Acoustic method for leak size estimation in fluid-carrying pipelines

Georgios-Panagiotis Kousiopoulos, Spyridon Nikolaidis
Physics Department
Aristotle University of Thessaloniki
Thessaloniki, Greece

Abstract—**Pipeline networks are frequently used in a vast number of applications and their secure and undisturbed operation is very important. However, leaks can occur at any time and cause serious problems. For this reason, extensive research has been conducted over the years on the development of effective leak detection and localization methods. On the other hand, very few papers concerning the estimation of the leak size in a pipeline have been published in the literature. This was a main incentive for the development of the leak size estimation method proposed in the present paper. This non-intrusive method uses the acoustic signals produced in the leak point and propagating in the pipeline and it relies on the energy of the signals, which is reflected in the RMS value, and also on proper filtering. Specifically, by the help of some initial measurements, certain position-dependent threshold values are extracted which separate the different leak categories. This way, by the RMS value of a certain acoustic signal, the corresponding leak can be classified into one of the available categories, which differ from each other on the range of the included leak orifice diameters. The proposed method was tested experimentally in a laboratory setup, which contains a water-filled steel pipeline, and its success rate was examined under different ambient noise conditions.**

Keywords—leak size estimation, accelerometers, acoustic signals, non-intrusive technique, ambient noise, signal filtering

I. INTRODUCTION

Nowadays, a large number of industrial, commercial and urban applications require the use of pipeline networks. Such networks provide useful and reliable solutions for the transportation of any kinds of fluids. Nevertheless, they suffer from the occurrence of leaks, which appear quite frequently and pose an obstacle to the safe and normal operation of a pipeline. Hence, the implementation of efficient and reliable pipeline monitoring systems is crucial.

For this reason numerous papers have been published over the years, concerning the development of various methods that can be used for the detection [1-3] and localization [4-8] of leaks in pipelines. However, as far as the estimation of the leak size is concerned, the corresponding research available in the literature is very limited.

One of the few papers about this subject is [9]. In this paper Aamo proposes a method that can be used for leak detection, size estimation and localization, which belongs to the category of "Real Time Transient Modelling (RTTM)" methods. The estimation of the leak size relies on a set of two coupled hyperbolic partial differential equations concerning the flow dynamics. The measured physical quantities in this study are the flow rate and the pressure at the inlet and outlet of the pipe. Therefore, this approach falls into the category of intrusive methods, since it needs manometers and flowmeters installed on the pipe. In addition, it is mathematically quite complex and the results provided by the author have been derived only from simulations and not from experimental testing.

Furthermore, Piltan et al. [10] proposed a hybrid method for leak detection and size estimation which relies on the Takagi-Sugeno (T-S) fuzzy sliding mode extended ARX-Laguerre Proportional Integral observer. This method is also intrusive, as the one in [9], since it requires flow and pressure measurements. Moreover, the length of the experimental setup pipeline is very small (i.e. 2m).

In the present paper, a non-intrusive technique for estimating the size of a leak in a pipeline is proposed. This method uses two accelerometers mounted externally on the pipe (without drilling or otherwise impacting the pipeline structure, which would make the method intrusive) and it relies on the energy of the acoustic waves propagating from the leak point towards the sensors. The presented method is tested on a laboratory pipeline setup and its efficiency is examined both for the case of a pipeline placed in a quiet environment and in a noisy one. The estimation of the leak size is performed by means of separating the possible leak orifice diameters into three categories and the experimental testing shows that the proposed method can provide efficient results, which in the case of no ambient noise can reach a success rate of 100%.

II. PROPOSED METHOD FOR LEAK SIZE ESTIMATION

The objective of the method presented in this paper is to make an estimation of the size of a leak in a pipeline. This estimation is performed after the detection and localization of the leak have been achieved, based on proper methods like the ones presented in [11] and [12], respectively. To this end, two accelerometers are mounted on the external surface of the pipe at a certain distance between them, as shown in Fig. 1. This setup is also used for the identification of the leak position, as described in [12]. The proposed method for the size estimation is comprised of the following steps:

1. Step 1: One of the two available sensors is selected, based on the position of the leak. Specifically, the sensor which is chosen is the one closer to the leak point. For example, in Fig. 1 the leak point is closer to Sensor 1 (i.e. $x < L/2$), so this is the sensor that is going to be selected. The data from this sensor are the ones that are going to be processed in the next steps. Also, the information about the leak position is available from the localization procedure [12].

