Investigation on the Effects of Environmental and Operational Conditions (EOC) on Diffuse-field Ultrasonic Guided-waves in Pipes

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ABSTRACT

In spite of many favorable characteristics of guided-waves for Nondestructive Evaluation (NDE) of pipes, real-world application of these systems is still quite limited. Beside the complexities derived from multi-modal, dispersive and multi-path characteristics of guided-waves, one of the main challenges in guided-wave based NDE of pipelines is sensitivity of these systems to variations of environmental and operational conditions (EOC).

This paper investigates the effects of varying EOCs on guilded-wave based NDE of pipelines. We first provide a review of the studies to date in the field of guided-wave based testing to identify research gaps for enhancing the application of these systems in pipeline NDE. To study the identified gaps, guided-wave data from a fully operational piping system, with continuously varying flow rate and temperature, is used. Time-shift and amplitude drift effects due to flow rate variations are evaluated along with those of temperature. It is observed that masking effects of flow rate for damage detection can be at least as significant as temperature effects, and that such effects become more dominant when flow rate and temperature variations co-occur.

INTRODUCTION

Reliable prediction of degradation in structural integrity of pipes is important to ensure delivery of expected serivces, to minimize environmental/human-safety risks associated with not/late-detected damages, and to reduce cost/time of repair and handling the impacts of damages. However, according to Department of Transportation, Pipeline and Hazardous Materials Safety Administration report (Shaw et al. 2012), 1,337 release incidents in transmission pipelines were reported during 2010 to 2012, while less than 10% of these reported leakages were identified by data acquisition and testing systems.

Difficulties, cost, and safety risks associated with accessing different portions of the pipes make non-destructive evaluation (NDE) techniques attractive for damage detection and monitoring (Cawley et al. 2003).

Hence, during the past decade, non-destructive monitoring and evaluation of pipelines based on guided-waves have been widely considered by researchers and service providers in different applications, ranging from water supply pipes to gas/oil transmission, chemical or power generation pipes (*e.g.*, Alleyne et al. 2001; Siqueira et al. 2004; Sun et al. 2000; Wang et al. 2010). Guided-waves are mechanical stress waves propagating along a media, guided by its boundaries. The advantages of guided-waves for pipeline NDE include full coverage of the wave guide over long ranges without significant energy loss, high sensitivity to various types/sizes of damage, and high time and cost efficiency (Rose 2004; Wang et al. 2010).

However, the multi-modal, dispersive and multi-path characteristics of guided-waves result in complex signals whose interpretation is a challenging task. Guided-wave based damage detection becomes even more difficult when EOCs vary (Liu et al. 2012b; Scalea and Salamone 2008; Sohn 2007). The effects of EOC variations, such as changes in temperature, humidity, flow rate, etc., on guided-waves range from generation of additional wave modes to changes in the wave velocity, attenuation rate, etc. (Aristégui et al. 2001; Long et al. 2003; Scalea and Salamone 2008). Such effects degrade the performance of damage detection, by masking the changes caused by structural anomalies and introducing type I and II errors.

During the past decade, a number of researchers have utilized recent advances in data analysis techniques to overcome some of these challenges and enhance the potentials of guided-waves for damage detection (*e.g.*, Liu et al. 2012a, Lu and Michaels 2009, and Ying et al. 2013). However, real-world application of guided-waves for pipeline NDE is still quite limited (Cawley et al. 2003).

In this paper, first, the current literature in the field of guided-wave based testing is reviewed in order to identifiy research gaps to be addressed for enhancing the application of these systems in pipeline NDE. The results of our literature review suggest that the effects of EOCs, namely temperature, flow rate and inner pressure, are not well-studied for guided-wave based systems in pipes. In addition, it is identified that there is a diconnect between the studied effects of EOCs and damage detection. This limits the extensibility of developed approaches to different scenarios.

Finally, the results of two case studies investigating the effects of flow rate variations on guided-waves from a fully operational piping system are reported. The findings verify the identified gaps and motivate further steps of this research, namely analytical incorporation of the effects of EOCs into damage detection of pipes.

