corrosion and structural integrity of the metal. Among other things, the inspection by ultrasonic method is widely used to monitor or control the wall thickness [14, 15] and, in general, the thickness of the inner wall becomes thinner due to corrosion that occurs in these structures. Laboratory corrosion tests [16, 17] such as the accelerated corrosion test have been developed by automotive manufacturers, where a higher level of accuracy is required, and classic valuation methods such as the size of a normal material weight are used.

Method for Top-of-Line (TOL) as support on the corrosion rate as a simulation methods to compared with new and old experimental data. The suitable material data model called super saturated iron. In this cases need to avoid water condensation rate is high due to the low temperature of the pipe wall because can get rid of TOL corrosion. The protective corrosion product scale established in TOL corrosion can be affected by the presence of organic acids [18].

2.0 THE PHENOMENON OF RUSTY WATER PIPES AND CHEMICAL REACTIONS

Corrosion is the process by which steel is oxidized by chemical attack [19]. Custom steel structures are exposed to environmental humidity. When there is moisture, an electrochemical process occurs and this creates a condition known as an electrolyte [20]. This will allow a current to move in the concrete. This process involves two parts, the cathode and the anode. Cathode will divide the oxygen is decomposed into negatively charged ions, while at the anode, metal in the concrete will degrade to a state that is not balanced. Thus a current flow occurs in which negatively charged ions flow to the anode and positively charged metal ions flow to the cathode [21].

When a piece of metal rusts, electrolyte helps provide oxygen to the anode. As oxygen combines with metals, electrons are freed. When they flow through the electrolyte to the cathode, the anode metal is gone, swept away by the electrical flow or converted into metal cations in a form such as corrosion [22].

This process occurs continuously until an equilibrium is reached. In a balanced manner, metal ions will combine with hydroxide ions to form metal hydroxides. The electrochemical reaction that occurs at the anode and at the cathode can be summarized by the following expression [23]:

Reaction at the anode [24]:

Metal -----> metal ion + electron

2Fe equation -----> 2Fe ++ + 4e-

Cathode reaction [25]:

Oxygen + water + electron -----> hydroxide ion

Equation O₂ + H₂O₂ + 4 H₂O -----> 4Fe (OH) 2

Balanced process

Fe + H₂O₂ + 4H₂O -----> 4Fe (OH) 2

Thus the process of corrosion in supposing with expression

Fe + O₂ + H₂O -> Fe₂O₃. H₂O

Iron + oxygen + water + ---> corrosion (rust)

From the above equation, several things can be concluded [26]:

- In dry conditions, corrosion is formed slowly and slightly. Thus the erosion rate is low.
- When steel piles are planted deep in the soil, erosion corrosion rates are also low because the oxygen content is low.
- At jetties and offshore platforms, for example, the corrosion rate is high. This effect can be seen in the area because there are splashes of water in the air. Salty sea water produces acidic conditions as well as accelerating the process of corrosion by acting as a rusting agent. Generally, the process of corrosion can occur in four circumstances: namely in the air, water, and soil and through bacterial reaction.

2.1 Damage from the Effects of Corrosion in Water Pipes

Copper and lead can be toxic and can leach into water pipes in both new and old residences. The leaching process is caused by erosion [27]. Copper contamination can cause gastrointestinal problems in the short term and damage the liver and kidneys from time to time. Lead contamination [28] can cause physical and mental development problems in children. In adults, it can cause high blood pressure and kidney problems [29].

The Environmental Protection Agency has set primary drinking water standards for copper and lead pipes, where the maximum permissible level for copper is 1.3 mg/L. The maximum allowed is 0.015 mg/L. Contaminants can be reported in units of milligrammes/litre (mg/L) or parts per million (ppm) [30] simultaneously. Iron and zinc are usually present and can cause the water to have a metallic taste but do not lead to medical problems.

Two similar tests can determine whether water is likely to cause erosion: the Langelier Saturation Index (LSI) method [32] and the Ryzner Stability Index (RSI) [33]. To use the LSI, laboratories need to measure pH, electrical conductivity, total dissolved solids, alkalinity, and total hardness [34]. LSI is usually negative or positive but rarely zero. Negative values predict that water is more likely to cause corrosion [35]. Potentially corrosive water usually has an LSI value of -1 (mild) to -5 (severe). When RSI is used, a value of more than 6.5 [36] shows that the water is likely to cause erosion with higher eroding [37, 38].

