FEASIBILITY STUDY OF STRUCTURAL HEALTH MONITORING TOWARDS PIPELINE CORROSION MONITORING: A REVIEW

Shahruddin Mahzan and Muheieddin Meftah Farag Elghanudi
Structural Integrity and Monitoring Research Group, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia
E-Mail: sharudin@uthm.edu.my

ABSTRACT

Corrosion is one of the main causes of failures in onshore or offshore transmission pipelines (both gas and hazardous liquids). The reduction in the number of corrosion incidents in pipelines is strongly desirable regarding to safety and financial reasons. Owners of energy companies, industry trade organizations, and the scientific community have worked to increase pipeline safety and reduce incidents and related costs for many years. In fact, they have made significant improvements to corrosion detection, assessment, and mitigation technology. However, all the current approaches are not sufficient completely. On the other hand there are valuable results in the other engineering fields which have employed structural health monitoring technique in their applications. This paper provides a critical review about the pipeline corrosion monitoring techniques. Moreover, a brief description of Structural Health Monitoring method is discussed for its flexibility and viability for corrosion monitoring in pipeline.

Keywords: pipeline integrity, corrosion, monitoring technique, structural health monitoring.

INTRODUCTION

Importance of pipeline integrity

Pipelines that carry and distribute oil, gas, chemicals, water, steam, petroleum products and other substances are of critical significance for the world economy. The economy of the world is greatly dependent upon a wide network of distribution and transmission pipelines to transport the countries' energy sources. This is due to the single largest part of economic in many countries is the petroleum industry, which includes oil and gas. As the extensive network of pipelines continues to age, monitoring and maintaining its structural integrity and reliability becomes more and more essential to the world's energy requirements. Pipelines are susceptible to a variety of damage and aging defects. Some of the most common causes of failure in pipelines are corrosion, stress cracks, seam weld cracks, material flaws, and externally induced damage by excavation equipment (Popoola *et al.* 2013, John and Neil, 2006).

Importance of corrosion study

As stated in the above section corrosion is one of the main causes of failures in onshore or offshore transmission pipelines (both gas and hazardous liquids). It also is a threat to gas distribution mains and services, as well as oil and gas gathering systems. Corrosion failures can be either leaks or ruptures. Corrosion affects pipeline and accessories made of both metals and non-metals. Pipeline corrosion - and the related catastrophic failures it can cause - costs billions of dollars to the economy. Referring to (U.S. Department of Transportation) Pipeline and Hazardous Materials Safety Administration (PHMSA) has reported that corrosion was responsible for 18 percent of the significant incidents (both onshore and offshore) in the 20 year period from 1988 through 2008 (Figure-1).

Pipelines are subjected to internal and external agents that can cause corrosion affecting their safety, integrity, and profitability. Corrosion causes metal losses that may hamper the supply of energy and could lead to substantial damage to the ecology. In additional words, corrosion is a big problem. It mainly affects pipeline made of metals such as copper, aluminum, cast iron, carbon steel, stainless steel and alloy steel pipes used for buried, underground, submerged or other pipelines. That makes designing and selecting the best available systems and materials for pipelines and their corrosion protection systems an extremely important issue for the oil and gas industry.

Recently corrosion due to its noticeable accidents has become a major concern for the oil and gas industry. Restoring pipelines to safe operating condition is the main goal of all pipeline owners. Detection of pipeline defects as early as possible can eliminate the corrosion dangers. Therefore, accurate monitoring system techniques represent the main solution for this serious problem.

APPROACHES FOR PIPELINE'S CORROSION MONITORING

Most of companies over the world works to establish and implement good techniques for corrosion monitoring. The monitoring procedure signifies the ongoing monitoring of the corrosion process and the measures taken to control it. As a result, operators can evaluate corrosion damage and predict remaining life, reliability and the safety for structures.

