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Monitoring of Distributed Pipeline Systems by Wireless Sensor Networks

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Abstract

This paper describes a sensor network platform for pipeline system monitoring. Pipeline systems are widely used for distribution and transportation of petroleum, natural gas, water, and sewage. Leaks and ruptures due to an aging and fast decaying pipeline system infrastructure cost millions of dollars a year; they also make clear the necessity for continuous, automatic monitoring systems that can provide early detection and early warning of defects, such as corrosion and leaks, before they reach the magnitude of a major disaster. In this paper, we discuss how sensor networks can detect, localize, and quantify bursts, leaks and other anomalies in pipeline systems.

Lamb waves are guided ultrasonic waves that can propagate for considerable distances in plates. Research has shown that it is possible to detect flaws over a large area with active sensing devices such as Lead Zirconate Titanate (PZT) for simultaneous actuation and sensing. PZT sensors can be mounted on the curve surface of the pipelines for generating and measuring guided waves that propagate along the pipes. A network of PZT actuators/sensors provide a real-time continuous and automatic monitoring of the health of the pipeline systems. Complications that encountered in Lamb wave propagation include the existence of multiple propagation modes and the dispersive nature of the modes, which makes the sensing, communication, and control a difficult task. In this paper, we will address the detection and localization problems for the proposed acoustic sensor networks using signal processing techniques. We will discuss strategies to deal with the Lamb wave dispersive propagation to achieve reasonable performance for real-time monitoring.

Introduction

Transmission pipelines for gas and oil are an important part of national energy-transportation infrastructure vital to the national economy. Because these pipelines are operated at high pressure, pipeline failure can cause severe damage to human health and property and interruption of gas or oil supplies. For example, a spill of about 267,000 gallons (1 million liters) of oil in the tundra of Alaska's North Slope went undetected for five days before a field worker smelled the crude oil while driving through the area on March 2, 2006 due to a quarter-inch (two-thirds of a centimeter) hole corroded in a pipeline; British Petroleum (BP) subsequently announced that it had to close a portion of the distribution network in Alaska because of extensive corrosion of the pipe walls. This example illustrates the magnitude of the problems associated with an aging and fast decaying pipeline system infrastructure.

Pipeline inspection technologies using sensor networks have drawn significant attention, for example, in the applications of natural gas pipeline inspection and monitoring by acoustic sensors [1], [2]. In this paper, we discuss how sensor networks can detect, localize, and quantify bursts, leaks and other anomalies in general pipeline systems using acoustic guided waves and signal processing techniques.

In general, pipeline defects can occur in the manufacture, construction, and operation processes. In this paper, we focus on the operational defects that encompass internal corrosion, external corrosion, erosion, fatigue, third party damage, denting and buckling. The leading cause of pipeline incidents is damage by digging near existing pipelines. According to the statistics by the U.S. Department of Transportation's Office of Pipeline Safety, excavation damage accounted for almost 60 percent of all reported distribution pipeline incidents between 1995 and 2004. Corrosion sometimes results from excavation damage, which, while not severe enough to trigger a puncture or failure of the pipeline, could create weaknesses in the pipeline. Such a weakness later renders the pipeline more susceptible to corrosion. Most pipelines have protective coatings and cathodic protection systems that limit the potential for external corrosion. Despite these protective systems, internal and external corrosion and stress corrosion cracking occur in the pipelines due to aging. To ensure the continued safe operation of the transmission pipelines, continuous monitoring or periodic assessment of the integrity of the pipelines is necessary. In pipeline monitoring and inspection, the ultimate objective is to identify the locations that have defects, and obtain an accurate measurement and assessment of the defects so that human operators can take appropriate actions to prevent further damage. The goal of our study is to investigate the feasibility of developing a continuous, remote, and real-time monitoring and inspection system using acoustic sensors that can provide early detection and early warning of defects, such as corrosion and leaks, for pipeline systems.

