Digital Signal Processing 76 (2018) 59–65

Contents lists available at ScienceDirect

Digital Signal Processing

www.elsevier.com/locate/dsp

A passive acoustic based system to locate leak hole in underwater natural gas pipelines

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ARTICLE INFO

Article history:
Available online 15 February 2018

Keywords:
Gas bubble
Leakage
Received signal strength
Source localization
Underwater natural gas pipeline

ABSTRACT

Underwater natural gas pipelines can be punctured for a variety of reasons, but the most notable are corrosion and aging. This study proposes a novel passive acoustic based system, to detect acoustic signals, locate the leak holes, and determine the size of the leak holes remotely. The nature of acoustic signals, which are generated by leakages in underwater natural gas pipelines, is also examined. The success of this proposed localization method, which is based on the received signal strength technique, is analyzed by numerical studies and simulation works. Parameters, which are used in the numerical studies, are taken from a hypothetical pipeline whose specifications are similar to Maghreb-Europe Gas pipeline. The proposed method is examined for various measurement numbers, underwater ambient noises, the diameters of the leak holes and receiver numbers. It is shown that leakages can be located with low average position errors from several kilometers by depending on underwater ambient noise, detection method, receiver number, source strength and measurement number.

1. Introduction

Natural gas is an important energy resource transported from production locations to demand centers using pipelines. A significant percentage of pipelines are installed underwater. Underwater sections of the pipelines can be punctured by internal and external corrosion, pitting, erosion, fatigue cracking, ship anchors, manufacturing flaws and tectonic movements of the seabed [1]. Underwater natural gas pipelines (UNGPs), which were installed in the late 1900s, are still in use [2]. These pipelines are especially susceptible to corrosion, combined with aging and the reasons stated above, they are prone to puncture. Therefore, monitoring the pipelines, detecting and locating leakages and refitting leak holes have an important role in energy safety.

In the literature, various methods were proposed to detect gas leakages and/or locate leak holes in UNGPs [1,3–6]. These methods are classified into two parts internal (based on only software) and external (based on hardware) methods. Internal based methods were composed of pressure/flow change, mass/volume balance, pressure point analysis, negative pressure wave and real time transient modeling [1,3,4]. It is possible to detect a gas leakage using internal methods. However, these methods are expensive, and have proven to be unsuccessful in locating gas leak hole, and working on long pipelines [1,3,4]. External methods are comprised of capacitance, semi-conductor, optical camera, bio sensor, fiberoptic cable, fluorescent and acoustic [1,5,6]. It is also possible to detect a gas leakage using external methods. However, with the exception of the acoustic method, the success of these methods depends on the turbidity and the current of the water, they are also expensive, and fail in gas leak hole localization [5].

The passive acoustic method is based on listening to acoustic signals using underwater microphones, known as hydrophones. Unlike the active acoustic method, an acoustic transmitter is not required in the passive acoustic method. The passive acoustic method works effectively in an underwater medium, because the acoustic propagation is not dependent on the current and turbidity of the water. Additionally, even if a leak has small dimensions, the acoustic signal generated by the leak can be strong. Thus, the passive acoustic method may be considered superior for locating leak holes in the UNGPs when compared to other methods. According to [7] and the best of Author's knowledge, passive acoustic detection for underwater gas pipelines is only performed in [6] with a commercial purpose. The said work was performed in Adriatic Sea in 2001. An acoustic leak detection (ALD) system was suspended 10–20 meters height above a 30 km pipeline and towed along the pipeline for a few hours. This method successfully detected a single leak with a diameter of 4 mm from a distance of 90 m. However,

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https://doi.org/10.1016/j.dsp.2018.02.007
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this work was performed as a utilitarian work, thus there was no examination of the nature and propagation of the acoustic signal.

Generally, the localization of a leak hole, in the underwater natural gas pipelines, is a source localization problem. The literature contains passive acoustic based various techniques to pinpoint a typical source in the underwater medium. These are time of arrival (TOA) [8], time difference of arrival (TDOA) [9], received signal strength (RSS) [10] and direction of arrival (DOA)[11] techniques. The TOA, TDOA and DOA techniques are not suitable for locating leak holes in UNGPs. The TOA technique needs to know exactly when the signal has reached the hydrophones from the hole. It is not possible to know the moment a UNGP was punctured. On the other hand, the TDOA technique requires the difference of arrival times, which may not be observed since pipeline may not be punctured all at once. DOA technique is inapplicable to underwater medium because hydrophone mobility effects introduce the Doppler shift. Unlike the TOA, TDOA and DOA techniques, the RSS technique does not require time synchronization, arrival time information and it is not sensitive to mobility effects [12]. Additionally, the RSS technique is cost effective and easier to implement when compared to the TOA, TDOA and DOA techniques. According to the best of our knowledge, the RSS technique has not been previously used for the localization of a leak hole in the UNGPs.