VOL. 11, NO. 14, JULY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

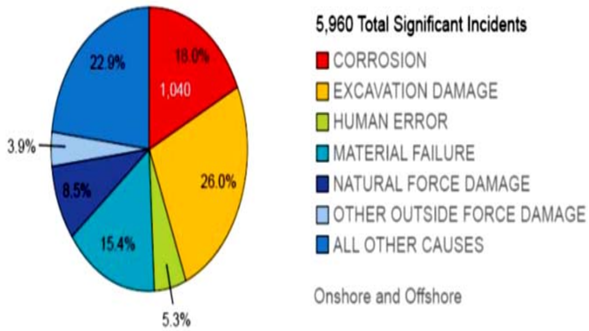

Figure-1. Causes of significant pipeline incidents (1988 – August 2008) -Source (PHMSA).

Hydrostatic testing

Hydrostatic testing involves filling a section of the pipeline with water and pressuring it to a level significantly above the normal operating pressure. The main purpose is to detect and remove joints of pipe that contain defects, such as corrosion pits or cracks, by causing them to leak or rupture without causing an explosion or release of a hazardous liquid and to demonstrate the structural integrity when the pipe passes the test. It also is used to determine whether leaks exist in the pipeline. Hydrostatic tests typically have the lowest direct costs, but the highest associated operational costs and impacts. The direct costs include the costs to isolate the line for testing, purge product from the line, fill the line with water, gather the test data, find and repair any pipe failures, purge the water from the line, dry the line, re-pack the line with product, and return the line to service. Hydrostatic testing requires removing the line from service, perhaps for more than a week, and may require making arrangements for alternative sources to deliver product to downstream customers. Waste disposal costs can also be significant, since hydrostatic test water cannot always simply be discharged to the ground upon completion of the test. Because of service interruptions and water removal difficulties, hydrostatic testing is not used with natural gas pipelines (Tucker Jr, Kercel, & Varma, 2003).

There are two limitations for using of hydrostatic testing to validate integrity of pipelines:

1. Economic drawback:

When a part of a pipeline taken out of service that means loss of service for the period of the test and that will increase the costs.

2. Technical drawback:

The test reveals the weak areas that causing ruptures or leaks; but does not indicate any other zones where active corrosion may be taking place.

Non-destructive evaluation

Non-destructive evaluation (NDE) is used for assessing the integrity of critical structures without destroying the structures. Various NDE methods are available, and the selection of an inspection method depends on the material type and the kind of damage that could occur in the structure. The most common methods which used today to detect corrosion damage and material loss in pipelines are long-range ultrasonic testing and intelligent pigging which includes magnetic flux leakage. Some publications refer to three non-destructive testing technologies being applied for metal loss and crack inspection (Barbian & Beller, 2012), namely magnetic flux leakage, piezo-electric ultrasound and ultrasound using EMAT (where EMAT actually stands for electro-magnetic acoustic transducers).

Long range guided wave ultrasonic testing

Long range guided wave ultrasonic testing is a non-invasive method used for the detection of both internal and external corrosion and erosion in thermally insulated. Coated and buried pipelines, corrosion under pipe supports and hidden welded joints. Use is made of low frequency guided waves to detect corrosion, erosion and material loss in the pipelines being tested. A unit comprising three rings of piezoelectric transducers is clamped around the pipe and ultrasound is sent first in one direction along the pipe and then in the other direction. Figure-2 demonstrates an assembly of guided wave inspection in pipeline monitoring (Wikipedia, 2015). The signal obtained is similar to a conventional ultrasonic A-scan, where the horizontal axis represents distance along the pipe and the vertical axis represents signal amplitude, which is indicative of the severity of the corrosion.

Although propagation distances may vary according to pipe geometry, contents, coating, insulation and general condition, in ideal conditions, it is not unusual that a range of up to 30 m in either direction from the transducer belt can be inspected. However care must be taken as this distance is substantially reduced for buried pipelines and pipelines with heavily attenuating coatings. The technique is equally sensitive to internal and external corrosion. The principal advantage of this technique is that it provides 100% initial screening coverage, and only requires local access to the pipe surface (i.e. removal of a small amount of insulation) at those positions where the transducer unit is to be attached. It is suitable for use on pipe diameters above 50 mm (2.0") and on wall thicknesses up to 40mm.

