CAAP Quarterly Report

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Project Title: Distributed Fiber Optic Sensor Network for Real-time Monitoring of Pipeline Interactive Anomalies

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For quarterly period ending: 12/29/2019

Business and Activity Section

(a) Contract Activity

Discussion about contract modifications or proposed modifications

None.

Discussion about materials purchased

None.

(b) Status Update of Past Quarter Activities

High level summary of the work performed for the reporting period.

In the first quarter, the university research team partially completed Task I and Task IV of the above mentioned project, including a kick-off meeting with PHMSA program managers on Nov. 14th, 2019, and a literature review on related topics, in addition to hiring two graduate students and two undergraduate students for the project and an outreach event to primary school students in New Jersey on Nov. 21th, 2019 to expand the educational impact of this project.

(c) Cost share activity

None.

(d) Task I: Developing and Characterizing Distributed Fiber Optic Sensors

In Task I, we aim to develop and characterize distributed fiber optic sensors under (i) deformation and (ii) corrosion, (iii) characterize the acoustic waves due to excavation, and (iv) conduct a sensitivity study. Four subtasks will be conducted. Each of the first three subtasks will focus on investigating an individual anomaly type. The fourth subtask investigates the effects of fiber type and installation technique on the measurement of different anomalies and their interactions.

In the first quarter, two activities were performed for Task I, including (1) a kick-off meeting with PHMSA program managers on Nov. 14th, 2019 to ensure that the project objectives and tasks follow the DOT and PHMSA's expectations and guidelines; (2) a thorough literature review performed on related topics of the proposed research, which included but not limited to the existing pipeline defects detection techniques, fiber optic sensors for condition assessment, and their limitations and advantages.

Detailed discussion and descriptions for the following:

1. Background and Objectives in the 1st Quarter

1.1 Background

A transportation pipeline network of about 2.6 million miles delivers the energy products that the American public needs, in order to keep its homes and businesses running. While various measures have kept the pipeline failure rate low, incidents continue occurring and causing fatality, injures, and significant revenue loss. Recent investigations conducted by National Transportation Safety Board (NTSB) have shown that interactive threats and anomalies play important roles in pipeline incidents. There is an urgent need to develop effective nondestructive evaluation technologies to detect and analyze interactive anomalies. The current practice of pipeline anomaly detection mainly relies on the use of smart pigs that are only performed as scheduled or needed, which may have delayed actions to anomalies, operation downtime, and significant revenue loss. An alternative to monitor a pipeline in real time is to use field sensors installed on pipelines, such as ultrasonic or point fiber optic sensors. However, the use of point sensors requires a large quantity of sensors for a long distance, resulting in high cost and intensive labor efforts for long-term condition monitoring.

The overarching goal of this research is to pave a path which may transform the current pipeline anomaly detection technologies to a distributed fiber optic sensor network for real-time detection, localization, and quantification of interactive anomalies of pipelines, thus improving the pipeline safety and management. The distributed fiber optic sensor network will seamlessly integrate multifunctional distributed and point fiber optic sensors and provide fully distributed measurement along the pipeline. A continuous optical fiber will serve as both the transmission line and distributed sensor based on light scatterings in the optical fiber. Along the pipeline, the location of an event is determined by measuring the time of flight of the backscattered light signal. Point fiber optic sensors (e.g. fiber Bragg grating sensors) will be incorporated at critical locations for improving the measurement accuracy and reliability of the distributed fiber optic sensor network. Both the distributed and point fiber optic sensors will measure multiple pipeline anomalies and their interactions that are associated with the integrity of the pipeline. To exemplify the functionality of the proposed sensor network, this project will demonstrate the sensor network in monitoring the spatial distribution of cracks, dents, corrosion, and excavation along the pipeline. The sensor network will be characterized under individual anomaly type and tested under interactive anomalies. Data processing programs will be developed for real-time sensor data analysis. Different co-existing anomalies will be distinguished by analyzing the sensor data using the data processing programs. Anticipated outcomes will improve not only the safety but also the management of pipelines through providing real-time information of the locations, types, and severity of the anomalies. In the first quarter of this project, literature review was expected to direct the research to the right direction for sensor development and testing in future quarters.

1.2 Objectives in the 1st Quarter

In the first quarter, we aimed to effectively communicate with PHMSA personnel to understand the specific requirements. More specifically, there are two sub-objectives as aligned in the proposal:

(1) Kick-off meeting with PHMSA personnel to ensure that the project objectives and tasks follow DOT and PHMSA's expectations and guidelines.

(2) Literature review performed on related topics of the proposed research, which included but not limited to the current pipeline defects detection methods and their limitations and advantages.

(3) Mechanical testing of optical fibers to understand the load-carrying capability and deformability of the optical fibers that will be used as distributed sensors.

2. Results and Discussions

2.1 Kick-off Meeting

On Nov. 14th, 2019 (2:00-3:00 pm), a video kick-off meeting was conducted between the PHMSA program managers and the research team. The two PIs, Dr. Bao and Dr. Huang, attended the kick-off meeting. A web presentation was made to the PHMSA program managers, including questions, answers, and discussions.

2.2 Literature Review

A thorough literature review was performed on existing pipeline defects detection methods and practices. Focus is placed on understanding the strengths and weaknesses of the existing methods, and analyze the challenges of the existing methods in addressing interactive defects detection problems. The detailed reviews are provided below. As the project moves forward, more in-depth review and discussions will be conducted.

(1) Introduction

Pipelines convey fuels (fossil fuels, gases, chemicals and other essential hydrocarbon fluids), electric power, telecommunications, transportation, waste disposal, and water supply that serve as assets to the economy of the nation and security of modern communities [1]. It has been shown that pipeline networks could be considered as the most preferred method of transportation of energy products, water etc. through economic, safety, and environmental point of view [2]. As shown here, the total existing worldwide length of cross-country pipelines is truly phenomenal. On a worldwide basis, existing pipelines for all commodities run over 2 million miles (3.2 million km), and the estimated deaths due to accidents per ton-mile of shipped petroleum products are 87%, 4% and 2.7% higher using truck, ship and rail, respectively, compared to using pipelines [3]. With pipelines being the safest, costliest, largest and most widely installed component of the infrastructures, they also bear the highest possibility of suffering damage and the chance of pipeline failures accidents increases in decades from both artificial and natural causes [4]. Incidents of pipeline failure can result in irreversible damages which include serious ecological loss, human casualties and financial extreme environmental pollution, particularly when the leakage is not detected in a timely way. According to the US Pipeline & Hazardous Materials Safety Administration (PHMSA, 2019), there were more than 11,900 pipeline incidents in the U.S. in the past 20 years, which costed nearly $8.4 billion, killed over 300 people, and caused over 1300 injury (https://portal.phmsa.dot.gov/analytics/saw.dll?Portalpages) [5].

Unexpected pipeline failure can occur when the time dependent integrity threats are coupled with stable anomalies. ASME B31.8S standard identified nine primary threat conditions, which fall into three categories: time-dependent threats (external, internal and stress corrosion), stable threats (manufacturing, fabrication/construction and equipment), and time-independent (third party/mechanical, incorrect operations and environment-related/outside forces) [6].

Historical pipeline failures indicate that there are multiple factors that lead to pipeline failure [7]. Individual threats can each be at "acceptable" levels but when overlaid result in a significant threat to the pipeline or even a failure, there could be circumstances when two or more anomalies threats can occur coincidentally and interacting with each other (Figure 1). Actually, many pipeline incidents are the result of multiple and interacting anomalies, not a single threat.

Figure 1. Concept of pipeline failure due to interactive anomalies [8].