2.2 The Importance of Controlling Corrosion in Gas Pipe System

Pipelines are one of the foundations of modern civilization and have become an important part of the infrastructure. More than three million miles of pipeline connect oil and gas reservoirs, shipment ports, and refining and storage facilities today [39]. Non-destructive testing of the pipeline system through online

examination using smart pigs has become an important part of this system in ensuring safe and economic operation [40].

Although pipelines provide high level of security for the transport of gas, oil, and other products, there are various factors that can cause defects in the pipe wall, eventually leading to the risk of pipeline failure during operation [12]. The main types of defects can be categorized as:

- a. Deformation dents, ripples, wrinkles, buckles, and so on often occur during the installation of pipes, for example when a pipe is laid in rocky soil. Other causes of disruption are agricultural equipment, landslides, for the example in Figure 1.



Figure 1 Example of deformation damage (wrinkle probably caused by landslide) [12]

- b. Metal loss is one of the main reasons why the erosion process may take place on either side of the pipe wall. Internal corrosion is primarily associated with a medium containing aggressive substances; external corrosion (see the example in Figure 2) often occurs at the site of the damaged layer and in corrosive soil conditions. Other reasons for the loss of metal are grinding and erosion. Changes in the wall thickness of seamless pipes and the growth rate of other types of corrosion are usually below 1 mm/year but could amount to several millimetres per year under certain conditions. Corrosion defects are usually the cause of the leak.



Figure 2 Example of external corrosion damage [12]

- c. Cracks when loading conditions in pipeline pressure is a key component of the hoop pressure acting in the circumferential direction. Therefore, the majority of cracks developing in the pipeline have an axial orientation. In most cases, the crack (or crack-like defects) is due to manufacturing-related defects in the weld longitudinal such as hot cracking, lack of a joint, or similar. Existing cracks can grow during operation, for example, by the fatigue mechanism. Another type of fracture encountered in the pipeline is stress corrosion cracking (SCC), which often occurs in the form of cracking colonies (see the example in Figure 3). This type of cracking is due to a bad combination of stress levels and chemicals in the ambient soil type. Crack-like defects usually lead to failure by rupture if the critical crack size is reached.



Figure 3 Example of an SCC colony [12]

To prevent failure of the pipeline, any defects that may be critical should be detected early enough. As most of the pipelines that are constructed are also protected by a protective layer, a complete examination can only be done from the inside. This is achieved by online examination using an automatic inspection system called intelligent pigs (or smart pigs). The main goal of this type of screening is to detect certain types of defects with a high probability of detection (POD) and to provide high-resolution data that allow the precise size of the defects to be detected. Following the inspection run, the process of data analysis is applied to produce a list of all the anomalies found, including their locations, types, and sizes.

Based on these results, the assessment of damage is usually carried out using an appropriate standard to measure the level of defects detected, thus allowing the operator of a pipeline to take adequate measures such as repair or replacement of the affected pipe. In cases where high-precision data are available from for next inspection, a comparison can be made to find the growth rate of defects, which acts as input data for the fitness-for purpose (FFP) study. The objective of FFP is to recommend immediate actions and also to determine strategies that will ensure the future integrity of the inspected pipeline.

■3.0 IMPLEMENTATION OF CORROSION MONITORING IN THE PIPING SYSTEM

The maintenance and rehabilitation of pipeline systems provides a key challenge for many municipalities and industries need to provide quality services, and it is necessary to preserve the existing pipeline infrastructure. An ultrasound acoustic-based methodology is proposed to obtain measurement of depth and imaging complete for two dimension [41] and cracks emanating from pipe inspection by sensor for concrete [42]. Surveys show that immersion ultrasound scanning and C-scan imaging [43] provide strong data to build a reliable defect-detection system.