Figure-2. A technician performs a guided wave test (Wikipedia.com).

VOL. 11, NO. 14, JULY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Intelligent pigging

Pipeline pigs are intrusive devices that are inserted into and travel throughout the length of a pipeline driven by product flow. They were originally developed to remove deposits which could obstruct or retard the flow through a pipeline. Nowadays pigs are used during all phases in the life of a pipeline for cleaning purposes and for internal inspection.

The pigs used as in-line inspection tools provide information on the condition of the line as well as the extent and location of any problems. Intelligent pigging uses ultrasonic thickness measurement and magnetic flux leakage methods to determine areas of corrosion, pitting, erosion and cracks. As a result, the magnetic flux leakage technique leads to a substantial time and financial savings, which has been used for the testing of hundreds of kilometers of piping in the desert. The evaluation of the data has shown that a testing rate of 1 km per day was easily achieved - a rate far greater than that achievable through conventional wall thickness measurement.

There are many drawbacks of NDE methods as follows:

- Pipeline requires inspection at scheduled intervals that requiring the structure to be shut down and go out of service throughout the period of inspection.
- NDE methods need specialized and expensive equipment, structures often need to be dismantled to inspect inaccessible components, and the inspection needs to be conducted by qualified trained personnel.
- Intelligent technique cannot used for small diameter pipes and for zones where elbows exist.
- All those requirements impose large costs to the industry.
- Moreover, scheduled inspections may not be adequate or timely for detecting impending risks due to unexpected dangerous situations.

MOTIVATION FOR STRUCTURAL HEALTH MONITORING

Almost all private and government industries want to detect damage in their products as well as in their manufacturing infrastructure at the earliest possible time. Such detection requires these industries to perform some form of SHM and is motivated by the potential life-safety and economic impact of this technology (Farrar & Worden, 2012).

All the above safety drawbacks of current techniques have led to numerous accidents in oil and gas transportation industry. So far, the related specialists still consider the current approaches which used in the pipeline structure monitoring are not sufficient to give good information at appropriate time. They believe that knowing the integrity of in-service structures on a continuous real-time basis is a very important objective for manufacturers, end-users and maintenance teams. Structural Health Monitoring (SHM) is the suggested solution because it is a technique which is more reliable and economical for the monitoring of pipeline system.

Actually, SHM have the potential to:

- allow an optimal use of the structure, a minimized downtime, and the avoidance of catastrophic failures,
- gives the constructor an improvement in his products,
- drastically changes the work organization of maintenance services by:
  - aiming to replace scheduled and periodic maintenance inspection with performance-based (or condition-based) maintenance (long term) or at least (short term) by reducing the present maintenance labour, in particular by avoiding dismounting parts where there is no hidden defect;
  - drastically minimizing the human involvement, and consequently reducing labour, downtime and human errors, and thus improving safety and reliability.

Definition of structural health monitoring

There have been several authors who define and explain SHM. Structural health monitoring is an "integration of sensing and possibly also actuation devices to allow the loading and damaging conditions of a structure to be recorded, analyzed, localized, and predicted in a way that non-destructive testing becomes an integral part of the structure and material", as defined in the book of Encyclopedia of Structural Health Monitoring (Boller, Chang, & Fujino, 2009). Also SHM is defined as the process of establishing some knowledge of the current physical condition of a structure (Rao, Bhat, Murthy, Madhav, & Asokan, 2006). The essence of SHM technology is to develop autonomous built-in systems for the continuous real time monitoring, inspection, and damage detection of structures with minimum labor involvement with a high level of confidence and reliability. According to (Chung, 2001), SHM refers to the monitoring of the integrity of a structure for the purpose of hazard mitigation, whether the hazard is due to live load, earthquake, ocean, waves, fatigue, heat, ageing and other factors. SHM has the ability to perform its intended function in the light of the inevitable ageing and degradation resulting from operational environments (Sohn, 2007). A typical health monitoring system is composed of a network of sensors that measure the parameters relevant to the state of the structure and its environment.

