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Novel leak localization in pressurized pipeline networks using acoustic emission and geometric connectivity

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ABSTRACT

Time dependent aging and instantaneous threats can cause the initiation of damage in the buried and on-ground pipelines. Damage may propagate all through the structural thickness and cause leaking. The leakage detection in oil, water, gas or steam pipeline networks before it becomes structurally instable is important to prevent any catastrophic failures. The leak in pressurized pipelines causes turbulent flow at its location, which generates solid particles or gas bubbles impacting on the pipeline material. The impact energy causes propagating elastic waves that can be detected by the sensors mounted on the pipeline. The method is called Acoustic Emission, which can be used for real time detection of damage caused by unintentional or intentional sources in the pipeline networks. In this paper, a new leak localization approach is proposed for pipeline networks spread in a two dimensional configuration. The approach is to determine arrival time differences using cross correlation function, and introduce the geometric connectivity in order to identify the path that the leak waves should propagate to reach the AE sensors. The leak location in multi-dimensional space is identified in an effective approach using an array of sensors spread on the pipeline network. The approach is successfully demonstrated on laboratory scale polypropylene pipeline networks.

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1. Introduction

Pipeline networks are regularly inspected using methods such as smart pigs that are cylinder-shaped electronic devices to detect metal loses, mapping tools based on GPS for above ground pipelines, guided wave ultrasonics and hydrostatic testing [1]. Rose et al. [2] are the pioneers in the use of guided wave ultrasonic method to inspect pipelines, and they discuss the latest generation guided wave approach for long range pipeline inspection. Elliott et al. [3] developed “SmartBall” which is a spherical acoustic device traveling through the pipeline for leak detection. The inspection methods are applied based on the maintenance schedule of pipelines. They cannot detect instantaneous changes in the structure due to sources such as impact, crack growth. Caleyo et al. [4] demonstrated that prioritizing the pipeline inspection and maintenance based on the failure data might establish incorrect prioritization due to significant uncertainty of pooling failure of dissimilar pipeline systems data.

As continuous online monitoring methods, Kishawy and Gabbar [1] list the conventional monitoring methods for leak detection such as mass-balance method, pressure drop method, and consider these methods as the laborious and inefficient, and conclude that the pipeline integrity technologies must continue to evolve. As a real time monitoring system, Shinozuka et al. [5] developed wireless MEMS based acceleration sensor (frequency in the range of Hz) networks for monitoring damage in water pipeline networks. Wan et al. [6] developed an automated pipeline monitoring system for detecting cutters as potential threats to pipelines. The system uses audible acoustic waves and a pattern recognition algorithm to differentiate cutter noise and others. Higgins and Paulson [7] implemented the use of fiber optic sensor for Acoustic Emission sensing for detecting wire breaks in concrete pipelines. Inaudi and Glisic [8] presented the use of fiber optic sensor to monitor temperature and strain as an indirect way of leakage. The authors claim that a single fiber optic instrument can monitor up to 60 km.

As discussed above, there are various studies in the literature on sensor development using MEMS and fiber optic technologies for damage detection in pipelines using acoustic methods. In this paper, a new source location methodology is tested on a pipeline network in order to locate the leak source in 2D using 1D source location algorithm and geometric connectivity. The methodology is applicable to any types of novel acoustic sensors.

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2. Acoustic emission method

The Acoustic Emission method is a nondestructive testing method that relies on propagating transient waves generated by sudden stress-strain change in a material such as crack growth, leak, impact. There are two types of acoustic emissions as defined by ASTM E 1316 [9]: burst type as a qualitative description of the discrete signal related to an individual emission event occurring within the material, and continuous type as a qualitative description of the sustained signal level produced by rapidly occurring acoustic emission sources. Majeed and Murthy [10] defined the AE signals including nonzero rise time as compared to traditional zero rise time signal presentation. In this study, the burst type AE signal $V_{\mathrm{burst}}(t)$ for single frequency f_o is idealized in order to include the arrival time factor into the formulation using the following equation:

$$V_{\mathrm{burst}}(t) = V_o \sin(2\pi f_o t)\left\{\left(1 - e^{-(t-t_{\mathrm{arrival}})/t_{\mathrm{rise}}}\right)\in 0..1\right\} \times e^{-(t-t_{\mathrm{arrival}})/t_{\mathrm{decay}}} H[t - t_{\mathrm{arrival}}] \quad (1)$$