RESEARCH BACKGROUND AND GAP ANALYSIS

In this paper, research studies in the field of guided-wave based testing are analyzed in terms of: (1) types and features of the structures (complex vs. simple, or pipe *vs*. plate), (2) types of the experimental testbeds (simulated, controlled laboratory, and field), (3) characteristics and complexities of the signals (single-mode excitation *vs*. broad-band/multi-mode excitation), (4) consideration of EOCs (presence *vs*. absence of EOC variation, and type of EOC), and (5) methods for reflecting or coping with the effects of EOCs (compensation methods for baseline subtraction, damage sensitive features, or none). Based on the results of our literature review, research studies to date fall under one or more of the following categories regarding the consideration of EOCs:

(a) Many of these approaches either ignore or control the effects of EOCs (*e.g.*, Alleyne et al. 2001; Davis et al. 2008; Deng et al. 2008; Wang et al. 2010).

(b) When EOCs are considered, these approaches rely on baseline signals, which either need to be recorded under very similar conditions to the test observations, or are insufficiently manipulated to compensate for only part of the effects of some EOCs (mainly, time-shift effects of temperature in plates) (*e.g.*, Clarke et al. 2009; Scalea and Salamone 2008; Konstantinidis et al. 2006).

(c) There is a disconnect between the studied effects of EOCs and damage detection approaches (*e.g.*, Croxford et al. 2010; Lu and Michaels 2005).

These results suggest that although a growing number of studies have focused on investigating the impacts of varying EOCs on guided-waves in different media (*e.g.*, Aristégui et al. 2001; Clarke et al. 2009; Scalea and Salamone 2008), significant gaps still need to be addressed for characterization of the effects of typical EOCs in pipeline applications. Identified gaps are dicussed under two main challenges:

Effects of EOCs. Research gaps regarding the effects of two types of EOCs, namely *temperature variation* and *existence of coupling material*, are reviewed here, due to two main reasons: (1) theoretical/experimental studies to date reveal that these EOCs can significantly affect physical characteristics of guided-waves; thus, damage detection; (2) a wide range of pipeline applications are exposed to these EOCs.

Effects of Temperature Variations. Effects of temperature variations on guided-waves are more widely studied compared to other EOCs, mainly because it is the most commonly encountered varying EOC in different structures (e.g. Clarke et al. 2009; Scalea and Salamone 2008). Moreover, guided-wave systems can be very vulnerable to temperature variations because several components of the system can be affected by such changes. Temperature-dependent parameters of these systems include (a) physical/geometrical properties of the media, (b) physical properties of the transducers, and (c) the interactions among transducers and the media (Croxford et al. 2007; Lu and Michaels 2009; Scalea and Salamone 2008; Schulz et al. 2003).

The effects of the media are mainly through changes in boundary conditions of the wave guide due to thermal expansion/compression, and change in material properties. This can be in the form of (1) a change in the length of travel path of the wave; (2) a change in thickness of the media; (3) a change in the material properties of the media such as Young's modulus (E), stiffness (G), and bulk wave velocity. Changes in these properties will alter wave characteristics mainly through affecting the solutions of the equations of motion, so called dispersion or frequency equations. Moreover, studies suggest that temperature variations can affect other aspects of guided-waves, such as amplitude, due to impacts on other *temperature-dependent parameters* (Scalea and Salamone 2008; Schulz et al. 2003).

The majority of the studies investigating the effects of temperature variations are limited to individual modes propagating in plate-like media. However, the propagation and dispersion behavior in cylindrical media shows significant difference compared to plate. For example, dispersion curves are completely different in low frequency ranges (Rose 2004), which are used in the majority of guided-wave based

NDE approaches (Long et al. 2003; Raghavan and Cesnik 2007). Moreover, in the case of cylindrical media, three different types of modes need to be studied, namely longitudinal (L), torsional (T) and flextural (F) modes, as opposed to two Symmetric and Antisymmetric modes in plates. There are infinite number of each type of modes in cylindrical media. These modes have different propagation and dispersion characteristics, making them sensitive to different types of damage/EOC, which adds to the complexity of wave behavior in pipes.

To the best of our knowledge, the literature of guided-wave testing needs more formal investigations on the effects of temperature variations in pipes. Previous laboratory and field experiments conducted in our group on damage detection of pipes with varying temperatures suggest that linear machine learning and signal processing methods can separate the effects of damage from those caused by temperature under certain conditions (*e.g.,*Liu et al. 2012a and 2012b; Ying et al. 2013). However, the physical process through which temperature variations influence wave propagation in pipes is not studied. Moreover, the effects on the performance of the developed damage detection approaches are unknown.

Effects of Coupling Media. Generally, the complex behavior of the ultrasonic guided-waves at the interface of two media is due to (1) refraction and reflection of the energy, and (2) mode conversion at the interface through distribution of the wave energy into longitudinal and torsional waves (Rose 2004).