A pipeline monitoring and inspection system has a long list of tasks to accomplish. For example, [3], for natural gas pipelines, these tasks include:

1. measuring wall thickness;
2. detecting gas contamination in pipeline;
3. measuring velocity and flow of gas;
4. detecting presence of gas leaks;
5. determining the variation in pipe cross-section;
6. determining structural defects in pipes, etc.

To achieve these goals, we rely on various acurators and sensors. There are many types of sensors that have been studied and tested for pipeline inspections including acoustic sensors, fiber optic sensors, and magnetostrictive sensors. Each type of sensors has its unique feature and operational condition. In this paper, we survey the pipeline inspection technologies using acoustic sensors and describe an active acoustic sensor network platform for pipeline monitoring and inspection. We discuss basic components of the proposed sensor networks and the signal processing techniques to detect, localize, and quantify bursts, leaks and other anomalies in a pipeline system. Sensor networks technology has a wide array of applications in industry and military. We will discuss a new course on sensor technology and applications to be developed for the engineering program at the University of Maryland Eastern Shore.

Pipeline Monitoring by Acoustic Sensors and Lamb Wave Propagation

The working principle of an acoustic sensor is the piezoelectric effect. Piezoelectric effects occur in dielectric materials, causing physical dimension changes due to electric fields and, conversely, generating electric charges due to strain or stress. Piezoelectric devices have dominated the field for applications, such as sonar, ultrasonic transducers, electronic filters and resonators, delay lines, and accelerometers. In transmission pipeline monitoring and inspection, acoustic sensors can operate in passive mode or active mode. For example, an impact caused by a third party on a pipe wall creates acoustic waves that travel upstream and downstream in the pipeline. A passive sensor measures the timing and relative magnitude of these waves to determine the impact location and severity. However, passive sensors provide limited functionality and are not adequate for pipeline inspection. Acoustic emission sensors can generate acoustic wave forms that adapt to the various pipeline operational environments to better probe the pipeline systems for defects detection and localization. In pipeline inspection, piezoelectric ceramic Lead Zirconate Titanate (PZT) based electro-mechanical impedance technique for structural health monitoring has been successfully applied to various engineering systems [4]. A PZT sensor can produce electrical charges when subjected to a strain field and conversely mechanical strain when an electric field is applied. PZT possesses the property of piezoelectricity that can be used to launch guided waves along the pipes and to measure the corresponding response time signals. However, the conventional PZT materials are brittle and susceptible to cracking especially when the surface of the pipeline is curved. To address this issue, research has shown that flexible smart materials such as macro fiber composite sensors, shown in Figure.1, and active fiber composite sensors are the sensing and actuating devices that can adapt to the curved pipeline surfaces [1],[4].

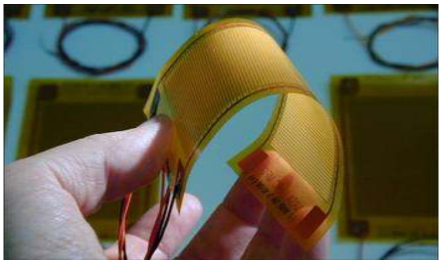

Figure1: Flexible Macro Fiber Composite (MFC) sensors developed by NASA are mounted on the curve surface of the pipelines for generating and measuring guided waves.

Those composite materials are composed of ceramic fibers that can bend or flex when a current is applied to them. These materials can also generate a current when they are vibrated or flexed. These unique properties provide sensing flexibility for pipeline inspection by adjusting the size and spacing of the PZT sensors and the effective configuration along the circumference. The fact that a controlled input signal can be generated and applied provides various advantages for the subsequent signal processing and damage diagnosis.

Recently, the use of Lamb waves for non-destructive testing has attracted many researchers [1]-[2],[4]-[5]. Lamb waves are guided ultrasonic waves capable of propagating relatively long distances without much attenuation in plates and laminated structures, such as airframe skins, storage tanks, and pressure vessels. This is because they are guided plane strain waves constrained by two free surfaces. The long sensing range makes Lamb waves attractive for damage inspection and diagnosis. Moreover, if a receiving sensor is positioned at a remote point on a pipe, the received signal contains information about the integrity of the line between the transmitting and receiving sensors. The test therefore monitors a line rather than a point. Hence we save considerable testing time compared with the conventional ultrasonic inspection methods where each point of a structure needs to be scanned and tested.