where the term $\{(1 - e^{-(t-t_{\mathrm{arrival}})/t_{\mathrm{rise}}})\in 0\ldots1\}$ indicates the rise time function normalized to be in the range of 0–1, t_{rise} is rise time, the term $e^{-t/t_{\mathrm{decay}}}$ indicates the decay time with t_{decay}, the term $H[t - t_{\mathrm{arrival}}]$ is Heaviside function indicating the waveform arrival to the sensor at t_{arrival}. Examples of burst type include crack growth, impact, which are instantaneous sources as shown in Fig. 1a based on Equation (1) for 100 kHz frequency, 40 μs arrival time, 20 μs rise time and 40 μs decay time. The continuous type AE signal $V_{\mathrm{continuous}}(t)$ for single frequency f_o is idealized using the following equation:

$$V_{\mathrm{continuous}}(t) = \sin(2\pi f_o t)\sum_{i=1}^{\infty} V_i\left\{\left(1 - e^{-(t-t_{\mathrm{arrival}})/t_{\mathrm{rise}}}\right)\in 0\ldots1\right\} \times e^{-(t-t_{\mathrm{arrival}}(i))/t_{\mathrm{decay}}(i)} H[t - t_{\mathrm{arrival}}(i)] \quad (2)$$

Examples of continuous type include leak, friction which are spatially stationary sources as shown in Fig. 1b based on Equation (2). As compared to the burst type AE signal, the continuous AE signal does not have a definite rise time, and can be idealized as the summation of multiple wave arrivals using Heaviside functions. The AE patterns of different sources can be used in source discrimination algorithms.

The AE method has been successfully applied to monitor crack growth in pressure vessel steels [11], and assess the structural integrity of various pressurized components [12]. Miller et al. [13] studied the leak rate of 0.38 dm^3/h generated in flange gaskets and pipe threads using the AE method, and showed that below 689 kPa the leak at this rate may not be turbulent so the flow of the liquid produces little or no AE. Kosel et al. [14] showed the combination of cross correlation function with an appropriate bandpass filter for locating continuous AE sources.

The AE method is capable of source localization by means of local, global, remote and online monitoring. The ability of the AE method to locate time dependent (e.g. crack growth) or instantaneous sources (e.g. impact) with the sensors further from the flaws is a major advantage as compared to other NDE methods. However, the complexity of the pipeline networks makes the applications of AE method for the source localization using conventional source location methods difficult. Typical assumptions of the source location algorithms are: (a) the AE event originates from a point source, (b) the source to the sensor path is straight, (c) the medium is isotropic and (d) a set of acoustic arrivals is related to a single source [15]. The second assumption causes significant error if the conventional source localization algorithm is applied to structures that are spread in two dimensions while they could be idealized as one dimensional due to the length to cross section ratio.

3. Theory of leak location methodology

The location methodology used in this study is based on the source location algorithm developed by Ozevin [16] for truss bridges. The methodology combines the geometric boundaries of the structure to define the shortest wave paths from the leak sources to the AE sensors using the local coordinate system. For example, Fig. 2 shows a 2D pipeline network formed by six

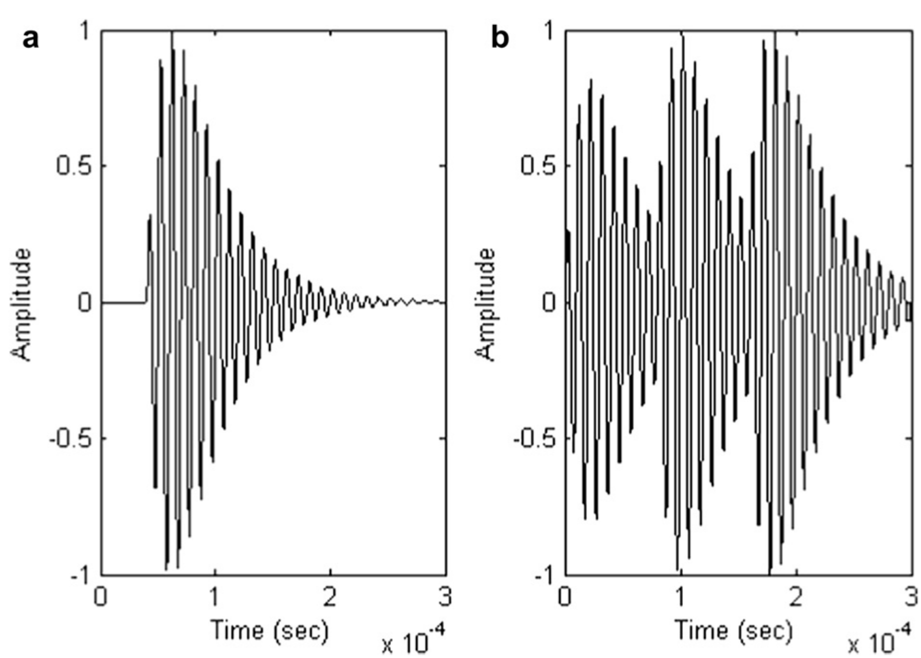

Fig. 1. Simulated AE signatures, (a) burst type, (b) continuous type.

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