In this paper, we proposed a novel passive acoustic based system to detect leakage, locate leak hole and determine size of the leak hole remotely; using RSS technique based localization. The nature and propagation of the acoustic signal is also examined. It is mentioned that diameter of the leak hole and the source strength can be found by using the frequency of the received acoustic pressure signal and necessary parameters, which are taken from a hypothetical pipeline. It is also emphasized that, in a case with more than one hole with various diameters, the number and diameter of the leak holes can be identified by using the frequencies of received signals and the necessary parameters. Simulation results showed that leakages can be located with low average position errors from a distance of several kilometers.

The rest of paper is organized as follows. In Sections 2 and 3, gas bubbles and ambient noise in underwater medium are described. In Section 4, a leak hole localization method is outlined. In Section 5, numerical results are given and the conclusions are summarized in Section 6.

2. Gas bubbles in underwater medium

Gas bubbles entrained in the water can produce considerable sound pressures. Acoustic signals, which are generated by air bubbles produced at a nozzle, was first scrutinized by Minneart [13]. Afterwards, it is shown empirically that the sound is related with volume pulsations of the bubble. Connected with these pulsations the bubble acted as an oscillating system with damping [14]. The relationship among ambient pressure, bubble diameter and oscillation frequency for a bubble with volume pulsation is given in (1) by Minnaert [15].

$$f_0 = \frac{1}{\pi\,(d_b)}\sqrt{\frac{3\kappa P_{amb}}{\rho}} \tag{1}$$

Here, f_0, ρ, d_b, P_{amb} and κ are oscillation frequency (Hz), water density (kg/m^3), bubble diameter (m), ambient pressure (Pa) and the ratio of the specific heats of the gas in the bubble, respectively. P_{amb} can be calculated as $P_{amb} = \rho g h$ where h and g are depth (m) and gravitational acceleration (m/s^2), respectively.

The diameter of the leak hole directly affects bubble diameter. In [16], which is about formation of bubbles from single nozzles in liquid iron, a bubble diameter formula (2) was developed using nozzle diameter. Following this development, (2) is used for bubble formation in water [17].

$$d_b = \left[\left(\frac{6Sd_{no}}{\rho g}\right)^2 + \left(0.54\left(Q\,d_{no}^{0.5}\right)^{0.289}\right)^6\right]^{1/6} \tag{2}$$

Here, S, d_{no} and Q are surface tension (mN/m), outer diameter of nozzle (m) and gas flow rate (m^3/s), respectively. In water, oscillations of bubbles whose diameters are larger than 0.1 mm decrease according to the dissipation constant given in (3) [15].

$$\delta = 0.014 + 4.5.10^{-4}\sqrt{f_0} \tag{3}$$

The instantaneous acoustic pressure signal, which is generated by a single bubble, is given in (4) [15].

$$P = P_0 e^{-(\pi\delta f_0 t)} cos\,(2\pi\, f_0 t - \vartheta) \tag{4}$$

Here, δ, ϑ, P_0, t and f_0 are dissipation constant, phase angle (rad), acoustic pressure amplitude (Pa), time (s) and oscillation frequency (Hz). Phase angle ϑ can be obtained as in (5) by using $(v_0 – V_0) = V_0\ (P_t/P_{amb})$ approximation [15].

$$\vartheta = arctan\left(\frac{-\dot{v_0}}{2\pi\, f_0(v_0 - V_0)}\right) \tag{5}$$

Here, $\dot{v_0}$, v_0, $V_0(=\frac{4}{3}\pi R_0^3)$ and P_t are volume velocity (m^3/s), bubble volume (m^3), mean bubble volume (m^3) at P_{amb} pressure and excess pressure (Pa). P_t and $\dot{v_0}$ are given in (6) and (7), respectively [15]. R_0 (m) is bubble radius.

$$P_t = 2S/R_0 \tag{6}$$

$$\dot{v_0} = 4\pi R_0^2\sqrt{\frac{2P_t}{3\rho}} \tag{7}$$

Peak acoustic pressure at the reference distance d (m) is simply given in (8) [15].

$$P_0 = \left(\frac{R_0}{d}\right)\sqrt{2\kappa P_{amb} P_t} \tag{8}$$

Acoustic pressure signal of a continuous train of bubbles is obtained by using (8) and (4) as in (9).

$$P = \sum_{i=1}^{B} P_0 e^{-(\pi\delta f_0 (t-\tau_i))} cos\,(2\pi\, f_0\,(t - \tau_i) - \vartheta) \tag{9}$$

Here, B and τ_i are the number of oscillating bubbles and the time delay between the first and ith bubbles, respectively. In [18] it is reported that a posterior bubble is generally detached from a leak hole in the instant before the first minimal in the envelope of the prior bubble. As it is seen, (9) is the sum of damped and delayed sinusoidals. Hence, (9) is a continuous sinusoidal signal with f_0 frequency.

3. Underwater ambient noise

Gaussian distribution and a continuous power spectral density (PSD) can characterize most underwater ambient noise sources [19]. Four sources; turbulence (N_t), shipping (N_s), waves (N_w) and thermal noise (N_{th}), are used to model ambient noise in the ocean [19]. The empirical formulae of the PSDs of the four noise components in dB re 1 µPa/Hz as a function of frequency in kHz are given in (10)–(13) [19]. The minimum ambient noise, in the sea, is the combination of waves noise where 0 Beaufort scale (an empirical