Furthermore, "coincident anomalies" result in a likelihood of damaging and failure greater than that due to either anomaly individually or merely the superposition of the anomalies [7, 8]. An example of such an interaction is earth movement exacerbating construction-related imperfections such as wrinkle-bends or certain vintages of girth welds. Either of these two conditions, absent the other, may not be a significant threat to pipeline safety. However, when they are both present at the same location, the resulting condition could be a concern [9]. Another example is that, the loss of corrosion protection, meaning a combination of aging coating, aggressive environment, and rapid corrosion growth that may lead to a failure. This type of failure is not simply a corrosion failure, but a corrosion control system failure. Similar observations can be drawn for failures due to external interference, stress corrosion cracking, etc. (Cosham and Hopkins, 2002) [10]. There are also examples of time-independent and time-dependent threats that may interact with resident threats on most pipelines include [11]:

a) Wall loss due to external corrosion and/or internal corrosion can begin at locations that have manufacturing imperfections or have had previous mechanical damage

b) Flooding with construction defects

c) External corrosion and latent third-party damage

d) Stress corrosion cracking at bottom side dents and/or at narrow axial external corrosion

e) Fatigue at defects

Based on the above statistics, it is difficult to totally eliminate pipeline incidents, because there are diverse causes of incidents [12]. However, in order to reduce the impacts of pipeline incidents on society, it is important to continually monitor pipelines for timely detection or prediction of breaches of integrity (i.e., leakage, spills and blockage), as early detection of conceivable threats will allow quick responses to minimize damage and maintenance pipelines properly. Hence, it is possible to reduce the loss rate, injuries and other serious social and environmental consequences due to the pipeline failures [13].

A brief survey of various pipeline integrity detecting strategies, based on integrity management (IM) regulations, applied on pipelines is provided. The integrity management (IM) regulations allow four types of pipeline assessment methods [14]:

i. In-line Inspection (ILI): ILI is an internal pipeline inspection technique that uses magnetic flux leakage, ultrasound, eddy current, or other sensing technology to locate and characterize indications of defects, such as metal loss or deformation in the pipeline. The sensor is mounted on a device (known as a "smart pig"), which is inserted into the pipeline segment between a launching station and a receiving trap. The smart pig moves through the pipe, scanning the pipe for specific types of defects. Pipeline segments that can accommodate ILI tools are considered "piggable". Different sensors have been used to detect different defects [15].

ii. Pressure Testing: A pressure test can be used as a strength or leak test. A common type of pressure test is a hydrostatic test, which involves taking the pipeline out of service and pressurizing a section of pipe with water to a much higher percentage of the pipe material's maximum design strength than the pipe will ever operate at with natural gas. This verifies the capability of a pipeline to safely operate at the maximum allowable operating pressure and can reveal weaknesses that could lead to defects and leaks in the pipe. Pressure testing of pipelines is designed to find critical seam defects (as well as other defects caused by corrosion, stress corrosion cracking, and fatigue) by causing the pipe to fail at these critical defect locations [16].

iii. Direct Assessment: Direct assessment relies on the examination of the pipeline at pre-selected locations to evaluate a pipeline for external corrosion, internal corrosion, or stress corrosion cracking threats. Most of the pipeline segment being inspected is usually not directly examined. Direct assessment uses multiple steps (four steps for external and internal corrosion, and two steps for stress corrosion cracking). For example, for external corrosion direct assessment, the steps are (NACE 2008): pre-assessment (the operator determines the feasibility of external corrosion direct assessment, determines external corrosion direct assessment regions, and selects tools for indirect inspection), indirect inspection (the operator conducts above-ground inspections, such as a close interval survey, to identify and classify indicators of corrosion and pipe coating defects), direct examination (the operator excavates the pipe at selected locations to measure actual corrosion damage), and post-assessment (the operator determines reassessment intervals and evaluates the effectiveness of the external corrosion direct assessment process). This method requires the identification of regions within the pipeline segments for excavation and direct examination. Therefore, although a pipeline segment may be inspected with direct assessment, only a small sub-segment is directly examined [17].

iv. Other Technologies: These technologies include methodologies that follow performance requirements with documentation or methods that are industry-recognized, approved, and published by an industry consensus standards organization. A staggering amount of different technologies are available and are being developed for inspection and monitoring of pipelines, such as sensor technologies, which cover a wide range of physical principles, including electrical, optical, radiographic, chemical, and acoustic domains. [18].

Methods described above have been used successfully to prevent, detect, and mitigate the pipeline threats individually, but the same level of guidance is not as readily available for real-time monitoring of interactive anomalies [19]. Most methods are focused on dealing with threats independent on each other, and only examines a small part of pipeline segment, which may result in overlooking the potentially more damaging effect of interactive anomalies, the result of which is more damaging than either of the individual threats themselves [20, 21]. For example, ILI tools can only consider "piggable" pipeline segments, which means not all pipelines contain a suitable ILI tool launcher and/or receiver with considerations of barred tees, bore restrictions, multi-diameter, etc. [22]. Another problem is that the typical pipeline segment is roughly 50 to 100 miles long. Some are much longer, extending over many hundreds or even thousands of miles. Therefore, it is a challenge for ILI to realize real-time monitoring of every segment to detect and locate leaks or spills, due to the limitation of pig speed [23]. Moreover, intelligent pigs require a clean pipeline to function correctly, which means debris or obstruction in the line could lead to a stuck pig [24]. At the same time, there are weaknesses of pressure testing and direct assessment: pressure testing is a kind of destructive method; direct assessment involves in multiple steps and only examines a small sub-segment of pipeline [25, 26].

In the first quarter, we reviewed promising inspection and monitoring technologies of real-time monitoring for pipeline interactive anomalies, such as fiber optic sensors [27,28], acoustic emission [29,30], ultrasonic [31,32], ground penetration radar [33,34], infrared thermography [35,36], etc. Research gaps and future research issues that required attention in the field of real-time monitoring for pipeline interactive anomalies are discussed.

(2) Promising real-time monitoring methods for interactive anomalies

In the literature review, a brief survey of various promising inspection and monitoring strategies, based on different working principles and approaches, applied on real-time monitoring for pipeline interactive anomalies is provided. These methods have been classified in various frameworks. Some authors have classified them into two categories: hardware and software-based methods [37,38]. Some authors led to the classification into three major groups: namely direct methods, indirect methods and other technologies based on technical nature [39]. In this project, we classify different methods based on different working principles: electromagnetic, acoustics and vibrations, robots and fiber optic sensors [40]. A detailed classification of these methods is shown in Figure 2.

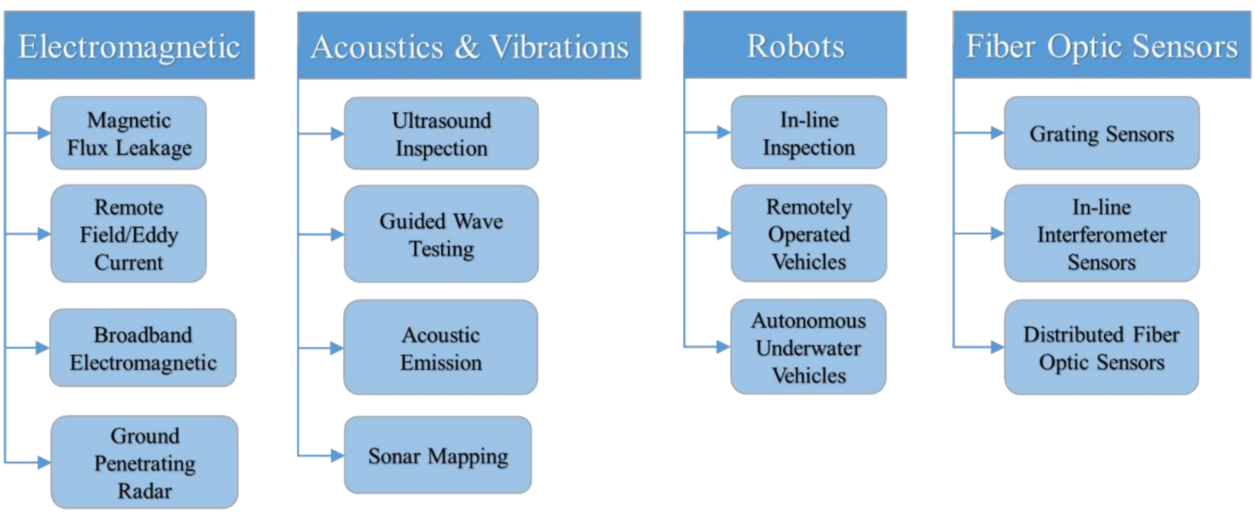


Figure 2. Flow chart of real-time monitoring methods for interactive anomalies.