The propagation of Lamb waves is complicated due to their dispersive and multimode characteristics. Their propagation properties in pipelines depend on the vibration frequency as well as on the thickness and material properties of the structure. In theory, the dispersion and multimodes of Lamb waves can be described by the Rayleigh-Lamb equations for the symmetrical and anti-symmetrical modes on an infinite plate with thickness *2d* [1],[6].

$$(k^2+s^2)^2\cosh(qd)\sinh(sd)-4k^2qs\sinh(qd)\cosh(sd)=0$$

$$(k^2+s^2)^2\sinh(qd)\cosh(sd)-4k^2qs\cosh(qd)\sinh(sd)=0$$

where $q^2=k^2-k_l^2$ and $s^2=k^2-k_t^2$. The symbol k denotes a wave number, k_l and k_t are the wave numbers for the longitudinal and shear modes, respectively. $\sinh(x)$ and $\cosh(x)$ are hyperbolic functions. Lamb wave behavior is described by the group and phase velocity as a function of the frequency-thickness product for a number of both symmetrical and anti-symmetrical modes where each mode corresponds to a root of the Lamb wave equation [7] referred to as (S_0, S_1, S_2, …, S_n) and (A_0, A_1, A_2, …, A_n) respectively. The zero order symmetrical mode (S_0) and the zero order anti-symmetrical mode (A_0) are the most important because they exist at all frequencies. In most practical situations they carry more energy than the higher-order modes. As the frequency increases, the higher-order wave modes appear in addition to the zero-order modes.

The modes are also generally dispersive, which means that the shape of a propagating wave changes with distance along the propagation path. Lamb waves exhibit velocity dispersion, i.e., their velocity of propagation *c* depends on the frequency (or wavelength), as well as on the elastic constants and density of the material. This phenomenon is central to the study and understanding of wave behavior in plates. There are two types of velocity dispersion for Lamb wave propagation: group velocity dispersion and multimode dispersion [1],[6],[8]. The group velocity dispersion is caused by the frequency dependency of a single Lamb wave mode. That is, the different frequency components in a single mode travel at different speeds. As a result, the group velocity dispersion causes spreading of the wave packets. The multimode dispersion exists because different modes at a given frequency travel at different speeds. Therefore, when an input acoustic waveform with a discrete frequency is applied to a thin medium, it is separated into multiple modes that travel at different speeds. In addition, the amplitude attenuation of a Lamb wave is also frequency dependent, which results in amplitude dispersions. Hence, Lamb wave signals have complicated dispersion characteristics.

Traditionally, Lamb waves are generated in a plate or a pipe using angled contact transducers. This means that the transducers are held against the plate at an angle. Depending on the angle and the frequency, many different modes can be excited. If a plate has defects, these waves interact (e.g., reflect, scatter, etc.) with these defects; the information about the defect then can be extracted from the propagating waves.

Acoustic Sensor Networks for Pipeline Inspection

A sensor network is composed of a large number of geographically distributed sensor nodes [9],[10]. Though each sensor is characterized by low power constraint and limited computation and communication capacities, potentially powerful networks can be constructed to accomplish various high level tasks via sensor cooperation, such as distributed estimation, distributed detection, and target localization and tracking. In pipeline monitoring and inspection, we will use a network of acoustic sensors that are mounted internally or externally on the walls of pipelines to detect, locate, and analyze various defects. Data processing using acoustic sensors distributed along the pipelines differs substantially from conventional centralized processing methods. In conventional data processing, all the sensors transmit their measurements at every time step to the central unit for final processing. However, there are two main reasons why centralized processing is not preferred for pipeline monitoring:

1. operational pipelines are subject to complex, often highly non-linear, and localized temporal and spatial processes. Hence we want to perform some local processing to collect information in the neighborhood of localized defects;
2. the central node needs to handle matrix operations that increase in size as the number of sensors increases.

