https://doi.org/10.1016/j.ymssp.2021.107994

A comprehensive review of acoustic based leak localization method in pressurized pipelines

Zhongyu Hu *, Salman Tariq, Tarek Zayed

Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

ABSTRACT

Pipes are widely used in the transportation of water, oil, gas, etc. Leakage in pipelines leads to a great waste of natural resources and sometimes constitutes a public health risk. Due to its wave-like nature, acoustic is one of the most studied technology for leak detection and localization in pipelines. Over the past decades, numerous articles have been published to address leak localization problems with acoustic-based methods. However, a review of the research development on acoustic-based leak localization technology is lacking. Therefore, this paper utilized bibliometric analysis to systematically examine the published research articles in this field. Analyses showed that investigations on acoustic-based leak localization technology became popular in the last decade. Most existing research focused on or exploited the cross-correlation based methods. Furthermore, the most frequently investigated research objective was developing a signal processing algorithm for denoising and extracting leak signals. Other efforts included altering the number of sensors, developing wireless detection systems, etc. Potential future directions were presented based on a summary of the limitations of the existing research. This paper has provided an in-depth understanding of the state-of-the-art in this field to researchers and engineers. Additionally, it has identified prospective research areas based on the findings and limitations of the previous studies.

Keywords: literature review; leak localization; pipeline; research trend

[1] Post-doctoral Fellow, Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. Email: zyzyzy.hu@polyu.edu.hk

[2] Professor, Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. Email: tarek.zayed@polyu.edu.hk

1. INTRODUCTION

Pipelines are of vital importance in the transportation, collection, and distribution of gas and liquid resources like water and oil. The world has 2,175, 000 miles of pipeline constructed in 120 countries [1]. The US possesses a 65% share of the total pipeline length, followed by Russia at 8% and Canada at 3%. Despite the significant role of pipelines in modern society, it has long been plagued with leakage problems. Consequently, this leads to a waste of natural resources and money. And sometimes, it poses risks to public health and safety because the leak could serve an entry point for contaminants when the pressure drops [2]. Therefore, economic and safety concerns have motivated the development of leak detection and localization technologies in pipelines. For instance, water leakage is a serious problem in many regions of the world [3]. In some countries, water loss due to leaks in pipelines even exceeds 40% of the total water in the supply system [4]. Therefore, many countries prioritize the reduction of water loss from leaks [5].

Tokyo has one of the most well-developed water systems in the world and it is a typical success story of minimizing water leakage. The adopted methods for the detection and localization of leaks have drastically reduced leakage rate from 20% in 1956 to 3.6% in 2006 [6]. The key principle of this excellent achievement relies on same-day-repair work. Therefore, besides a reliable warning system for the detection of leaks, an efficient and accurate localization of the leaks plays a significant role as well. Whereas leak detection in a large pipeline system relies more on analyzing the data from a sensor network, its localization is predicated on signal processing techniques. The signal investigated depends either on the monitoring method or on the method applied to the detected leak region. Following the general review conducted by Murvay and Silea [7], Li and Liu [8] summarize and compare the techniques commonly used in leak detection and localization, as shown in Table 1. The definition of each indicator is presented as follows: (1) sensitivity is the smallest leakage that can be detected; (2) accuracy is the relative error between the measurement error and the total pipe length; (3) false rate refers to two conditions, activating an alarm in the absence of a, or not activating an alarm when there is a leak; (4) time refers to the time length between the occurrence of a leak and its detection and localization; (5) investment is the financial cost at the beginning and for maintenance thereafter; (6) average life cycle of the diagnosis system. The ratings range from 1 - 5, with 5 being the best performance or the most economical.

Table 1 Evaluation ratings for different leak detection and localization methods.

Methods / Criterion	Mass/Volume Equilibrium	Statistical-based	Negative Pressure	Transient-based	Acoustic-based
Sensitivity	2	4	4	5	5
Accuracy	2	4	4	3	5
False Rate	3	5	3	2	5
Time	2	3	4	2	5
Investment	5	5	5	4	3
System Life	5	3	5	3	4

It can be concluded from Table 1 that acoustic methods are the most relatively balanced compared with the other groups. Acoustic-based methods are predicated on the measurement of acoustic waves radiating from a leak. Figure 1 shows examples of the sensor types that have been identified in the existing literature. The received acoustic wave can be in the pipe, the filled fluid within the pipe, or the surrounding soil and air. In recent years, statistical-based methods are increasingly becoming popular for leak detection due to the development of data science. Notwithstanding, the acoustic-based methods are still the most reliable and efficient in leak localization. This is attributed to their close connection with the physical mechanism of leak generation and propagation. Therefore, a large amount of research efforts have been expended on the acoustic-based leak localization methods. This includes fundamental researches in leak signal propagation, signal processing techniques to denoise and extract the effective signals, optimization of the number of sensors and connections to adapt to wider applications, etc. According to the analyses of existing literature, the academic interest in this area is increasing fast. Therefore, a systematic review of the previous publications will considerably benefit future researches in this area [9]. It is widely accepted by the research community that a literature review can significantly facilitate the understanding of the extent of research on a specific subject. Studies [10, 11] have shown that a systematic review not only assists researchers to have insights on a topic but also inspires them on new research directions to avoid duplicating past efforts.