Guided-wave based testing of pipelines is a multi-layer problem. Interaction of the real-world pipelines with multiple materials, such as soil or water surrounding the burried pipes, and/or fluid carried by pipes, weaken the validity of approaches that are based on single-layer assumptions.

The radial displacements (u_r) of the pipe wall associated with longitudinal, torsional, or flextural modes can generate longitudinal waves along the coupling material (*e.g.,* soil or fluid). On the other hand, axial (u_z) and angular (u_θ) displacements can generate other mode types in the coupling media. Only longitudinal waves can propagate through fluid, while other mode types can also be generated in soil. Such phenomena affect guided-waves through impacting attenuation, dispersion curve, wave velocity, *etc.* (Rose 2004).

Although the studies to date provide necessary foundation for understanding the effects of coupling media, one of the main gap in the current body of knowledge in guided-wave based NDE of pipes is that the fluid inside the pipe is assumed to be *static* and *unpressurized*, which is not realistic for most of the pipeline operations. Previous studies conducted in our group (e.g. Harley et al. 2012; Liu et al. 2013; Ying et al. 2013), have shown the masking effects of internal air pressure of the pipes on ultrasonic guided-wave based damage detection. These studies have identified features and corresponding damage detection algorithms that are less sensitive to air pressure variations. However, these approaches still lack the necessary understanding about the effects of inner pressure on both wave propagation characteristics and different aspects of the developed damage detection approaches. Moreover, to the best of our knowledge, studies to date have not formally incorporated the effects of flow rate variations on guided-wave based NDE of pipelines.

Complexity of the Signals. Guided-waves travelling along complex structures, like pipes, under varying EOCs, lead to complex signals, due to refraction and reflections from boundaries, welding, and/or damages. These complex waves are known as *diffuse-field* (Lu and Michaels 2009).

However, the results of our literature review reveals that the majority of studies on guided-wave based testing of pipes are based on individual wave modes, through narrow-band excitation and/or specifically designed transducer setups (e.g. Alleyne et al. 2001; Long et al. 2003; Wang et al. 2010). Narrow-band single-mode excitation reduces the complexity of the received signals and thus makes their interpretation easier. However, due to the aforementioned effects, the received signal will not maintain the purity of the excited individual mode. The cost and implementation difficulties associated with excitation of individual modes further limits the real-world applicability of approaches relying on single-mode excitations.

Studies such as Weaver and Lobkis (2000), and Lu and Michaels (2009) have showed that the effects of temperature variations in *diffuse-field* guided-waves in plates can be characterized as time-shift impacts. The results of these studies are promising, however, there is still a gap in studying such effects on *diffuse-field* guided-waves propagating in pipes.

PRELIMINARY WORK: EFFECTS OF FLOW RATE

The aforementioned research gaps in studying the effects of EOCs other than temperature, such as flow rate, motivated the following case studies. Ultrasonic pitch-catch records are collected from a campus building hot water piping system, operating continuously under changing temperature, flow rate, and pressure (Liu et al. 2012b). It is a Schedule 40 steel piping system with 25.4 *cm* inner diameter and 9.2 *mm* wall thickness. Due to periodic pumping of hot water into the heat cycle, the hot water flow rate varies from 0.76 to 1.7 m^3/min, and the water temperature fluctuates from 37 to 60 ^oC. Temperature and flow rate values for each observation are recorded using the in situ sensors. The dataset consists of 10,000 records from undamaged and damaged (simulated by placing a grease-coupled mass scatterer) scenarios.

Case Study #1. Our experiments show that possible *time-shift* effects of flow rate variations can be as considerable as those caused by temperature variations. The method used by Weaver and Lobkis (2000) for estimating *time-shift* effects of temperature variations in plate is employed here. In summary, the method consists of (1) time-windowing the signals, (2) applying cross correlation in each window between two signals with different temperatures, and in this study, different flow rates (*i.e.*, ΔT and ΔF), and (3) plotting the time-delay, corresponding to maximum cross correlation, versus the center of each time-window. The slope of the least-square fitted line represents the *time-shift* due to EOC difference between two signals. Figure 1 shows *time-shift* in signal pairs with $0 \leq \Delta F \leq 0.53$ m^3/min, and $\Delta T = 0$. It is observed that *time-shift* rate increases as ΔF betweem the signal pairs increases, and this effect becomes more recognizable at larger ΔFs (mainly, $\Delta F >\sim 0.19$ *m3/min*). Similar experiment is conducted on pairs with different temperatures ($\Delta T \neq 0$) but the same flow rate ($\Delta F = 0$). It is observed that *time-shift* caused by flow rate differences (ΔF) can be as significant as that caused by temperature variations (ΔT).