Monitoring the rate of erosion and corrosion thinning of pipelines is an important issue in the petrochemical and power generation industries. Research was conducted in which two signal processing techniques were used to estimate the rate of depletion of the pipe structure from ultrasonic pipe-wall-thickness data collected in a short period [4]. The first is a combination of cross-correlation and polynomial curve fitting and the second is a model based on the budget of the scheme (MBE). Techniques in which data were collected from the apparatus showed accelerated depletion rates and both indicated that they were able to estimate the rate of thinning rapidly within a short time with good accuracy [44]. In the laboratory, depletion rates as low as 10 m/year were measured within 15 days with uncertainty of ± 1.5 m/year by both techniques. While the MBE technique can produce a slightly better accuracy, the greater stability and speed of the cross-correlation calculation technique mean that it is the preferred choice for use in industry [45].

In an effort to help expand the coverage of pipe inspection, an inspection approach for monitoring the thinning of the walls uses Direct Current Reduction Potential (DCPD) [46]. To improve usability for complex pipe networks such as secondary cooling water systems, the same method to control by eliminate unwanted leakage currents [47]. Wide range monitoring and short range monitoring with the same method can immediately turn on the current potential drop to rapidly monitor the depletion of the pipe [48]. Based on the results can easy to identified for further examination by the ultrasound technique (UT). Online monitoring location can detect with a thin arm. The results of finite element analysis and the model developed to form comparison with wall thinning was measured. Experimental verification was carried out using UT as a reference. The results showed that the model predictions and experimental results agree based on ES-DCPD [49].

Research on fouling detection in pipes in the food industry using acoustics and ultrasonics can provide cost-effective solutions. Fouling will be effect to food product development, corrosion, or baked on food products inside the wall of the pipe or on a plate. The existence of pollution can make problem at the pump machinery, reduce the efficiency of heat conduction in the pipe fouling, and reduce the product quality and/or safety [50, 51]. Early detection and quantification of the extent of fouling can reduce the costs incurred due to wear on machinery, pipe maintenance, and production time. Two methods were investigated for acoustic detection of potential fouling of pipes: the ultrasonic waveguide and acoustics [52, 53]. The guided wave method is related to energy loss due to viscous load or semi-solids on a plate or pipe. Efficiency of acoustic signal depend on changes in wave velocity and attenuation signals caused by the presence of fouling [54].

Corrosion sensors should have high sensitivity that is sufficient to measure the corrosion rate in corrosive media and environments and the ability to detect the corrosion mechanism [55]. Therefore, a steel thin-film electrical resistance (FER) [56] sensor is developed and used by measuring changes in the electrical resistance of the sensing element following the corrosion of steel in various environments. A sensor with a thickness of 600 nm is fabricated by DC magnetron sputtering deposition on steel Al₂O₃ substrate [57], followed by silk-screen printing to increase the sensitivity of the sensor, particularly when measuring the corrosion rate in low corrosive environments such as toxic in neutral solution, this condition will be happen to the steel corrosion [58].

These sensors also have various sensing elements for online detection of local corrosion of steel. Safer sensors are laboratory and field tested. All the studies show that the newly developed FER sensor can be a promising tool for reliable monitoring of corrosion of steel exposed to various environments [59].

The pressure system manager at NASA Ames Research Center (ARC) has initiated a project to collect data and develop a risk assessment model to support risk-informed decision making about the future of underground pipe inspection at ARC. It consists of a pipe corrosion-segment model, a pipe wrap protection model, and a pipe segment pressure model. A Monte Carlo simulation model shows the distribution of probability of failure. The results of the study showed that the sensitivity of model uncertainty, or lack of knowledge, is a major contributor to the unreliability of the calculated underground pipes. As a result, the system to consider investing dedicated resources to focus on reducing these uncertainties. Future work includes the compile of data collection for system existing ground-based and uses a risk model to inspection strategies underground pipes in the ARC [60].

4.0 ACHIEVEMENTS IN THE DEVELOPMENT OF ULTRASONIC TOMOGRAPHY APPLICATIONS IN INDUSTRY TODAY

Guided wave ultrasonics is used for monitored pipes for guided waves can propagate over long distances and are sensitive to structural damage such as cracks and corrosion loss [61]. However, the characteristics of the various modes and dispersion wave guide make it difficult to interpret the signal arrival records. In addition, guided waves are also sensitive to environmental changes and operations, limiting the effectiveness of the ultrasonic method for detecting defects in pipes in real environments. A damage detection method based on Singular Value Decomposition (SVD) [62] can identify changes of interest, because the scatterer mass resembles subtle damage under realistic environmental variation. This shows the effectiveness and robustness of this method for the collection of experimental data from pipe segments under varying environmental conditions and realistic operations during a few months [63].