The following sections attempt to cover the most commonly used sensor technologies while also including recent research into sensor advancements. The review begins with sensors that rely on electromagnetic phenomena. Thus, this section focuses on magnetic flux leakage (MFL), eddy current sensing, broadband electromagnetic, and ground penetrating radar (GPR). Then, the review focuses on the inspection technologies that rely on acoustics and vibrations, including ultrasonic inspection, guided wave testing (GWT), acoustic emission (AE) and sonar mapping, respectively. In the section "Robots", the review covers in-line inspection, remotely operated vehicles (ROV), and autonomous underwater vehicles (AUV), which shift gears toward inline inspection and underwater robotic vehicles, respectively. The operational principle, strengths and weaknesses of these methods are discussed in the subsequent sections.

(2.1) Electromagnetic method

(2.1.1) Magnetic flux leakage (MFL)

MFL method uses strong, powerful magnets to induce a saturated magnetic field around the wall of a ferrous pipe. If the pipe is in good condition, a homogeneous distribution of magnetic flux is obtained; however, anomalies will alter the distribution of the magnetic flux. The damaged areas cannot support as much magnetic flux as undamaged areas, resulting in an increase of the flux field at the damaged areas [41]. In other words, a damaged pipe causes a flux leakage. This aberration is referred to as the leakage, hence the name magnetic flux leakage, as shown in Figure 3. As will be discussed, the properties of the leaked magnetic field can provide information about the cause of leakage. By scanning the surface systematically, defects in a pipeline can be detected and mapped out. Depending on the application, three different methods for magnetizing the pipe wall are available: direct current (DC) magnetization, alternating current (AC) magnetization, and permanent magnets [42].

AC magnetization in an external circuit is used to generate an oscillating magnetic field across the pipe surface. Due to its oscillating nature, eddy currents, which produce an opposing magnetic field, will be generated (i.e. the "skin effect"). The skin effect limits the magnetic field to a smaller area and also prevents the field from penetrating deeper into the pipe wall. However, devices based on AC current are readily available, low cost, and easy to control. Due to low surface penetration, AC magnetization is mainly used for surface and near-surface inspection.

In DC magnetization, a unidirectional magnetic field is generated and can penetrate more than 10 mm into a pipe surface. As the residual magnetic field may interfere with other electronic components (e.g. using other electronic sensors in the future) or with any welding process (e.g. before the pipe segment is welded to the pipeline during the pipe-laying process), demagnetization of the pipe wall may be needed after using DC magnetization.

Permanent magnets are the most commonly used method for pipe wall magnetization. The penetration of magnetic fields generated by permanent magnets is similar to those of DC magnetic fields. The high energy density of rare earth magnets allows for small-sized magnets and coupled with the fact that no power is needed, make permanent magnets popular for MFL.

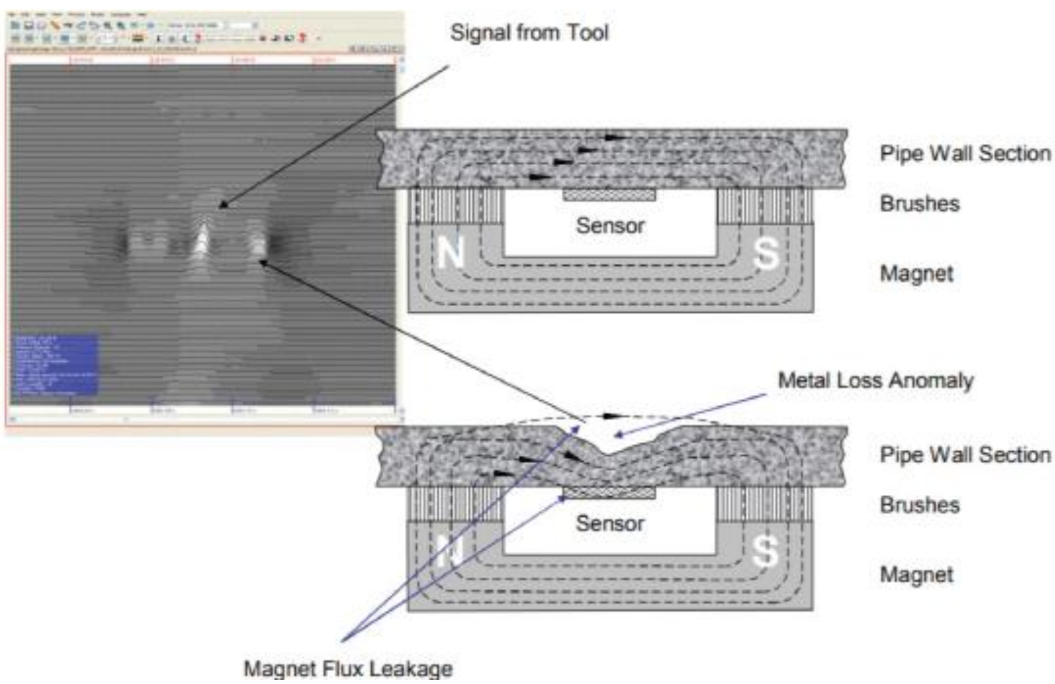


Figure 3. Principle of magnetic flux leakage [43].

Although primarily used to detect corrosion, MFL tools can also be used to detect features that they were not originally designed to identify [44]. The modern High Resolution MFL tool is proving to be able to accurately assess the severity of corrosion features, define dents, wrinkles, buckles, and, in some cases, even cracks. There are cases, where large non-axial oriented cracks have been found in a pipeline that was inspected by a magnetic flux leakage tool [45-47].

Advantages of MFL sensors in real-time monitoring of pipeline interactive anomalies is that the testing mode is non-invasive and accurately detects any kind of metal loss in a pipeline including cracks, corrosion, and the thinning of pipe walls [48]. Owing to their robust magnetic and sensor designs, MFL inspection devices ensure an excellent anomaly detection performance, even under harsh operating conditions [49].

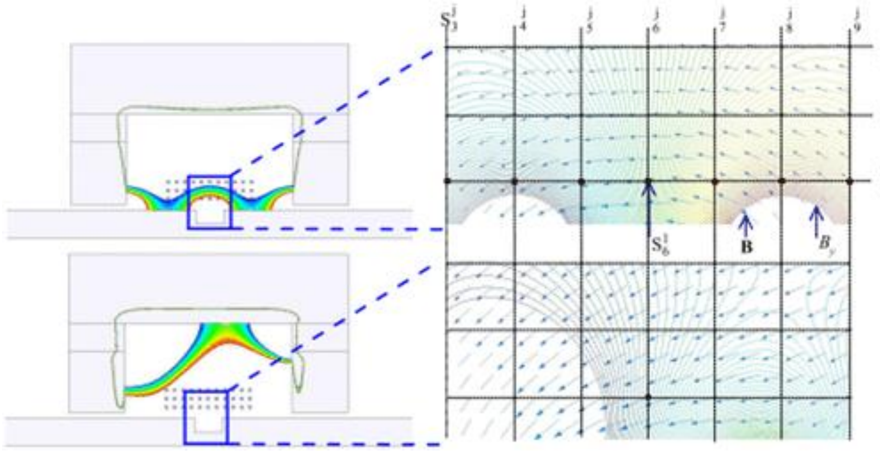


Figure 4. Distribution of magnetic flux lines at two different speeds for the same defect.

Despite the advantages that make MFL a popular tool for pipeline inspection, there remain some drawbacks that are still subjects of research:

a) MFL is usable only on ferrous pipes and requires access to the surface of the pipe [50].

b) MFL measurements are influenced by the dimensions of the MFL tool, including the distance between magnet poles, speed of the pig, and quality of the brushes [51]. Figure 4 shows a recent study that attempts to capture defects induced MFL as the tool moves at different speeds [52].

c) External factors such as the strength of magnetic field in the pipe wall, reading experience, and debris in pipeline affect the MFL readings [53]. The strength of the applied magnetic field should be adjusted based on the pipe wall, with thick walls requiring stronger fields in order to reach full saturation. Reading MFL signals requires skill and experience. The distance of MFL tool to surface can also be affected by debris, further complicating interpretation of measurements.

d) The orientation of the defect along the pipe also affects the sensitivity of the MFL tool in detecting defects [54]. If the magnetic field direction is parallel to the defect shape, the magnetic field may not be deflected adequately enough for the tool to detect the anomaly (Figure 5).

