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An energy-based sparse representation of ultrasonic guided-waves for online damage detection of pipelines under varying environmental and operational conditions

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A B S T R A C T

This work addresses the main challenges in real-world application of guided-waves for damage detection of pipelines, namely their complex nature and sensitivity to environmental and operational conditions (EOCs). Different propagation characteristics of the wave modes, their distinctive sensitivities to different types and ranges of EOCs, and to different damage scenarios, make the interpretation of diffuse-field guided-wave signals a challenging task. This paper proposes an unsupervised feature-extraction method for online damage detection of pipelines under varying EOCs. The objective is to simplify diffuse-field guided-wave signals to a sparse subset of the arrivals that contains the majority of the energy carried by the signal. We show that such a subset is less affected by EOCs compared to the complete time-traces of the signals. Moreover, it is shown that the effects of damage on the energy of this subset suppress those of EOCs. A set of signals from the undamaged state of a pipe are used as reference records. The reference dataset is used to extract the aforementioned sparse representation. During the monitoring stage, the sparse subset, representing the undamaged pipe, will not accurately reconstruct the energy of a signal from a damaged pipe. In other words, such a sparse representation of guided-waves is sensitive to occurrence of damage. Therefore, the energy estimation errors are used as damage-sensitive features for damage detection purposes. A diverse set of experimental analyses are conducted to verify the hypotheses of the proposed feature-extraction approach, and to validate the detection performance of the damage-sensitive features. The empirical validation of the proposed method includes (1) detecting a structural abnormality in an aluminum pipe, under varying temperature at different ranges, (2) detecting multiple small damages of different types, at different locations, in a steel pipe, under varying temperature, (3) detecting a structural abnormality in an operating hot-water piping system, under multiple varying EOCs, such as temperature, water flow rate, and inner pressure; and (4) detecting a structural abnormality as the ratio of the damaged pipe's signals in the reference dataset increases.

1. Introduction

Pipelines are crucial infrastructure components for a variety of applications at different scales. Undetected damages in pipelines, or a delay in detecting them, can have significant consequences. For example, between 1994 and 2013, on average,

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531 incidents have been reported every year [1]. Among the annualized impacts of these incidents are 19 fatalities, cost of almost $309 million, and more than 133,000 barrels of spilled hazardous liquid [1]. In spite of recent advances in data acquisition and testing systems, between 2010 and 2012, only 28% of the reported incidents in the instrumented pipelines have been detected by such systems [2]. In order to improve the reliability of structural health monitoring (SHM) systems for pipelines, and to fully benefit from the advances in sensing technologies, as well as data-driven analytics, the practical challenges of these systems need to be studied and formally incorporated into the monitoring process.

Among nondestructive evaluation (NDE) techniques, the benefits of guided-wave based NDE systems for pipeline SHM have been discussed for over half a century, since Worlton recognized their potential [3]. Guided-waves are mechanical stress waves propagating along a media, guided by its boundaries [4]. They are very sensitive to different types and sizes of damage, travel long distances without significant energy loss, and provide full coverage of the thickness and surface of the pipe as they travel [4–9]. However, despite their many advantages, real-world application of guided-wave based systems for monitoring of pipelines is still quite limited [6]. Based on our previous work [10], the challenges of guided-waves can be summarized under three main headings, namely multiple modes, multi-path reflections and sensitivity to environmental and operational conditions (EOCs). In any given frequency, often more than one guided-wave mode is excited. These wave modes have different propagation characteristics, and have different sensitivities to different types and ranges of EOCs [11,12] and to different damage scenarios [8,13–15]. Therefore, extracting damage information from complex superposition of multiple modes can be a challenging task. Multi-path reflections from the structural features and/or damage can add to these complexities. These reflections may include effects such as mode conversion, change in wave velocity, energy dissipation, *etc*., which may make the interpretation of the recorded signal more complicated [16–18]. Finally, yet importantly, similar to damage, EOCs alter guided-wave signals, and therefore may mask and/or appear as the effects of damage, leading to type I and type II errors [19–23].

Addressing these challenges and extracting damage information from complex guided-waves have been the subjects of vast number of studies. The majority of these works fall under one or more of the following categories: (A) single-mode excitation, (B) compensation methods for EOC effects, mainly temperature, and (C) decomposition of the signal into its components in order to extract the signal scattered from damage. One of the most widely considered solutions is to excite limited number of modes in a non/less dispersive range [7,8,15,24]. However, as many of these studies have revealed, different wave modes are sensitive to different damage features. Considering the fact that the geometry of a real damage can extend in any or all of the axial, radial and circumferential directions, damage diagnostics based on single-mode excitation may lose the benefits of multiple modes for full characterization of the damage. Moreover, in dynamic operational conditions of real-world pipelines, the propagated guided-wave may not maintain the purity of the excited single mode, because of the effects such as mode conversion, multi-path reflection, EOC effects, *etc*. In the second category of studies, the effects of temperature on wave velocity are often approximated as stretching/compressing of the signal in the time and/or frequency domain [19,25,26]. After compensating for such effects, baseline-subtraction methods can be used for damage detection under varying temperature. However, such stretching methods may successfully approximate the effects of only a small range of temperature variation, *i.e.,* 0.5–1 °C, depending on the complexity of the structure and the number of propagating modes [11,26,27]. Moreover, other EOCs, such as fluid flow rate and inner pressure [11,28–30], can further degrade the performance of such methods. Recently, some statistical learning techniques have been applied to decompose guided-waves into their base components, in order to extract the damage-sensitive basis of the signal [31–33]. Often time, these studies are based on linear decomposition techniques. However, as shown in our previous work [11], under varying EOCs, the bases of a multi-modal guided-wave signal are nonlinearly related to each other. This may limit the extensibility of the linear decomposition methods to cases with wider ranges/types of EOCs, where the dependencies between the bases may significantly deviate from linearity [11]. Moreover, improvements are still needed to address limitations such as reliance on a network of transducers, a dictionary of bases, prior knowledge about the damage characteristics, case-specific tuning parameters, *etc*.

In our prior work [10], we developed a supervised feature-extraction method for online damage detection of pipelines under varying EOCs, using diffuse-field multi-modal guided-waves. In the sparse discriminant (SD) method developed in [10], detection performance is maximized by imposing a sparsity constraint on the signals to best estimate the state of a pipe. In the training stage, data is recorded from an undamaged pipe, as well as a pipe with structural abnormality. During the monitoring stage, test signals are projected on the sparse discriminant vector to predict the state of the pipe. The validation results suggested that a simple binary-labeled training data (*i.e*. undamaged/damaged), obtained under a limited range of EOCs, is sufficient for the proposed supervised SD method (please refer to Eybpoosh et al. [10] for more details). However, the application of the supervised SD method is limited to the cases where imposing the structural abnormality to the pipe and obtaining the labeled training data is possible and practical.

This paper addresses this issue, in addition to the discussed challenges for damage detection of pipelines. In particular, the objective is to develop an unsupervised feature-extraction method for online damage detection of pipelines operating under varying EOCs, using diffuse-field guided-waves. We achieve this goal by simplifying diffuse-field signals into a sparse subset that is more affected by damages of different characteristics than EOC variations. The unsupervised approach eliminates the need for labeled training data, which, as mentioned before, can be a challenge for some applications such as the pipes with restricted accessibility. Moreover, as also verified by our results, this makes the detection method independent from prior knowledge about the damage characteristics (*e.g.* type, size, location, *etc.*). A set of unlabeled signals from a pipe, which is assumed to be in its undamaged state for the majority of the data collection period, are used as