2. Step 2: Noise rejection is performed by proper filtering of the measured signal. The sampling frequency of the data acquisition system that was used is 25.6 kHz, thus providing a useful spectrum from 0 to 12.8 kHz. When the ambient noise is negligible, the employed FIR filter rejects only the spectral region below 200 Hz, because at these low frequencies electromagnetic interference from the power grid and, also, spectral components from the pipeline machinery (e.g. the circulator) are present. On the other hand, when there is significant ambient noise, a highpass filter is applied to the measured signal with a cutoff frequency that depends on the spectrum of the noise and the pipeline setup. For the setup examined in this paper the cutoff frequency is set to 9.5 kHz, because there are some high-frequency noise components that need to be eliminated. This can be observed in Fig. 2.

3. Step 3: The root-mean-square (RMS) value of the filtered signal is calculated and it is compared to the position-dependent threshold RMS values separating the three different leak categories, which are the following: a) small leaks, b) medium leaks and c) large leaks. This way each leak can be classified to a certain category. The calculation of the threshold values will be explained in the next paragraphs.

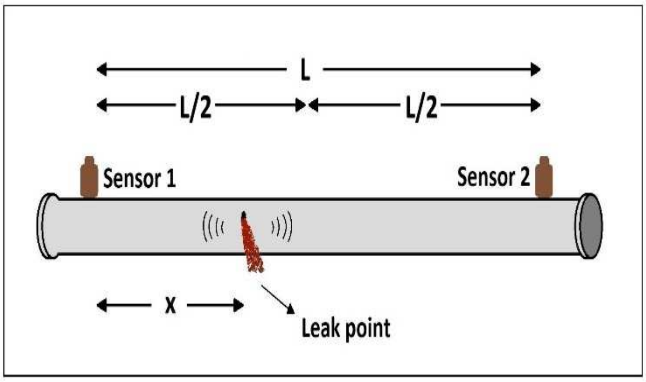

Fig. 1. Pipeline setup with the sensors mounted on the external surface for the estimation of the leak size.

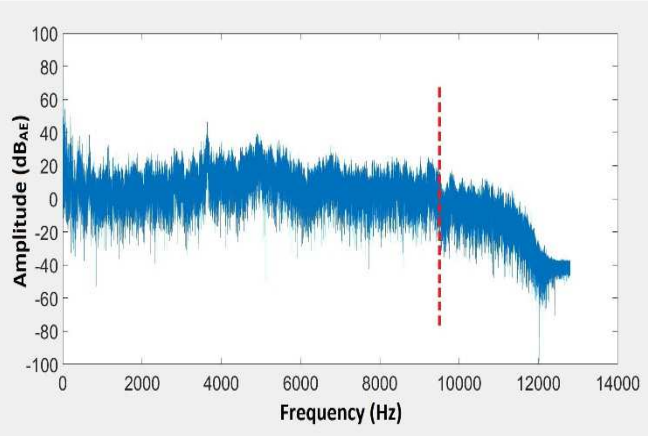

Fig. 2. Spectrum of the ambient noise. The horizontal axis shows the frequency in Hz and the vertical axis corresponds to the amplitude measured in dB$_{AE}$ (1 μV voltage reference). The dashed red line shows the cutoff frequency (9.5 kHz) of the highpass filter.

Prior to the application of the proposed method to a particular pipeline, a number of leaks with different orifice diameters are emulated at certain locations in the pipeline, by the help of proper valves. If only one valve is available, this can still be achieved by moving the sensors properly. Then, leak measurements are conducted and the RMS values of the filtered signals from the sensor closer to the leak are determined. These RMS values are plotted against the corresponding leak positions (i.e. distance of the leak from Sensor 1) and leak orifice diameters in a 3D diagram and then a multiple regression is applied to these data.