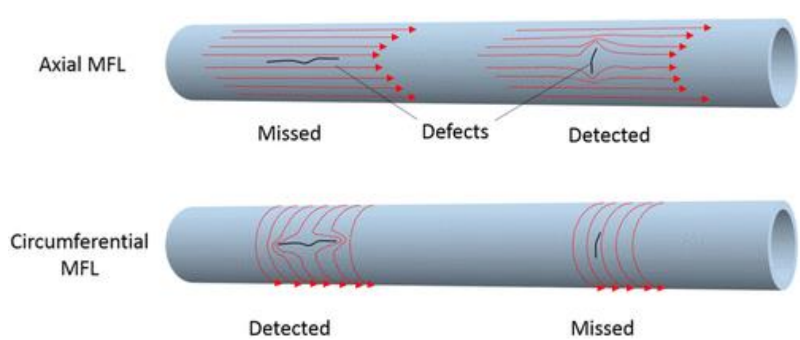


Figure 5. Orientation of the magnetic field is important depending on orientation of the defect.

(2.1.2) Eddy current sensing

Eddy currents are another common non-destructive testing tool and are useful for crack detection and material thickness measurements. Eddy currents are circular patterned electrical currents due to changes of a magnetic field passing perpendicularly to the conductor. A varying magnetic field can be created by passing an alternating current into a coil. When the varying magnetic field penetrates the target inspection surface, induction occurs, and eddy currents are generated in the surface material. Due to their circular path, the eddy currents in the pipe wall produce a secondary magnetic field which is opposed to the primary field inducing it. Anomalies in the pipeline, such as cracking or corrosion, leads to a change of flow direction of eddy current, and then causes disruptions in the eddy current (Figure 6). Based on this effect, anomalies can be detected, and their properties determined by evaluating the amplitude and the phase shift between the input and output signals [55]. Several different methods are available in inspecting pipelines: conventional eddy current, remote field eddy current (RFEC) [56], pulsed eddy current (PEC) [57], Lorentz force eddy current (LEC), magnetic eddy current (MEC), etc. [58].

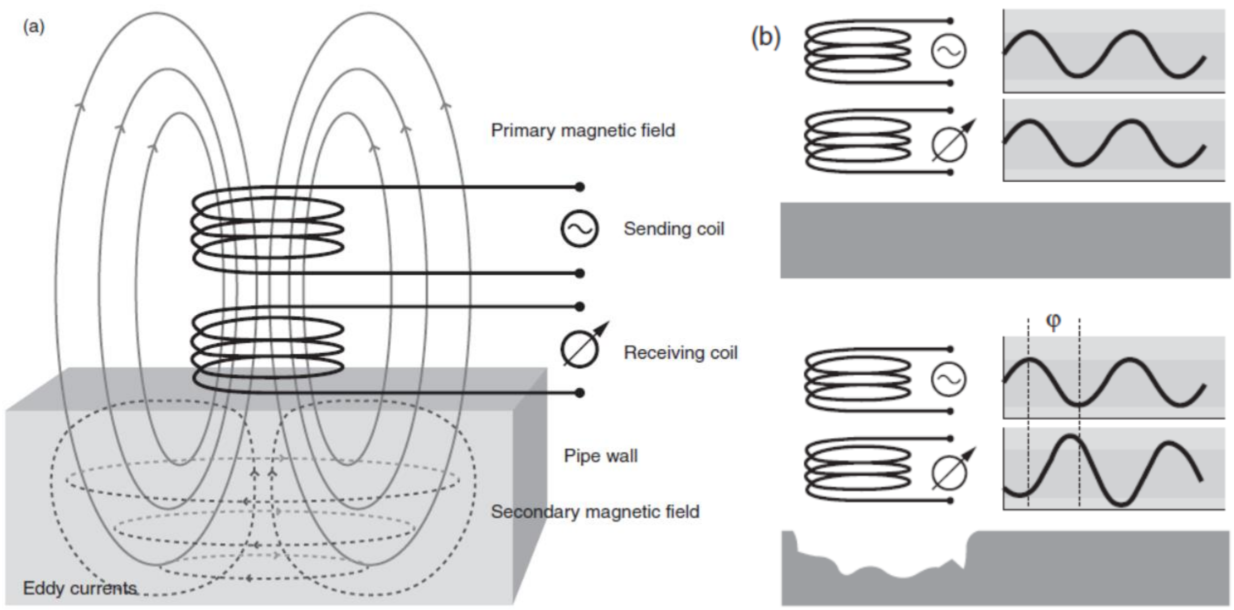


Figure 6. The principle of eddy currents. (a) An alternating current in a sending coil generates eddy currents in a steel sample. (b) Metal loss disturbs the eddy current distribution, resulting in a change in amplitude and phase of the received signal [55].

RFEC is a method using low-frequency alternating current whose main application is finding defects in steel pipes and tubes. The main differences between RFEC and conventional eddy current is in the coil-to-coil spacing. The RFEC probe has widely spaced coils to pick up the through-transmission field. The conventional eddy current probe has coils or coil sets that create a field and measure the response within a small area, close to the object being tested.

In PEC, the coil is electrified using a current following a pulse or step function, thus effectively exciting multiple frequencies simultaneously.

With the introduction of strong permanent magnets, eddy currents can be generated by relative motion between a constant magnetic field (e.g. a permanent magnet) and the pipeline surface. Lorentz forces are generated against the conductive metal of the pipe wall as the conductor moves relative to a magnetic field. By measuring the push back force on the magnet, defects can be detected in a pipeline. This process generally called LEC testing.

MEC method introduces a magnetic field (in a similar manner as MFL) that can increase the effective measurement depth of eddy current inspection. Magnetization of the ferromagnetic pipeline material decreases the permeability of the pipe wall and thus increases the penetration depth of the eddy current.

In-line inspection tools equipped with an eddy currents detection system are considered in the industry as reliable inspection devices with high sensitivity and accuracy for the detection of internal corrosion, especially when combined with a geometry sensor for scanning the pipe surface for geometric anomalies such as dents [59]. RFEC seems to be the prevailing technology in the drinking water industry for inspection of ferromagnetic pipes and ferromagnetic components in composite pipes [60]. For example, the commercial RFEC systems are widely used for detecting broken wires in prestressed concrete pipes [61]; the See Snake tool is applied to small-diameter ferromagnetic pipes [62]; what's more, the PipeDiver RFEC tool can be used to inspect large-diameter ferromagnetic pipes [63]. Commercial PEC system has been used for inspection of insulated pipe/vessels in chemical plants and the oil and gas industry [64].

Advantages of the technology in real-time monitoring of pipeline interactive anomalies include:

a) The technology does not require the sensors to be in close contact to the pipe wall [66].

b) RFEC can work in nonferromagnetic materials such as copper and brass [67].

c) PEC allows the interrogation of multiple depth layers at the same time [68].

d) The inspection tool is compact and can be easily deployed by remotely operated vehicles [69].

e) Compared with MFL, less power is needed for the MEC (about 10 kA/m for MFL v.s. 3 kA/m for MEC). The synergy with the eddy current system means that greater distances can be inspected for a lower energy cost [70,71].

A drawback of the eddy current is that the penetration depth is dependent on the AC frequency of the coil. The penetration depth decreases with the frequency. Thus, with operations normally at higher frequencies, the eddy current method is limited to skin-level defects. While low-frequency excitation can provide additional depth, the energy required to maintain the excitation may be prohibitive [72].

(2.1.3) Broadband Electromagnetic (BEM)

Unlike the conventional eddy current technique, which uses a single frequency for testing, the broadband electromagnetic technique transmits a signal that covers a broad frequency spectrum ranging from 50 Hz to 50 kHz [73]. A transmitter coil passes an alternating current to the pipe surface, which generates an alternating magnetic field. The alternating magnetic field induces a time varying voltage on the metallic pipe wall. This voltage produces eddy currents in the pipe wall, which induce a secondary magnetic field. Wall thickness is indirectly estimated by measuring signal attenuation and phase delay of the secondary magnetic field [74].