SHM can be defined as the system that has the potential to continually monitor the health of a structure through strategically located sensors coupled with monitoring technology enabling remote interrogation of the sensors (Herszberg, Bannister, Li, Thomson, & White, 2007). Most of the authors mentioned that a major challenge for the development of robust SHM system is all about the accurate interpretation of sensor measurement in terms of physical changes in structure. The summary of the concept of SHM is clearly presented by (Herszberg *et al.*, 2007), as demonstrated in Figure-3.

Objectives of structural health monitoring (SHM)

Structural health monitoring (SHM) is intended to improve safety and reduce maintenance costs by providing real time information about the structure's integrity and warnings about impending hazards. The integration of SHM systems within industrial structures would change current safety and inspection practices, eliminating the need for regularly scheduled inspections and migrating towards condition-based inspections. As the principles of SHM and its applications is not only in the inspection of existing infrastructure but also lifetime monitoring of future construction projects (Spencer Jr & Cho, 2011). The main goals of SHM are to:

- maximize the life of structure,
- minimize the whole life cost by reducing the number of scheduled non-destructive examination (NDE) services,
- provide additional safety measures.

Mechanism of (SHM)

A common approach to implementing SHM is to collect signals from the current state of a structure and compare them with those previously taken of the pristine condition (baselines). Changes between the current data and the baselines are attributed to damage in the structure (Dutta, 2010).

A SHM system uses a network of sensors that are permanently surface mounted or embedded in the structure. Those sensors measure physical quantities that are dependent on the structure's properties (mass stiffness and damping). Detecting changes in the measured values indicates the possible presence of damage. There are five different levels for damage identification in an SHM system:

Level 1: Existence of a damage in the system.
Level 2: Location of the damage.
Level 3: Type of the damage.
Level 4: Severity of the damage.
Level 5: The useful remaining life.

Identification of the type and extent of the damage requires knowledge of the failure modes of the structure, and how the sensing modality interacts with each failure mode. Also, the type of the structural part can introduce critical damage areas. For instance, stiffeners in a composite structure can produce delamination, fasteners in metallic structures can introduce stress concentrations or crack initiation sites, and adhesively bonded parts can be peeled. Locating damage depends on the type of sensing modality, sensor type, and the number of sensors. Prognosis relates the estimated defect type and extent to the ultimate strength of the material in order to predict the remaining useful life.

APPLYING SHM SYSTEM TO PIPELINES

Guided waves method

A SHM system must be capable of continuously monitoring the pipeline structure, even while it is in service. Accordingly, the sensor array for the SHM system must be permanently mounted to the structure, making the ideal location of the sensor array on the exterior of the pipeline so that it can remain in service during testing. In order to monitor the entire length of the pipeline, the sensor array must be capable of sensing damage over a long range. If the sensor array is mounted to the exterior surface of the pipeline and portions of the pipeline are installed underground, then sending a testing mechanism down the length of the pipe is not feasible. Therefore, a new method of testing is required to perform the damage detection.

One such testing method which is a solution for developing a SHM system for a pipeline is the use of ultrasonic, guided waves. The advantage of guided waves is the ability of propagation over great distances. This offers innovative possibilities for the investigation of large or difficult to access constructions. The testing method can be helpful in a broad variety of applications. It is useable for the characterization of plane or cylindrical, thin-walled surfaces of metal or fiber laminated materials. Particularly the investigation of aircraft wings and other aerospace components as well as the investigation of pipelines are addressed fields of application (Köppe, Bartholmai, & Prager, 2012).