In order to perform the multiple regression, the mathematical relationship between the RMS value and the leak position and orifice diameter (i.e. leak size) should be introduced. These three quantities are connected by the following equation:

$$V = V_0 \cdot e^{\alpha x} \cdot e^{kd} \Rightarrow V = V_0 \cdot e^{\alpha x + kd} \qquad (1)$$

where V is the RMS value of the signal acquired by the sensor, x is the leak position, d corresponds to the leak orifice diameter and V_0, α and k are constants. The above equation has been derived experimentally from numerous observations made in the laboratory pipeline setup (that will be described in the next section). Specifically, it was found that the energy of an acoustic signal drops exponentially with the propagation distance and also it increases exponentially with the leak diameter. By taking the natural logarithm of both sides of equation (1), we get:

$$\ln V = \ln V_0 + \alpha x + kd \Rightarrow z' = z_0 + \alpha x + kd \qquad (2)$$

where z' and z_0 are the natural logarithms of V and V_0, respectively. As it can be observed, the relationship between z', x and d is linear, therefore a multiple linear regression can be performed.

Since we are dealing with a linear regression, the least-squares model can be adopted. Based on this reasoning, the following function f(z_0, α, k) is defined, which is the sum of the squared values of the errors between the experimental data (z_i) and the prediction (z_i') of the regression model:

$$f(z_0, \alpha, k) = \sum_{i=1}^{N} (z_i - z_i')^2 \overset{(2)}{\Rightarrow}$$

$$f(z_0, \alpha, k) = \sum_{i=1}^{N} (z_i - z_0 - \alpha x_i - kd_i)^2 \qquad (3)$$

where N is the number of the experimental points. The values of the coefficients z_0, α and k that provide the best fitting to the experimental data are the ones that minimize the function f. In order to find these values, the partial derivatives of the function f with respect to the three coefficients should be calculated and be set equal to zero, simultaneously. This results in the following system of equations:

$$\begin{cases} \partial f / \partial z_0 = 0 \\ \partial f / \partial \alpha = 0 \\ \partial f / \partial k = 0 \end{cases} \qquad (4)$$

By solving this system for z_0, α and k, the mathematical formulas for these coefficients are obtained:

$$z_0 = \frac{AB\left(F^2 - EH\right) + B^2\left(DH - FG\right) + BC(EG - DF)}{\left(FC - BH\right)\left(NE - B^2\right) + \left(CE - BF\right)\left(BC - FN\right)} \quad (5)$$

$$\alpha = \frac{\left(DC - BG\right)\left(NE - B^2\right) + \left(CE - BF\right)\left(AB - ND\right)}{\left(FC - BH\right)\left(NE - B^2\right) + \left(CE - BF\right)\left(BC - NF\right)} \quad (6)$$

$$k = \frac{\left(FC - BH\right)\left(ND - AB\right) + \left(DC - BG\right)\left(BC - NF\right)}{\left(FC - BH\right)\left(NE - B^2\right) + \left(CE - BF\right)\left(BC - NF\right)} \quad (7)$$

where $A=\sum z_i$, $B=\sum d_i$, $C=\sum x_i$, $D=\sum z_i d_i$, $E=\sum d_i^2$, $F=\sum x_i d_i$, $G=\sum x_i z_i$ and $H=\sum x_i^2$. Then, by substituting the values of the coefficients z_0, α and k into (2), we obtain the equation of the flat surface which is the output of the multiple regression process.