BEM technology has been primarily used for condition assessment of water mains [75]. Commercial BEM system now is available to measure corrosion pits [76]. The BEM system is being further modified to facilitate the inspection of pipes exposed in keyhole excavations. This will help acquire information about pipe condition without disrupting service or full access excavations [77].

Compared with other electromagnetic inspection methods, advantage of application of BEM in real-time monitoring of pipeline is that BEM is immune to electromagnetic interference and differs from other electromagnetic inspection methods because of its frequency independence [78].

A primary drawback is that it can only be used on ferrous materials to measure wall thickness, quantify graphitization, and locate broken wires in prestressed concrete cylinder pipes [79].

(2.1.4) Ground Penetrating Radar (GPR)

GPR is a non-invasive high-resolution instrument which utilizes electromagnetic wave propagation and scattering techniques to detect alterations in the magnetic and electrical properties of soil in the pipeline surrounding [80]. GPR antennae transmit electromagnetic wave pulses into the ground. The propagation of electromagnetic waves in soils is governed by parameters such as permittivity, magnetic permeability and conductivity. The occurrences of leaks increase the moisture content of the soil nearby and cause dielectric variation. Reflections occur at the interfaces between media with different electrical properties. The time lag between the transmitted and reflected waves determines the depth of the objects. The reflections are detected by a receiving antenna and subsequently interpreted [81]. A three-dimensional GPR image is obtained using the raw field data after significant work of software processing. Example GPR data before and after interpretation are shown in Figure 7.

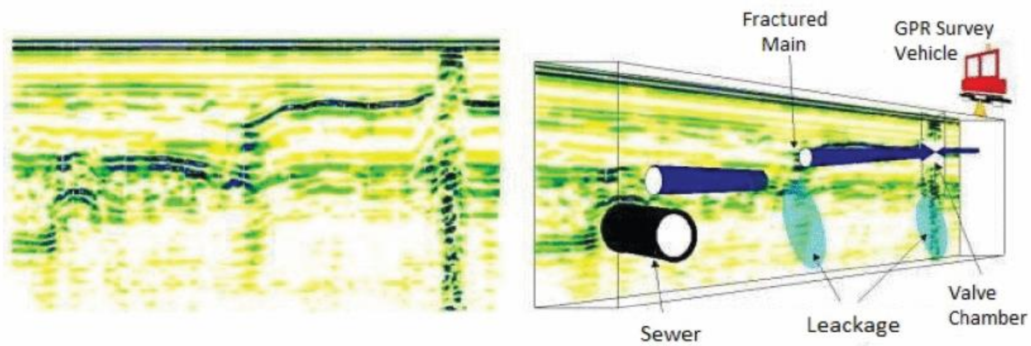


Figure 7. GPR data before and after interpretation [82].

From the perspective of system design, GPR falls into three main categories [82]: (1) Time domain: Impulse GPR; (2) Frequency domain: frequency modulated continuous waveform, stepped frequency continuous waveform, and noise-modulated continuous waveform GPR; (3) Spatial domain: Single frequency GPR.

The GPR has proved impressive potential as an effective non-destructive tool for detecting underground objects [83]. Conventional GPR systems are operated from the ground surface. In-pipe GPR systems were also reported [84]. Such systems use two or three antennae with different frequencies to investigate the structure of the surrounding soil, the interface between the soil and pipe, and the structure of the pipe. A prototype ground penetrating imaging radar (GPIR) was recently developed within a European Commission supported project “WATERPIPE” [85]. The capabilities of this high resolution GPIR reportedly include: (1) detecting leaks and damages in water pipelines of all types of materials; (2) penetrating the ground to a depth of up to 200 cm; (3) image resolution of less than 50 mm.

GPR can potentially identify leaks in buried liquid pipes either by detecting underground voids created by the leakage or by detecting anomalies in the depth of the pipe as the radar propagation velocity changes due to soil saturation with leakage [86].

However, GPR signals can be easily corrupted by environmental noise [87]. The effectiveness of GPR may be significantly reduced for buried pipelines, depending on the depth of the pipe and the use of covering media such as concrete. Similarly, the operation is limited in a clay soil environment as iron pipe corrosion materials can hide cast iron pipelines from the GPR. In addition, they are not applicable for long pipeline networks [88].

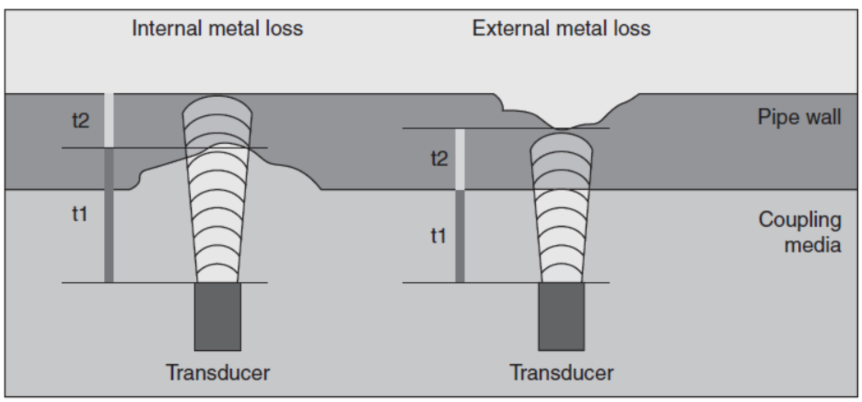
(2.2) Acoustics and Vibrations

(2.2.1) Ultrasonic inspection

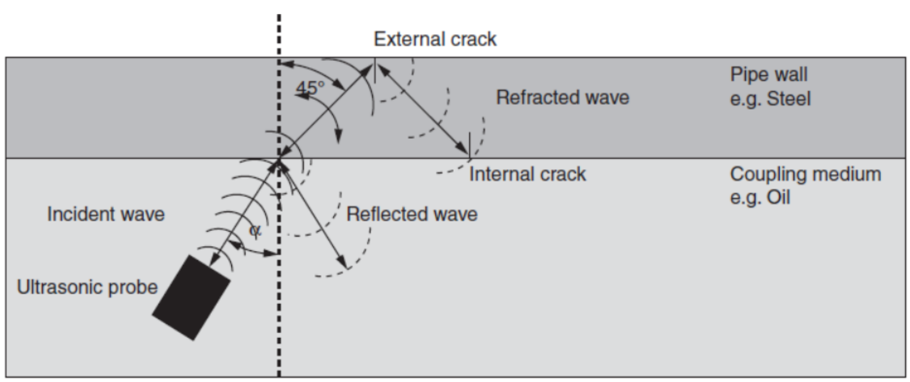
Ultrasonic testing is a non-destructive test method that utilizes sound waves to detect anomalies such as cracks, inclusions and laminations in parts and materials. It can also be used to determine a material's thickness, such as measuring the wall thickness of a pipe to monitor pipeline corrosion [89].

The ultrasonic module to monitor pipeline corrosion is based on the measurement of the time-of-flight of ultrasonic signals reflected from internal/external surfaces of the pipe wall and flaws [90]. With a knowledge of the speed of sound in the liquid and in the pipe wall, it is relatively straightforward to determine the distances between the transducer and the inner and outer pipe walls and thereby determine the thickness of the pipe wall (Figure 8(a)).

A typical ultrasonic crack detection inspection system consists of several transducers operated in an impulse-echo mode acting as both emitter and receiver. Slanted probes are used to ensure that the incident ultrasound signals are refracted in a manner such that they will propagate under 45° inside the pipe [91]. After emitting an ultrasonic testing pulse, each transducer listens for echoes originating from discontinuities in the pipe wall. Partial reflection of the ultrasound occurs at interfaces, such as the interface between two different materials, or cracks, inclusions and laminations in a homogeneous medium. External and internal crack echoes and their amplitudes can be assigned to associated time-of-flights. Reflected signals will be transformed into an electrical signal. Information about location, size and orientation received from the signals can be determined. Ultrasonic crack detection tools are designed for the detection of either circumferential or axial cracks (Figure 8(b)) [92].



(a) Principle of ultrasonic testing pipe wall thickness measurement



(b) Principle of ultrasonic testing for crack detection

Figure 8. Principle of ultrasonic testing pipe [82].