We may want the sensors to shoulder some of the computational burden. Therefore, data processing by sensor networks requires integrated methods and methodologies including conventional distributed systems, distributed control, distributed estimation and detection, distributed statistical signal processing, [10]-[11]. Our basic approach is to develop a general framework based on a ubiquitous network of acoustic sensors and controllers that provides continuous monitoring and inspection of pipeline defects. Although the problem is complex, in this paper we focus on using signal processing techniques to detect, analyze, and locate pipeline defects.

Acoustic Signal Detection

The discrimination between noise and signals (from defects) is essential for pipeline monitoring. The operational environment of a pipeline is usually very noisy. A noise analysis must be conducted to characterize the frequency bands of noise at different sections of a pipeline. We apply denoising procedures to reduce or remove electronic and other noise that contaminate the signature signals from pipeline defects. The denoising techniques including bandpass filtering and more sophisticated wavelet based filtering that reduce the noise level in the received acoustic signals.

Signals generated by acoustic sensors that propagate along the pipeline can be used to infer defects. For pipelines that do not contain defects, their propagation characteristics can be calculated from modeling. When defects, for example, corrosions occur, the acoustic signals may reflect and scatter due to the defects. Hence, the received signals differ from those propagating in the normal condition. We use simple discrimination techniques such as signal cross-correlation to discrimate defects. We discover that the cross-correlation of signals originating from similar parts of a structure shows a high correlation. Based on detailed knowledge of the structure, certain regions can be monitored directly by storing in memory the values of cross correlation between the actually recorded signal and a reference signal, yielding a simple map of signal similarities. Only the correlation coefficient, the event time and the "name" of the sensor node recording it have to be transmitted to the local processing unit. Finally, once the defect is detected and identified, an alarm message can be sent to the human operator through communication links.

Detection of burst signals caused by accidental heavy equipment impact is challenging. This is because burst signals can be very short in duration and may also be much lower in amplitude than the normal background acoustic signals. In order to detect third party damage signals, it becomes necessary to continually compare new acoustic signals to the background acoustic signal at that location. Fourier transform analysis is a power tool to achieve this goal. Fourier transform provides the synchronized signal characteristics required to properly remove background signal characteristics from new acoustic signals so that unique frequency variations caused by pipeline impacts can be revealed. Recently, time reversal based signal detection method that does not require reference signals has been porposed [13]-[16]. Time reversal is utilizes channel dispersiveness to enhance signal detection. For a dispersive channel $h(t)$, i.e., the characteristics channel of a pipeline, if we send a probe signal $s(t)$, the received signal is $y(t) = s(t) * h(t)$, where the symbol $*$ denotes convolution. The time reversed and energy normalized signal is $s_{tr}(t) = \alpha y(-t)$, where α is an energy normalization factor. If we re-send this signal, it propagates over the same medium. The received signal becomes:

$$r(t) = s_{tr}(t) * h(t) = \alpha s(-t) * (h(-t) * h(t))$$

For highly dispersive channel $h(t)$, the term $h(-t) * h(t) \approx \delta(t)$. Hence, the combined channel (i.e., forward propagation channel and backward propagation channel) is shortened. Thus, we obtain an increased signal to noise ratio for signal detection.

Defects Localization

Defect localization is another important task for sensor networks. There are various localization methods proposed in the framework of sensor networks. Depending on the operational environment and assumptions, the localization techniques possess varying degrees of complexity and accuracy.

A simple yet less accurate localization method is guessing the source origin using the "leading edge detection" technique, i.e., the sensor detects the first arriving signal whose signal power exceeds a pre-determined threshold. The range between the sensor and the defect can be calculated from the propagation speed and the estimated travel time. The advantage of this technique is that it does not require sensor arrays or data analysis. The sensor detects an acoustic signal and defines a radius from which the signal is originated. This technique requires certain empirical knowledge of the pipelines where defects may occur. A more accurate solution to the localization problem is to utilize different velocity profiles of Lamb waves propagating along the pipes. The differing velocities of the Lamb wave modes have been successfully exploited to locate sources using a single sensor [17]-[20], and to determine the orientation of a source [20]-[21].