With the equation of the regression surface known, the position-dependent RMS threshold values for the proposed method can be derived. Specifically, the “Small Leaks” category contains leak orifice diameters less than 2.5 mm, the “Medium Leaks” category includes diameters from 2.5 to 5.5 mm and the “Large Leaks” category corresponds to diameters greater than 5.5 mm. Hence, by setting in (2) the value of d equal to 2.5 and 5.5 mm, we obtain the equations describing the position-dependent threshold surface between small and medium leaks and the one between medium and large leaks, respectively. If we name the first one “Low Threshold Surface” (LTS) and the second one “High Threshold Surface” (HTS), then the equation:

$$z'_L = z_0 + 2.5k + \alpha x \quad (8)$$

corresponds to the LTS and the equation:

$$z'_H = z_0 + 5.5k + \alpha x \quad (9)$$

to the HTS. So, when the proposed method is applied to a certain leak measurement, the leak position (x) is inserted into equations (8) and (9) and the thresholds z'_L and z'_H are derived. Then, the natural logarithm of the RMS value of the leak signal is compared to z'_L and z'_H (in Step 3 of the proposed method) and this way the leak is classified into one of the three categories.

In Fig. 3 an example of a multiple linear regression surface is presented. This is from the case of no ambient noise. The blue dots represent the experimental points (from the measurements), the yellow plane is the LTS and the green plane is the HTS.

III. LABORATORY SETUP

The proposed method for leak size estimation in this paper has been tested experimentally in a laboratory pipeline setup. This setup is comprised of the following parts:

a. A 3½ inch diameter steel pipeline containing water, with a total length of around 120 m, the geometry of which is depicted in Fig. 4.

b. A pump needed for the circulation of the water in the pipeline.

c. An expansion tank required for the regulation of the pressure inside the pipe. In this study the pressure was set to 7 atm.

d. Three valves by the help of which leaks are emulated at different points on the pipe. These points and their relative distances from Sensor 1 can be seen in Fig. 4.

e. A set of metallic caps with an orifice in the center mounted on the valves, in order to achieve different leak diameters.

f. Two PCB 352C33 accelerometer sensors [13], with a sensitivity of 100 mV/g, mounted externally on the pipe surface at a distance of 66.83 m between them.

g. A National Instruments NI-9232 data acquisition (DAQ) card [14], which serves as an Analog-to-Digital Converter (ADC).

h. A computer equipped with NI LabVIEW software.

i. A National Instruments NI cDAQ-9174 chassis [15] required for the communication of the DAQ card with the computer.

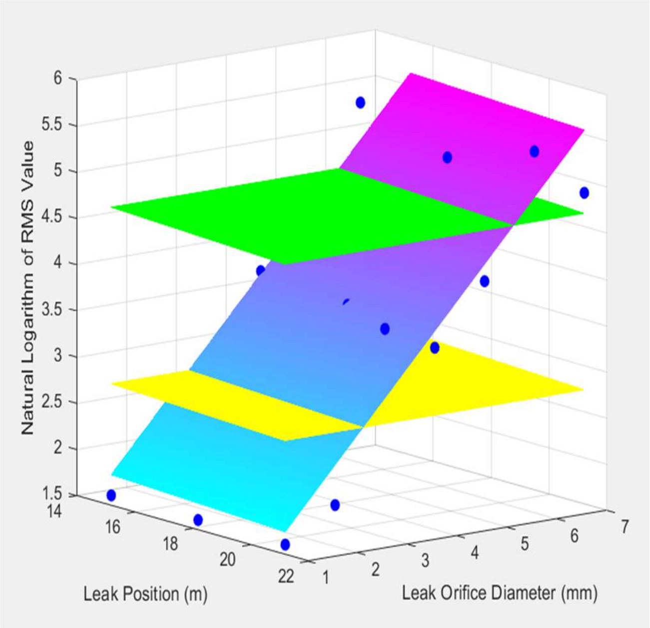

Fig. 3. Example of multiple linear regression between the natural logarithm of the signal RMS value, the leak position and the leak orifice diameter. In this example, the values of the coefficients are $z_0 = 1.4124$, $k = 0.6329\ \text{mm}^{-1}$ and $\alpha = -0.0139\ \text{m}^{-1}$.