Damage detection with guided waves involves exciting a pulse of ultrasonic waves in the wall of a pipe with an actuator. The waves are sent down the length of the pipe and received by a sensor at a second location on the pipe. In general, changes in the features of the wave propagation are used to monitor the pipeline for damage. Therefore, an extended length of the pipeline can be monitored using actuators and sensors which are permanently located at discrete locations along the length of the pipeline. As previous research has shown, guided wave techniques are extremely successful at detecting damage in the main body of a pipeline system.

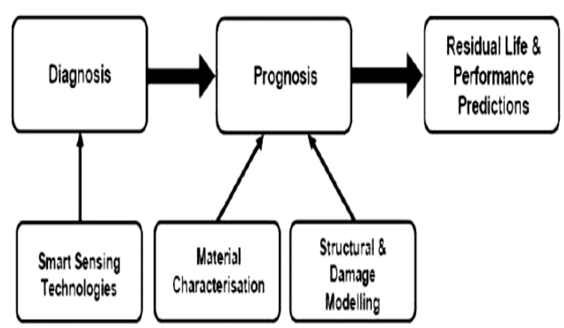

Figure-3. Integrated structural health monitoring approach (Herszberg *et al.*, 2007).

Impedance method

Guided waves are not very efficient at detecting damage in flanged joints, so a second testing method is needed to ensure the integrity of the entire pipeline system. Impedance methods have been implemented in pipeline research for detecting damage in flanged joints (Park, *et al.* 2001).

These methods involve monitoring the mechanical impedance of a structure at relatively high frequencies. The use of a relatively high frequency range makes the impedance measurements more sensitive to local changes in the system than to global changes. Therefore, the impedance methods can be used to detect and locate damage to the flanged joints of a pipeline system. In particular, impedance methods are extremely appealing for the SHM system to pipelines because the exact same sensor array can be used for both guided wave and impedance methods. This dual use implies that only a single sensor array is required to implement both methods, enabling the proposed SHM system to effectively monitor the structural integrity of the entire pipeline.

Advantages of SHM as compared to other techniques

The implementation of a SHM system with pipelines addresses each of the issues with Hydrostatic testing and NDE described above. The most significant advantage is that the sensor array for a SHM system could be permanently installed on the pipeline structure. With a permanent installation, the pipeline operator could likely perform damage detection measurements as often as he wishes with much less financial repercussions. Therefore, the potential of a short time duration event going undetected would be much less likely. In the event of an earthquake or other natural disaster, the operator could check the structural integrity of the pipeline system immediately following the event. Accordingly, the operator could potentially take all severely damaged pipelines out of service before a leak could accumulate sufficient material to cause an explosion.

In addition, a permanently installed system would enable the operator to perform an inspection following any excavation project in the vicinity of a pipeline. A permanent installation would also eliminate the need to perform excavation in order to obtain direct access to the pipeline. If the sensor array was permanently installed on the pipeline structure, then the need to obtain temporary access to the pipe would no longer exist, leading to reduced costs. Finally, the SHM system would have fewer limitations regarding the geometry of the pipeline. In fact, the SHM method could potentially be adapted to applications outside of transmission and distribution pipelines, such as chemical plant pipe networks and the tubes in industrial heat exchangers (Alleyne, Lowe, & Cawley, 1996)

CONCLUSIONS

Monitoring of pipeline integrity is vital aim of all energy companies. All the used techniques could not resolve the problems that related to monitoring of pipeline corrosion defects (safety, economy), SHM method have got good results in the fields of aerospace and civil engineering. In general, SHM is an emerging technology that can be defined as continuous, separate, real time, in-service monitoring of the physical condition of a structure by means of embedded or attached sensors with minimum manual intervention. Simply put, SHM provides the ability of a system to detect adverse changes within a system's structure to enhance reliability and reduce maintenance. SHM technology has many elements that make it a potential 'grand challenge' for the engineering implementation. Significant researching works have been done to develop this technology. In all likelihood the development and applying of this technology still need to multi-disciplinary research efforts in many fields such as structural dynamics, signal processing, motion and environmental sensing hardware, computational hardware, data telemetry, smart materials and statistical pattern recognition, as well as other fields yet to be defined. Without such a focus in mind, these technologies may not evolve in a manner that is not necessarily optimal for solving the SHM problem. Finally, the progress of SHM is not easy and that cannot be solved in the immediate future. Like so many other technology fields, improvements in SHM will most likely come in small increments requiring hardworking, focused and coordinated research efforts over long periods of time.