Compared Magnetic Flux Leakage (MFL) ultrasonic wall thickness measurement is a direct method which provides an absolute measure of the remaining wall thickness and the depth of a defect in the case of loss of metal. It has better accuracy than the ultrasound method and also allows a more reliable assessment of damage, which, in turn, leads to a reduction in the amount of excavation repairs needed after inspection [64]. However, a conventional ultrasound probe that uses the piezoelectric effect requires a coupling liquid medium to upgrade sufficient ultrasonic energy at the pipe wall. Thus, ultrasonic sensor types cannot be used for gas pipeline inspection except operating in liquid [65]. In order to enable better diagnosis of the wall thickness of gas pipelines, new tools have been developed which combine the advantages of different, independent non-destructive methods in one device. Specifically, the tools include Electro Magnetic Acoustic Transducer (EMAT) technology [66] for accurate ultrasonic measurement of wall thickness without the need for a liquid coupling medium following Figure 4.

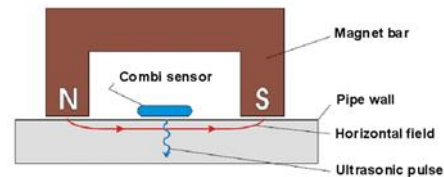


Figure 4 Measuring arrangement for generating EMAT based ultrasound [66]

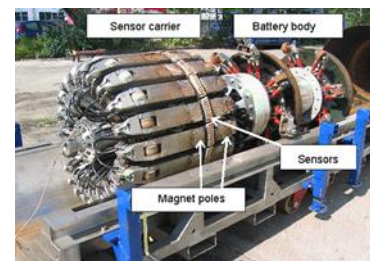


Figure 5 LineExplorer 3T-tool during launch. The 40" version contains 400 sensors [66]

The principle of operation of the new tool is based on EMAT technology, see Figure 5 [67]. As shown in Figure 4, a sensor located in the middle of a bar magnet generates a tangential magnetic field [68]. The sensor itself consists of a transmitter and a receiver coil design, which is optimized for the current application [69]. Ultrasonic shear wave polarization with a frequency of 2.5 MHz is generated using the magnetoresistance effect [70]. Ultrasonic pulses propagate perpendicular to the surface of the pipe wall. From the time of flight of the rear wall and the unknown echo ultrasonic velocity in the steel pipe [71], the (remaining) wall thickness is easily obtained.

By taking advantage of the fact that the principle is based on the EMAT coil, the coil can also be used to take an MFL signal [72] produced by induction the electromagnetic stray field from flux in the coil moves. MFL information is then easily separated from the ultrasonic signal with suitable frequency filtering and time gating. Furthermore, the EMAT transmission pulse generates an eddycurrent [73] during the pulsed signal in the separated coil. This signal depends on the height of liftoff of the coil following Figure 6. This information can be used, for example, to measure the depth of the defects due to internal corrosion [74].

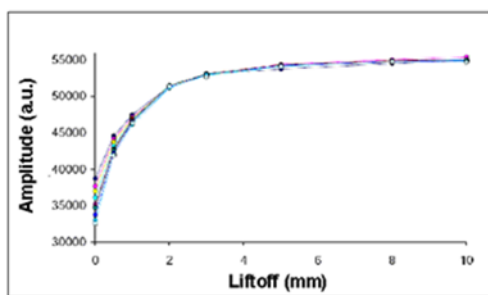


Figure 6 Dependency of the EC amplitude on the coil liftoff. For liftoffs > approx. 7 mm the amplitude shows a saturation behaviour [74]

The EMAT coil (sending and receiving) are set up in a concentric manner with a maximum outer diameter of 10 mm (Figure 7). The basic unit consists of two sensors. The units are covered by a layer of wear ceramics. Ten basic units are integrated into a larger unit that provides flexible suspension of the base unit so that the sensor can follow the inner surface of the pipe wall [75].