In the present study leak orifice diameters from 1 to 7 mm were used for the experimental testing of the proposed method. Also, the method was tested both with the water inside the pipeline flowing (i.e. “With flow” case) and static (i.e. “Without flow” case). In the case of the circulating fluid, the rotational frequency of the pump was set to 30 Hz, which corresponds to a flow rate of 22.2 m^3/h and a fluid velocity of 1.2 m/s. In addition, the efficiency of the presented method was checked for different noise levels. Specifically, there are three different cases: a) “No noise” case, where there is lack of ambient noise, b) “Low noise” case, which corresponds to SNR values ranging from -11.8 to 26.7 dB and c) “High noise” case, which corresponds to SNR values from -21.2 to 17.3 dB. The fluctuations of the SNR values are due to the different leak orifice diameters, which result in differencies in the leak signal energy. At this point, it should be mentioned that the noisy leak measurements have been derived from actual measurements in the laboratory setup to which recorded real noise from the field (i.e. refinery [12]) has been added by using Matlab.

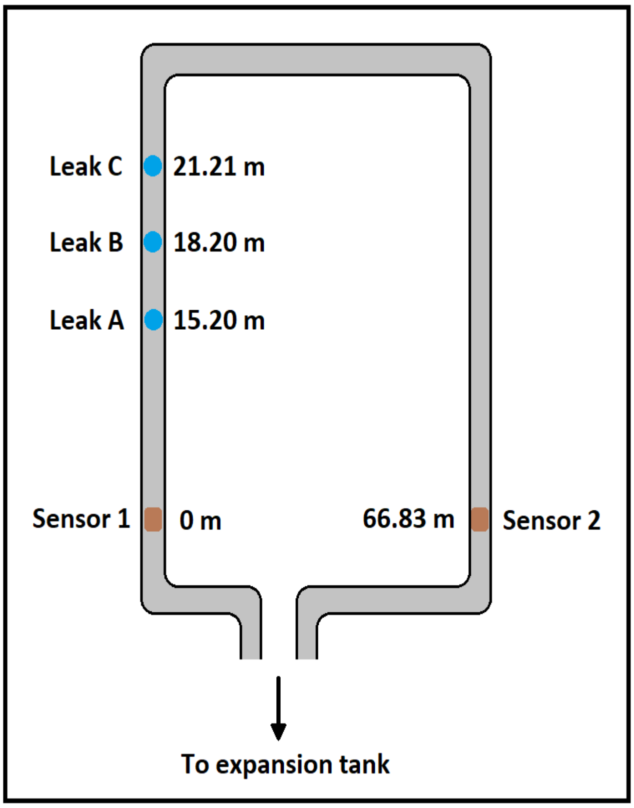

Fig. 4. A 2-D sketch of the pipeline of the laboratory setup. The blue dots represent the three available leak points, while the brown rectangles are the sensors’ positions.

IV. EXPERIMENTAL RESULTS

As mentioned earlier, there are three different leak categories in this study: “Small leaks”, “Medium leaks” and “Large leaks”. The first category (with leak orifice diameters less than 2.5 mm) corresponds to leak flow rates smaller than 7.6 lit/min, the second one (with diameters between 2.5 and 5.5 mm) includes leak flow rates ranging from 7.6 to 36.9 lit/min and the third one (with diameters greater than 5.5 mm) contains leak flow rates larger than 36.9 lit/min.

In Tables I and II the results of the experimental testing of the proposed method are presented. Based on the categories described above, 1mm and 2mm leaks are considered small, 3mm to 5mm belong to the medium leaks and 6mm and 7mm are considered as large ones. In this study, a number of 126 leak measurements were conducted and the results are provided in the tables below for each leak as a “Yes” or “No” indication, according to whether the classification of the leak to its category was successful or not, respectively. The positions of the leak points (i.e. Leak A, Leak B and Leak C) are the ones shown in Fig. 4. Moreover, it should be mentioned that three multiple regressions were performed, one for each of the three different noise levels (“No noise”, “Low noise” and “High noise”), based on the equations (5) to (7).