Case Study #2. To study the *amplitude effects* of flow rate, the metric introduced by Clarke et al. (2009) is examined:

$$AM\ ratio = \log\left(\frac{Signal1 - Signal2}{Amplitude\ of\ the\ first\ arrival}\right)$$

This metric measures the amplitude change among a pair of signals at any point of time. The idea is to investigate how comparable the effects of temperature and flow rate variations are on the signal amplitude. To investigate this, AM ratios are calculated for more than 350,000 pairs of signals with different ΔF and ΔTs. Baseline pairs, for which the AM ratio is supposedly small, are defined as those with no flow rate and temperature difference ($\Delta F = 0$ & $\Delta T = 0$). To determine the drift effects (D_j) of ΔF and ΔT for a signal pair *j*, first, the root mean square (RMS) errors among the AM ratio of this signal pair (AM_j) and the AM ratio of the *i*th baseline pair (AM_i) are calculated: $d_{ji} = RMS(AM_j - AM_i)$. Averaging the calculated d_{ji}s gives the average drift due to ΔF and ΔT of the *j*th signal pair: $D_j = \frac{1}{N}\sum_{i=1}^{i=N} d_{ji}$, where N is the number of baseline pairs. Figure 2 plots the average drifts (D_j) for all signal pairs with different values of ΔF and ΔT. Interestingly, it is observed that for $\Delta F <$~ 0.19 *m3/m*, the AM ratio drift is small, no matter how large the ΔT among the signal pairs is. Moreover, for $\Delta F >$~0.19 *m3/min*, the drift is large, even for small values of ΔT. The maximum drift occurs more often when $\Delta F >$~0.19 *m3/min* and $\Delta T >$~ 2.2 ^oC.

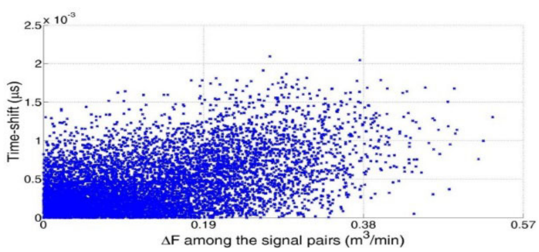

Figure 1. Time-shift rates for signals with $0 \leq \Delta F \leq 0.53\ m^3/min$ & $\Delta T = 0$.

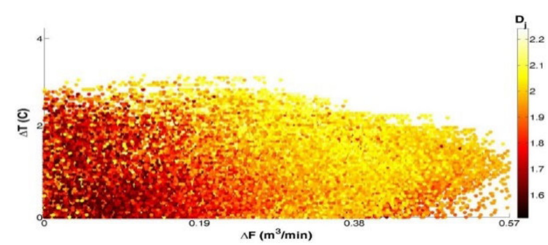

Figure 2. Amplitude drift effects (D_j) of flow rate and temperature variations.

CONCLUSION AND FUTURE WORK

This paper summarizes the results of an extensive literature review, gap analysis and preliminary case studies, which motivate further steps of a research project to address one of the main challenges in real-world application of guided-wave based NDE of pipelines, namely sensitivity of these waves to the variations in EOCs.

Our literature survey suggests that there is a need for (a) theoretically and experimentally grounded understanding about the effects of typical EOC scenarios in pipeline applications, and (b) analytically incorporating such effects into damage detection approaches. According to our analysis, lack of studies on temperature variations in pipes, unrealistic assumptions about static and unpressurized state of the fluid carried by pipes, and considering pure and single-mode signals are major gaps that need to be addressed to achieve the aforementioned goals.

These findings motivated case studies in which diffuse-field guided-waves are used to compare the effects of flow rate with thoes of temperature. Effects of flow rate, such as those presented in this paper, weaken the real-world applicability of damage detection approaches that ignore flowing fluid inside pipes. Moreover, it is observed that physical properties of guided-waves become more sensitive to temperature and flow rate variations when these EOCs co-occur.

Future work will focus on investigating the effects of EOC scnerios through experiments on numerically simulated, controlled laboratory and field measurements. The observed effects of EOCs will be analytically incorporated into damage detection, and data analysis techniques will be employed to linearly separate and/or compensate the characterized effects. The envisioned outcomes of this research will improve real-world applicability of feature-based and baseline-subtraction damage detection methods for pipelines.

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