Ultrasonic sensors are typically used in several configurations. As a single crystal, the sensor can be used to emit an unfocused, divergent beam of ultrasound along a straight trajectory. With multiple crystals, the sensors can form a sensing array that can reconstruct a cross-sectional image of the monitored structure. Furthermore, by adjusting the time delay of when each crystal emits the ultrasound wave, the overall wave front can be steered in order to cover a larger area and detect a wider range of defect orientations [93]. For example, efforts with an array of ultrasonic transducers have recently aimed to achieve online monitoring of pipeline wall thickness, and thus corrosion and erosion using ultrasound transducers can be permanently installed, and a map of a section of pipeline wall can be monitored [94].

Another widely used technique for ultrasound-based sensing is time-of-flight-diffraction [95]. In time-of-flight-diffraction, two ultrasound arrays are used as a transmitter and receiver, respectively. Instead of measuring only the reflection of the ultrasound waves, the time-of-flight diffraction technique also measures the effects of wave diffraction due to the edges/tips of defects in the pipe material. The expected signals come from lateral waves, which travel along the surface, and from the reflection of the wave from the opposing surface of the pipe wall. If a defect is present between the transmitter and receiver, then additional waves will arrive between the lateral and backwall reflection arrival times. Because this method has higher power potential than other non-destructive test types, ultrasonic testing can produce images that are more clearly defined than other methods and indicate characteristics deeper than surface level. Ultrasonic testing services for a variety of industries, including, oil, gas, power generation and water supply [96].

Although ultrasonic inspection techniques offer excellent resolution in spot checking pipelines for anomalies, the use of these techniques for inspecting an entire pipeline is excessively time consuming and will not be cost effective [97]. In addition, removal of pipeline coating is required for inspection, which makes point by point ultrasonic inspection become an even more formidable problem [98].

(2.2.2) Guided wave testing (GWT)

The guided wave technique (GWT) is based on the capability of propagating a wave for a long distance [99]. Guided waves are elastic waves that travel within a finite body. Elastic waves can be a combination of the fundamental longitudinal and shear waves, which can combine to form more complex types of waves (e.g. Rayleigh waves, Lamb waves, and Love waves) [100]. The propagation of the waves is guided by the geometry and boundary conditions of the body, hence the name "guided wave". When these guided waves encounter an anomaly or pipe feature, laminar waves reflect back to the transducer's original location (the transducers are used for both excitation and detection of the signals). The time-of-flight for each signature is calculated to determine its distance from the transducer. The amplitude of the signature determines the size significance of the defect (Figure 9).

Guided waves for pipeline inspection are usually generated in two ways. One way is using an array of angled piezoelectric transducers wrapped around the circumference of the pipeline. Another way is to use electromagnetic acoustic transducers (EMAT), which can excite guided waves through either the Lorentz or magneto strictive principles [101]. One of the key advantages of piezo-based transducers is capability to generate stronger signals compared with EMATs. For EMATs, they do not require much surface preparation because they are non-contact and are not affected by non-metallic debris on the surface. What's more, EMATs can be affected by any residual magnetic field in the pipeline and require more power than piezo-based transducers.

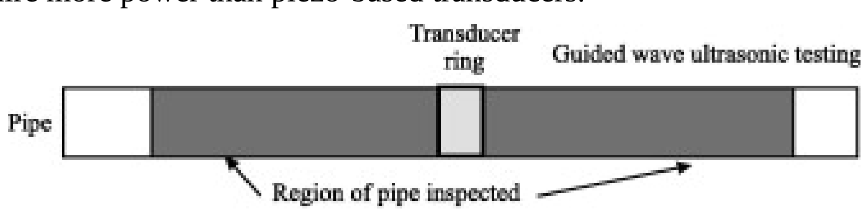


Figure 9. The principle of guided wave testing [86].

GWT can provide a much longer range (up to 100 m) inspection albeit at a lower resolution. Access to only a few points along the pipeline is required without the need to remove coatings for most of the pipeline [102]. The trade off in range and resolution is mainly due to the use of lower frequency waves (10–100 kHz) for GWT compared to the range of ultrasonic inspection [103]. Furthermore, the direction of the waves in GWT is also perpendicular to those used in ultrasonic inspection and will thus travel along the length of the pipeline [104]. Defects such as pipe wall thinning (e.g. due to corrosion), weld imperfections, cracks, and notches cause anomalous reflections with an amplitude that is proportional to the change in the cross-sectional area of the pipe at the defect [105].

For long-term monitoring, where the transducer array is permanently installed onto the pipeline, the use of a baseline (i.e. benchmark) is beneficial for detecting changes in the pipeline over time. The baseline signal can be effectively subtracted from the current signal to quantify changes. In this regard, index-based techniques have been developed to further provide insight into the pipeline status [106].

The guided wave system was originally designed for use on above-ground exposed or insulated pipes. It has been applied to buried and subsea pipes, but the range of inspection will be shorter due to the rapid attenuation of the signals [107]. To overcome this kind of weakness, recently, guided waves can be modulated using schemes such as pulse position modulation to encode information, which means a transducer can transmit a modulated guided wave through the pipeline to be received by another transducer further along the pipeline. Through a series of transmissions, information could theoretically be carried through the pipeline. Changes to the baseline of the transmission signal could also serve as a warning sign for damage in the pipeline. Such a communication method can allow a network of sensors to be permanently installed along a pipeline if there is power and a way to send and receive guided waves. Recent work in guided wave communications in different media is promising, [108-110] and practical application to subsea pipelines is foreseeable in the near future.

Despite the advantages of GWT, there remain some drawbacks that inform further research:

a) Lower frequency waves can travel further than high frequency waves but are unable to effectively interact with small defects [111].

b) Guided wave signal is typically in the form of a pulse, and multiple excitation frequencies are inevitably involved, which may make signals from the desired mode drowned out by the coherent noise [112].

c) Viscous coatings such as bitumen and concrete will dampen the wave energy and limit the range of GWT [113].

d) The geometry of the pipe can also limit the range of GWT. Sharp bends in the pipeline can severely distort signals, and the selected mode can be converted to other propagation modes due to the change in geometry [114].

e) Welds, clamps and flanges will cause reflections that attenuate the energy of guided waves and thus limit the inspection range [115].

f) The presence of dispersion, scattering, and multiple modes can make data interpretation a difficult task [116].

(2.2.3) Acoustic emission (AE)

According to American Society of Mechanical Engineering standard [117], acoustic emission (AE) is defined as “the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material, or the transient waves so generated”. AE employs release of localized stress energy within a pipeline structure (noise or vibration) due to several mechanical events, such as material failure, friction, cavitation, and impact, to detect the occurrence of pipeline leakage. By listening to these AE wave patterns with an array of dispersed sensors and by characterizing the wave pattern, the occurrence and severity of these events can be identified [118].

Acoustic methods for leak detection can be divided into two classes [119]: active and passive. Active methods detect pipeline defects by listening to the reflected echoes of sound pulses emitted due to leakage. On the contrary, passive methods detect defects by listening to changes in sound generated by pressure waves in the pipelines.

There are three major categories of acoustic sensors namely hydrophones, geophone and acoustic correlation techniques. Hydrophones require direct contact with hydrants and/or valves, while geophones listen to leaks on the surface directly above the pipeline. At the same time, steel rods can also be inserted into the buried pipe to transmit signals to mounted sensors on the rods. In acoustic correlation method, two sensors are required to be positioned on either side of the pipe to detect leakage. The time lag between the acoustic signals when the sensors sense a leak is used to detect and identify the point of leakage [120,121].

The use of acoustic emission methods for pipeline leaks detection have been reported in several studies [122-124]. In addition, severe obstruction of the pipe lumen can be detected within several kilometers [125].