Figure 7 Left: basic unit containing two sensors (shown without wear plate). Right: unit with 20 basic units with ceramic wear protection. Each sensor measures ultrasonic (EMAT), MFL, and EC signals [75]

A pipe inspection robot is used to control using a newly developed Ultrasonic Spherical Motor (USM) [76] as the camera driver. To control the rotational direction and to provide strategic control of the kinematics and characteristics of ultrasonic motors. The direction of rotation was defined by the applied voltage phase difference and the rotational speed was changed with frequency [77]. In addition, developed a very small sensing positioning

system using rotary potentiometers. In the control experiment performed using the sensing system, USM shows returnability to the default position of certain places with an accuracy of 1° [78].

A study applied an ultrasonic monitoring system to real-world operation in a hot water supply system. The purpose of this experiment was to study the effectiveness of continuous ultrasonic fault detection in pipes with permanently mounted piezoelectric transducers [79] under varying environmental and operating conditions. The ultrasonic wave detector was shown to be effective in damage testing in laboratory experiments. However, changes in the operating environment produce dramatic changes in the signal [80], and therefore a useful signal-processing approach must distinguish changes caused by the variable of the changes caused by continuous variation.

A pressurized pipe segment [81] was used in a work on a hot water supply system undergoing continual changes in pressure, temperature, and flow rate. The system was located in conditions of mechanical and electrical noise. In addition, field tests-haul, for a period of 10 ms, between the transducer is located approximately 12 mm diameter [82].

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Acoustic Emission (AE) and ultrasound techniques were used for the monitoring of crack initiation and growth in a ratcheting study on straight pipes made of 304LN stainless steel [83] reversed austenite under four-point bending. Ultrasound examination using multiple skip conducted periodically at regular intervals of 25 cycles confirmed the formation of cracks after only 1000 cycles [85]. The end of pipe rupture occurred due to cracks through the whole thickness after 1203 and 1225 cycles at two locations [86]. Upgrading in cycle for the cracks inspection, AE used increased with the cumulative number of cycles, showing a good correlation between the growth of cracks and AE [87].

Electrochemical synthesis of ZnO nanostructures in the presence of ultrasonic irradiation to the upgrading UT with ultrasonic irradiation 10 times faster [88]. Ultrasound is used for the synthesis of a calibrated using hydrophones and acoustic power is obtained. From the results of experiments it was found that ultrasonic irradiation played a role in the synthesis of ZnO nanoparticles [89]. The diameters of ZnO nanoparticles produced in electrolytes were compared and investigated in the absence and presence of ultrasonic irradiation using a UV-visible photo-spectrometer [90].

Then a ZnO layer electrodeposited on ITO glass as the cathode surface in the absence and presence of ultrasonic irradiation was studied by UV-visible spectrometry and photo-field emission scanning electron microscopy (FE-SEM) and the results were compared [91]. FE-SEM micrographs showed that greater growth of nanosheets occurred on the cathode electrode in the presence of ultrasonic irradiation.

A new family of transducers, with a wide radiator has been recently introduced. It consists of various types of transducers designed with an adjustable radiator for specific use in different liquids and multi-phase media [92]. Transducers such as high energy capacity [93], high efficiency, and radiation pattern control.

In addition, their designs incorporate strategies to eliminate or reduce the interaction mode generated at higher power due to their nonlinear behaviour [94]. The introduction of new transducers has contributed significantly to the development some industrial processes in the food and beverage industry, in the environment, and in manufacturing.

5.0 CONCLUSION

Rapid development with infrastructure to provide a short construction period, with the support of building materials easily installed at a cost that does not impose on the number of dependents of a development project. The main ingredient in the construction consists of a steel pile as a measure of the strength of a building. Steel pipes are used as utility materials and also as design elements in the structure. When durable steel is used for a particular exposure period, the effects of corrosion problems will be faced. The importance of monitoring of these steel materials should be taken seriously in order to protect and maintenance need for example the impact on health and the resilience of a building. This study considers matters related to corrosion occurring in water pipes, which is important for clean water supply through pipelines connecting destinations that are either close or far apart. A review of corrosion also has an impact on the development of the oil and gas industry, because when there is no effective method of monitoring there is not only a loss operational but can make environmental hazards. Monitoring methods in the ultrasonic tomography category as objective to study the contribution of the development process of periodic maintenance.

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