Using multiple acoustics sensors, we can detect a defect and locate the defect by simple triangulation methods based on time-of-arrival of the fastest propagating wave mode. Although this approach can be easily performed in bulk structures, it is somewhat more complicated in plate structures, for example, pipelines, where velocity dispersion can occur after propagation distances of several plate thicknesses, particularly if the plate is of non-uniform thickness. More sophisticated methods use planar techniques by recording acoustic emission signals at multiple sensors at the same time. This method requires time synchronization of the motes and communication between motes. Other options are methods based on array techniques [22]. In pipeline inspection, these array techniques can be implemented locally in the neighborhood of suspected defects. Current acoustic emission systems with localization capabilities are very costly and difficult to install. Sensors must be placed throughout the structure to ensure that the damage is encompassed by the array. We will use time reversal based array processing techniques that rely on sparsely placed sensors to achieve an improved resolution [16].

Integrating Sensor Networks Advances in Undergraduate Engineering Curriculum

Wireless sensor networks are nascent technologies that leverage the recent advances in electrical, computer, and mechanical engineering [23]. They include wireless communications, low-power embedded systems, sensor design, and instrumentation, etc. They are emerging technologies that have wide applications in industry and military. From a hardware perspective, sensors become very cheap, which makes it possible to add them in various instrumentation and process control system or deploy them in a significant large number. From a software perspective, extensive and sophisticated data gathering and data processing techniques designed specifically for sensor networks applications have been developed. These recent advances in sensor network technologies motivate us to develop a new curriculum for technical expertise at the level that is suitable for undergraduate engineering students.

The engineering program at University of Maryland Eastern Shore is relatively new with four specializations namely aerospace, electrical, computer, and mechanical engineering. This program is the only engineering program on the Eastern Shore of Maryland, and is the fast growing engineering program in the region. To attract new students into engineering and better prepare them for the new development in the engineering discipline, we anticipate that a new course will be developed that covers the topic of sensor design and applications. The objectives of this course are to:

- provide students with a better understanding of the electrical, computer, aerospace, and mechanical engineering disciplines;
- help students develop hands-on skills through self-motivating, team-based design activities;
- stress the importance of problem solving skills, critical thinking, and good communication;
- provide students a systematic view of sensor networks technologies at the component level, network level, and application level.

This course will have lecture modules and laboratory experiments. The lecturer component will focus on topics related to the engineering profession, engineering design, electrical-mechanical systems, and wireless sensor networks. The integrated laboratory experiments will be developed using popular data acquisition and simulation platforms, such as Labview, Matlab/Simulink and sensor network platform such as TinyOS and Java.

Conclusion

Pipeline operators face many threats to the integrity of pipelines. Many researchers have proposed pipeline safety solutions to pipeline damage prevention and leak detection. These research efforts include the Department of Energy awards focusing on inspection and remote sensing technologies for pipelines, Department of Transportation awards for pipeline safety research, and many commercial monitoring products for threats and impacts on pipelines. Our research focuses on developing a general framework using acoustic sensor networks to provide continuous monitoring and inspection of pipeline defects investigating how sensor networks can detect, localize, and quantify bursts, leaks and other anomalies in pipeline systems. Due to the complexity of the problem, we will use acoustic wave propagation theory, distributed systems, distributed control, statistical signal processing to analyze signals for defects detection and localization. Furthermore, the developed acoustic sensor network technologies can be integrated with robotic vehicles, for example, a gas pipe Explorer robot, that travel inside the pipelines. An Explorer type robot would be able to stop and even reverse motion in the pipe for in-depth, close inspection of detected defects. Hence, the non-destructive testing technologies designed for acoustic sensors could potentially be utilized for better characterization and analysis of pipeline defects, corrosion, or damage.

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