Experimental investigation of pipeline leakage subjected to socket joint failure using acoustic emission and pattern recognition was proposed in [126]. This indicates that acoustic emission-based methods can exhibit high sensitivity over long distances. Jia et al. conducted a gas leakage detection experiment on a gas pipeline length of 3.13 km using measured acoustic waves with the sensors positioned at different locations along the gas pipeline [127]. they concluded that applying acoustic emission for detecting leakage on pipeline networks can achieve early leaks detection, estimation of leak sizes and leak point localization [128]. Chen et al. demonstrated that small pipe leaks signal can be efficiently differentiated from noise and effectively localized. For prestressed concrete pipes, steel wires break release energy and cause a series of discrete events, which can be monitored by acoustic technics. As suggested by Shehadeh et al. [129], monitoring the AE, and thus the pipe stress, can be a method for real-time monitoring of the subsea pipeline. While such leakage detection research has not yet been deployed in subsea conditions, it is foreseeable that additional marinization redesigning of sensor and instrumentation components will be able to bridge the gap from lab testing to field implementation.

Generally, the benefit of using acoustic emission for monitoring of pipeline network are easy utilization of interrogation and the convenience of installation as it does not require system shutdown for installation or calibration, which makes this can continuously monitor a long pipeline.

An important drawback is their high susceptibility to noise sources, such as system noises, environment noises, radio chatter, wind, Doppler effects, etc. To eliminate system noises, various techniques, such as band pass filtering [130], Fast Fourier Transform (FFT) and time-averaging Wigner-Ville distribution [127], can be used. Acoustic sensors can be used along with other sensors to overcome these limitations.

(2.2.4) Sonar mapping

Sonar refers to the use of sound waves underwater to detect objects, typically for navigation and mapping. In the pipe inspection field, it has been adapted to provide information about elements in the pipe that are submerged below the water line. These may include submerged debris in the pipe (sewers), grease level (sewers), differential settling and other submerged deformations and defects. A sonar system may consist of an underwater scanner unit, collapsible sonar siphon float, sonar processor/monitor, skid set, and all necessary interconnect cables [131]. Each pulse provides an outline of the cross-section of the submerged part of the pipe [132]. Accurate measurements can be performed based on these outlines.

The sonar profiling system can be used with different frequencies to achieve different goals [133]. High frequency sonar can provide a higher resolution scan, but a high-resolution pulse attenuates quickly and therefore has a relatively low penetration capability. In contrast, low frequency sonar has a high penetration capability but is limited in its scanning resolution. High frequency sonar can be suitable for clear water conditions, turbid water with high concentrations of suspended solids may require a lower frequency signal. Small defects are more likely to be observed by a high frequency signal.

A system that integrates multiple sonars for use in submerged and large semi-submerged pipelines is also available. The use of multiple sonars overcomes the disadvantages of using one sonar and one ping at a time to map. However, depending on the size of the sonar array, computational costs can become increasingly significant. Thus, although costing more than the use of a single sonar, the use of multiple sonars may save on the costs for a longer period monitoring [134].

Wideband sonars are capable of a multi-frequency (each frequency component backscatters differently depending on the material reflecting the pulse) scan to obtain maximum information. Advantages of wideband sonars include higher resolution and wide range for customization and optimization according to the situation [135]. Wideband sonar has been recently used to not only inspect the positioning of subsea pipelines, but also inspect whether flow is being obstructed in pipeline [136].

The drawback of sonar is also obvious. A major drawback of sonar devices is that they cannot be operated above and below the water line simultaneously and they cannot be used for gas pipes. In addition, the cost of sonar inspections varies depending on the diameter of the pipe to be inspected.

(2.3) Robots

(2.3.1) In-Line Inspection (ILI)

In the last few decades, pipeline inspection gauges (PIGs) have become more prevalent for in-line inspection (ILI) and non-destructive evaluation of the pipelines [15,137,138]. The advanced versions of these autonomous systems, also called “smart pigs”, can move inside pipelines and measure irregularities that may represent corrosion, cracks, joints, deformation (e.g., dents, pipe ovality), laminations or other defects (e.g., weld defects) in the pipeline.

The most common ILI methods that have been installed on smart PIGs and confirmed to be successful for pipeline inspection are magnetic flux leakages (MFL) [139], ultrasonic transducers [21], electromagnetic acoustic transducers (EMAT) [140] and eddy currents [141].

However, certain constraints seriously limit the practicality of the aforementioned methods. In the MFL method for instance, it is very difficult to effectively saturate the entire cross-section of the pipeline with magnetic flux, and also the servicing process involves frequent calibration and complete analysis. Moreover, the method is not suitable to inspect non-ferrous pipelines [142–143]. The ultrasonic transducers method works well in liquid pipelines; however, the application in gas pipelines is not common since it requires liquid coupling between the transducer and the surface of the pipeline [144]. ultrasonic transducer is more suitable for thick-wall pipelines rather than thin-wall pipelines (less than 7 mm) [145]. Echo loss is another major challenge reported in the literature [146]. The EMAT method cannot be used in non-conductive materials such as plastics or ceramics, and it is not suitable for long pipeline inspection, which requires high power and complex signal processing in real-time [147]. This method faces challenges for high-speed scanning in pipelines, and it can be applicable up to 2.5 m/s [148]. The eddy currents method requires deep magnetic penetration in ferrous pipelines, and the major drawback is the spacing problem, which occurs while mounting the sensor array on the circumference of the smart pig [149,150]. In addition, recently, a few ILI methods have also been developed for the inspection of pipelines such as closed-circuit television (CCTV) [34] and mechanical contact probe (MCP) [151]. In the case of the CCTV method, the high-power supply and lack of visibility inside the long pipelines are the drawbacks [152]. The MCP method can inspect only convex defects such as deposit corrosion. It is not suitable for cavity corrosion or metal loss corrosion, and the friction involved in the inspection process is a major risk [153].

(2.3.2) Remotely Operated Vehicles (ROV) and Autonomous Underwater Vehicles (AUV)

It has been shown that ROVs and AUVs are durable for performing subsea pipeline inspection tasks and functioning in deep water that cannot be accessible by pigging or human divers [154].

Typically, the ROV consists of a top block made of buoyant materials, which is attached to a lower aluminum chassis that houses various controls and propulsion systems. The ROV can be equipped with many tools, such as video cameras, chemical samplers, and lighting systems, to carry out a wide range of tasks. The operation principle of ROVs is based on teleoperation that involves a master-slave system. The slave is a ROV, which is designed to interact with the extremely hazardous subsea environment. The master human operator is located in a safe place to remotely control the slave robot's motions using input devices [155]. All robot commands, sensory feedback and power are sent through an umbilical cable connecting the ROV and the deployment vessel.

The operation principle of AUVs is similar to ROVs; however, the AUV can operate independently without human intervention. Since there are no human operators, AUVs do not need tethering to a nearby vessel, and therefore the costs of subsea pipeline inspection can be significantly driven down.

There are numerous types of AUVs and ROVs available for oil and gas infrastructural monitoring. Examples of commercially available ROVs and AUVs primarily deployed in the oil and gas industry are shown in Figure 10.

Figure 10. Different kinds of AUVs and ROVs [156].

For pipeline inspection, ROVs are often equipped with a range of sensors described in the other sections of the review (e.g. acoustic, temperature, and radiographic) for leakage detection and side scan sonars for more global inspection of pipelines. Furthermore, unlike inline inspection with pigging, ROVs are not limited by pipeline geometry [157].

The challenge in AUVs is developing robust algorithms that allow the vehicle to identify and track pipelines while at the same time catching anomalies that may point to damage [158]. Some researchers are developing AUVs for long-term subsea operation. Such long-term AUVs will reside in a dedicated docking station and will be available for real-time inspection tasks. There is still ongoing research in improving the automatic operation of AUVs in subsea conditions, and better poise them for mission success in the face of uncertainty [159]. The introduction of AUVs has also allowed new inspection and monitoring methods. Through improvements to the AUV artificial intelligence, the AUV can be used to advance underwater acoustic networks [160].

Using ROVs and AUVs in subsea pipeline inspection and monitoring has reduced the extent of human operator involvement in unmanned vehicles and thus lower the chance of human casualties. The remote operating system makes it suitable for inspection in a remote and hazardous environment. Lower cost of maintenance and higher operation safety are also advantages of unmanned vehicles.

These systems also have drawbacks. First, the cost of an AUV/ROV is extremely high. Second, bad weather conditions such as clouds, winds or other climatological agents can restrict the performance of these vehicles. There are also legal constraints for the use of the unmanned system in some certain areas due to safety concerns.