ACKNOWLEDGEMENTS

The authors would like to thank to Universiti Tun Hussein Onn Malaysia for providing the environment to work on this project.

REFERENCES

[1] Alleyne, D., Lowe, M., & Cawley, P. (1996). The inspection of chemical plant pipework using Lamb waves: Defect sensitivity and field experience. Review of Progress in Quantitative Nondestructive Evaluation, Springer, pp. 1859-1866.

[2] Barbian, A. and Michael, B..(2012), In-line inspection of high pressure Transmission Pipelines: state-of-the-art and future trends, Proceedings of the 18th world conference on nondestructive testing, Durban, South Africa.

[3] Boller, C., Chang, F.-K., & Fujino, Y. (2009). Encyclopedia of structural health monitoring: John Wiley.

[4] Chung, D. (2001). Structural health monitoring by electrical resistance measurement. Smart Materials and Structures, 10(4), pp. 624.

[5] Dutta, D. (2010). Ultrasonic Techniques for Baseline-Free Damage Detection in Structures, PhD Theses, Carnagie Mellon University.

[6] Farrar, C.R., and Worden, K. (2012), Structural health monitoring: a machine learning perspective. John Wiley & Sons.

[7] Herszberg, I., Bannister, M. K., Li, H. C., Thomson, R. S., & White, C. (2007). Structural health monitoring for advanced composite structures.

Proceedings of the Sixteenth International Conference on Composite Materials. Kyoto, Japan.

[8] John A. B. & Neil G. T., (2006), “External Corrosion of Oil and Natural Gas Pipelines”, ASM Handbook, Volume 13C, Corrosion: Environments and Industries (#05145), 1015 – 1026.

[9] Köppe, E., Bartholmai, M., & Prager, J. (2012). Device Concept for the Generation of Guided Waves for Early Damage Detection. Procedia Engineering, 47, 1185-1188.

[10] Park, G., H.H. Cudney, D.J. Inman. (2001), “Feasibility of using impedance-based damage assessment for pipeline structures.” Earthquake Engineering and Structural Dynamics. Vol. 30: 1463-1474.

[11] Popoola, L.T, Grema, A.S., Latinwo, G.K., Gutti, B., & Balogun, A.S. (2013), “Corrosion problems during oil and gas production and its mitigation”, Int. Journal of Industrial Chemistry. 4:35.

[12] Rao, M. B., Bhat, M., Murthy, C., Madhav, K. V., & Asokan, S. (2006). Structural health monitoring (SHM) using strain gauges, PVDF film and fiber Bragg grating (FBG) sensors: A comparative study. Proceeding of National Seminar on Non– Destructive Evaluation, Indian Society for Non-Destructive Testing, Hyderabad.

[13] Sohn, H. (2007). Effects of environmental and operational variability on structural health monitoring. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365(1851), 539-560.

[14] Spencer Jr, B. F., & Cho, S. (2011). Wireless smart sensor technology for monitoring civil infrastructure: technological developments and full-scale applications. Proceedings of the World Congress on Advances in Structural Engineering and Mechanics (ASEM’11).

[15] Tucker Jr, R. W., Kercel, S. W., & Varma, V. K. (2003). Characterization of gas pipeline flaws using wavelet analysis. Quality Control by Artificial Vision.

[16] https://en.wikipedia.org/wiki/Guided_wave_testing