In Tables I and II it can be observed that the proposed method can achieve efficient results in the classification of a leak into a certain category. Specifically, the most accurate results occur in the “No noise” cases and the success rate decreases as we move towards the “High noise” cases. Moreover, the leak cases with a static fluid in the pipe present better success rates in the estimation of the leak size. In Table III the success rate for each leak case is presented and it can be observed that when there is lack of ambient noise, the success rate can reach 100%. This result is especially important in the case of buried pipelines where the ambient noise is negligible, since in this case the severity of the leak cannot be estimated by direct inspection, even if the leak location has been identified.

TABLE I. EXPERIMENTAL RESULTS OF THE PROPOSED METHOD – LEAK CASES “WITHOUT FLOW”

Leak diameter – Leak point	No noise	Low noise	High noise
1 mm - Leak A	Yes	Yes	Yes
1 mm - Leak B	Yes	Yes	Yes
1 mm - Leak C	Yes	Yes	Yes
2 mm - Leak A	Yes	Yes	Yes
2 mm - Leak B	Yes	Yes	Yes
2 mm - Leak C	Yes	Yes	Yes
3 mm - Leak A	Yes	No	No
3 mm - Leak B	Yes	Yes	Yes
3 mm - Leak C	Yes	Yes	Yes
4 mm - Leak A	Yes	Yes	Yes
4 mm - Leak B	Yes	Yes	No
4 mm - Leak C	Yes	Yes	Yes
5 mm - Leak A	Yes	Yes	Yes
5 mm - Leak B	Yes	Yes	Yes
5 mm - Leak C	Yes	Yes	Yes
6 mm - Leak A	Yes	Yes	No
6 mm - Leak B	Yes	Yes	No
6 mm - Leak C	Yes	Yes	Yes
7 mm - Leak A	Yes	Yes	Yes
7 mm - Leak B	Yes	Yes	Yes
7 mm - Leak C	Yes	Yes	Yes

TABLE II. EXPERIMENTAL RESULTS OF THE PROPOSED METHOD – LEAK CASES "WITH FLOW"

Leak diameter – Leak point	**No noise**	**Low noise**	**High noise**
1 mm - Leak A	Yes	Yes	Yes
1 mm - Leak B	Yes	Yes	Yes
1 mm - Leak C	Yes	Yes	Yes
2 mm - Leak A	Yes	No	No
2 mm - Leak B	Yes	Yes	Yes
2 mm - Leak C	Yes	Yes	Yes
3 mm - Leak A	Yes	Yes	No
3 mm - Leak B	Yes	Yes	Yes
3 mm - Leak C	Yes	Yes	Yes
4 mm - Leak A	Yes	Yes	Yes
4 mm - Leak B	Yes	Yes	Yes
4 mm - Leak C	Yes	No	No
5 mm - Leak A	Yes	Yes	Yes
5 mm - Leak B	Yes	Yes	Yes
5 mm - Leak C	Yes	No	Yes
6 mm - Leak A	Yes	Yes	Yes
6 mm - Leak B	No	No	No
6 mm - Leak C	Yes	Yes	Yes
7 mm - Leak A	Yes	Yes	Yes
7 mm - Leak B	Yes	Yes	No
7 mm - Leak C	Yes	Yes	Yes

TABLE III. SUCCESS RATE PER LEAK CASE

Leak case	**Success rate**
No noise - Without flow	100 %
No noise – With flow	95.2 %
Low noise - Without flow	95.2 %
Low noise - With flow	81.8 %
High noise - Without flow	81.8 %
High noise - With flow	76.2 %

V. CONCLUSIONS

In this paper an acoustic method for the estimation of the size of a leak in a fluid-carrying pipeline has been presented. The method classifies a leak into a certain category according to the RMS value of the measured signal and by the help of proper filtering and the technique of multiple linear regression. The proposed method was tested experimentally in a laboratory pipeline setup under different noise conditions and it presented efficient leak classification results, with a success rate that can reach even 100% in the leak cases without any significant ambient noise. Future research can be conducted in order to improve the success rate of the method in the "High noise" cases.

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