2.3 Mechanical Testing of Optical Fibers

The mechanical properties of optical fibers have been tested using an Instron load frame at room temperature (21°C). Optical fibers were tested under tension until ruptured using an Instron 5982, which uses a load cell with a load capacity of 1 kN capacity. The load measurement accuracy of the load frame is ±0.5% of reading down to 1/1000 of load cell capacity option. The data acquisition rate is up to 2.5 kHz. The speed range is 0.001-3000 mm/min. Each fiber was stretched to failure with displacement-controlled mode. The loading rate was 2 mm/min. Force-extension relation was obtained, and since the initial length of each fiber was measured, the force-strain relation could be achieved, and thus the tensile strength and elastic limit of strain ε_e became known.

Mechanical properties of Corning single mode fiber (SMF-28e+) were tested. Figure 11 shows the test set-up and the cross section of the fiber. With the consideration of the fragility of the fiber, the zones contacting the grips of the Instron were enhanced by protective sleeves that could be directly gripped by the fixtures of the load frame. The loading force and the extension were simultaneously recorded by the load transducer and the extensometer. Since the initial length of each fiber was measured, the force-strain relations were obtained. Thus, the tensile strength and the elastic limit of strain ε_e were achieved.

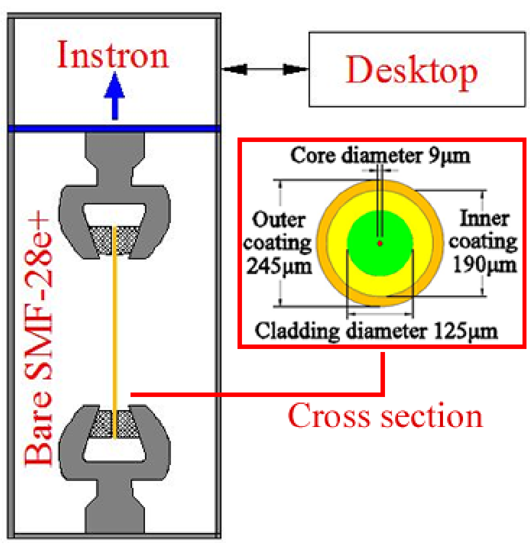


Figure 11. Test set-up for optical fibers under tension.

In total, 10 fibers have been tested, and one of the force-strain relations is shown in Figure 12. The optical fiber behaved linearly until ε_e; then there was a short plateau representing the fracture of the silica glass core and cladding of the fiber; after the plateau, the load was resisted solely by the coating. The tensile strength of the fiber was around 15 N and the corresponding strain was about

16,000 με (1.6%). At ε_e, the glass fiber fractured and thus the fiber sensor became invalid after that point. The force-strain coefficient is 9.63×10^{-4} N/με that can be taken as the tensile stiffness of the optical fiber. The peak forces of the fibers are summarized in Figure 12(b).

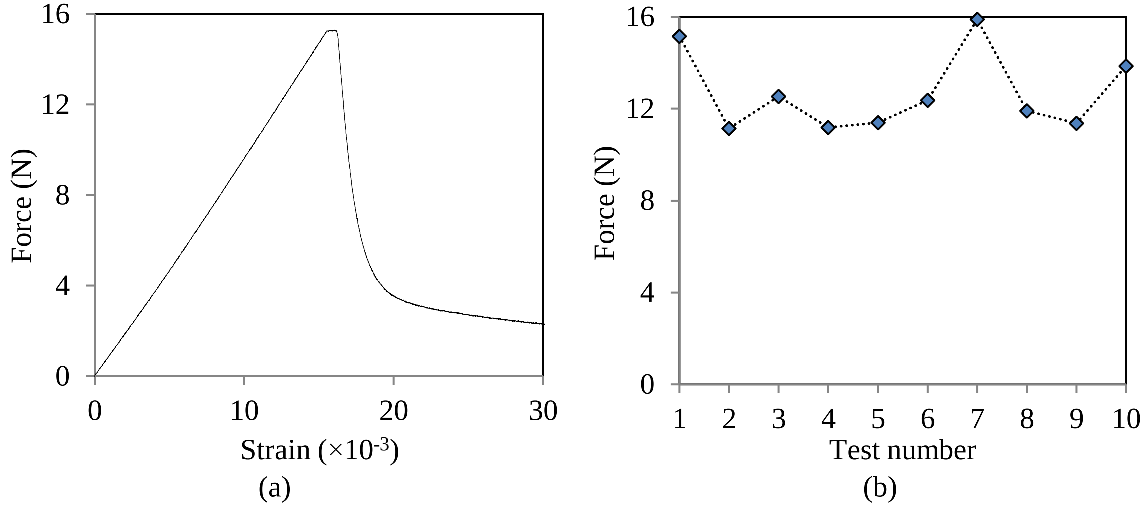


Figure 12. Tension test results: (a) force-strain relationship, and (b) peak forces of 10 samples.

(e) Task IV: Student Training and Reporting

In Task IV, we will recruit and educate two graduate students (one from Stevens and one from NDSU) and two undergraduate students. Through the research, the students will be trained to become future experts in the related fields.

In this quarter, two activities were performed for Task IV, including (1) hiring two graduate students and two undergraduate researchers to work on this project; and (2) an outreach event named “Smart Infrastructure” to primary school students as a part of the Sustainable Challenge Program in New Jersey on Nov. 21st, 2019.

2.4 Student Mentoring

During the first quarter, two graduate students (Xiao Tan, Ph.D. student from Stevens, and Shuomang Shi, Ph.D. student from NDSU) and two undergraduate research assistants (Gina Blazanin and Hashem Sonbol) were hired to work on this project. The two graduate students completed their hiring process in October 1st, 2019 and started their contract on this project. The two graduate students will work on this project from Quarter 1 to Quarter 4 of Year 1. Their contracts will be renewed, depending on their performance. The two undergraduate students were hired from October 2019 to December 2019. New undergraduate research assistants will be hired in January 2020 for the second quarter of this project.

2.5 Outreach Activities

On Nov. 21st, 2019 (1:30 pm to 3:30 pm), an outreach event named “Smart Infrastructure” workshop was conducted based on this project. The workshop is a part of the Sustainable Challenge Program in New Jersey. The PI (Dr. Yi Bao) serves on the panel of the Program. This workshop intended to let the primary school students have basic knowledge to plan and build smart pipelines. It is expected to encourage and generate interests for young kids to pursue pipeline engineering for future college education or careers. Table 1 is the schedule of the event.

Table 1. Outreach Workshop Schedule

1:30	-	1:45	Presenter Arrival
1:45	-	2:00	Student Arrival
2:00	-	2:15	Introduction of the Smart Infrastructure workshop and Sustainable Challenge Program
2:15	-	3:00	Lecture
3:00	-	3:30	Questions and Answers

Approximately 80 primary school students attended this workshop. One graduate student volunteered in this outreach event to guide the primary school students. Figure 13 shows the photos taken from this event. More outreach events are planned for primary school students in next quarter.

Figure 13. Photos of outreach event: (a) lecture given by the PI Dr. Bao, and (b) discussions.

3. Future work

In the second quarter, there will be three objectives:

1) Focus on the remaining activities planned in Task I: Developing and Characterizing Distributed Fiber Optic Sensors. Based on the literature review of existing methods and the testing of the mechanical properties of the optical fibers, we will conduct further experiments on using the optical fiber as distributed sensors to test the sensor responses under multiple individual types of defects and the combined defect conditions.
2) Conduct the research activities planned in Task II: Distinguishing Interactive Anomalies Using Point Fiber Optic Sensors. More specifically, fiber Bragg grating sensors will be tested to evaluate the performance of point sensors under multiple individual types of defects and the combined defect conditions.
3) Supervise the two graduate students in performing research Tasks I and II. The two graduate students will conduct the experiments and analyze the data under the supervision of Dr. Yi Bao and Dr. Ying Huang.
4) Conduct an “Intelligent Pipeline” workshop outreach event in the Sustainable Challenge Program to primary school students in Grades 4-6 in New Jersey. Dr. Yi Bao and a graduate student will visit a local primary school, presenting the research and discussing with the students.

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