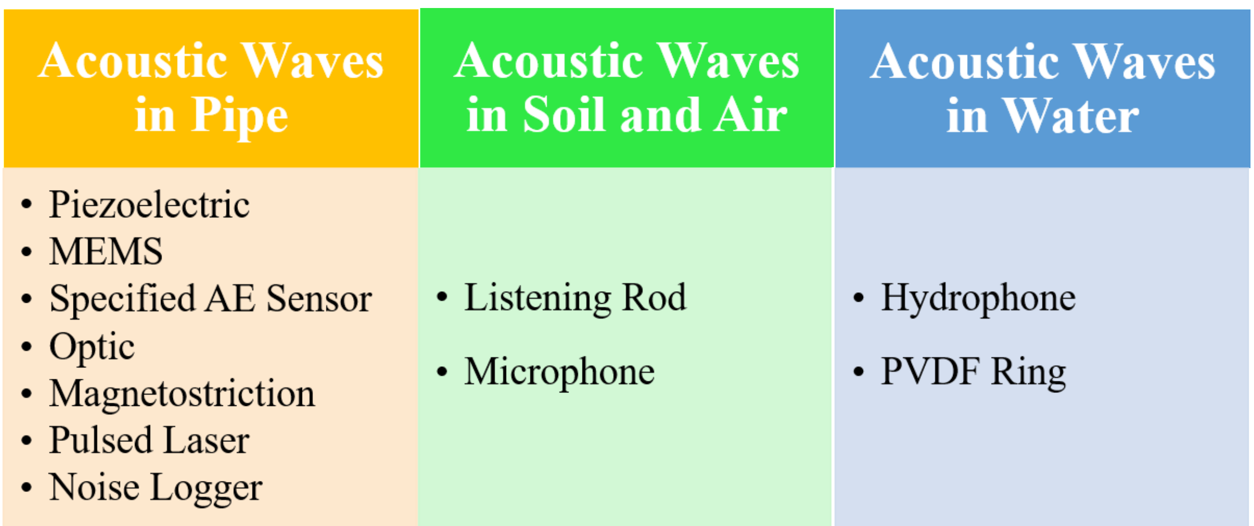


Figure 1 Representative sensors for acoustic wave measurement.

Despite the significance of a research review, no such work has been conducted on exploiting acoustic techniques for the location of a leak in pipelines. Existing reviews in this area are either not specific on acoustic methods [7, 12-14] or focusing more on the localization of the pipeline system [15], which barely treats leak localization technologies. Reviews have been conducted on leak detection and localization methods in oil/gas [7, 12] and water distribution pipelines [13, 14].

Both categories have tried to cover all the existing methods. However, the background knowledge required for different methods varies significantly that the reviews for a single technology, like acoustic- or hydraulic-based, are usually not comprehensive enough. For those specifying acoustic-based methods, Liu et al present a review of the acoustic location of underground pipelines [15]. However, leak localization methods are not discussed. Additionally, as the development of data science advances, the difference between detection and localization becomes more evident. The keyword “detection” refers to both the identification and localization of a leak about a decade ago [16]. However, in recent research, some authors have used “detection” for leak identification and recognition only [17, 18]. Therefore, this paper aims to conduct a systematic analysis and present a review of the leak localization methods with acoustic techniques. Researches that only focus on “detection” will not be included in the review list. The objectives of this paper are to 1) obtain a publication list for acoustic leak localization methods with proper bibliometric searching; 2) conduct quantitative and scientometric analyses of the obtained publication list; 3) review the existing researches based on a reasonable classification of the obtained publications; and 4) to reveal the current limitations in this area to provide suggestions for future research.

2. RESEARCH METHODOLOGY AND DATA ANALYSES

2.1 Research Methodology

The review methods used in some previous researches [19-21] offered valuable guidance in the development of this paper. The workflow of this review-based study is shown in Fig. 2. The adopted method of analysis consisted of three steps, namely bibliometric search, scientometric analysis including quantitative and scientometric mapping analyses, and qualitative discussion. In the end, research limitations and gaps of the present works were summarized from the qualitative review.

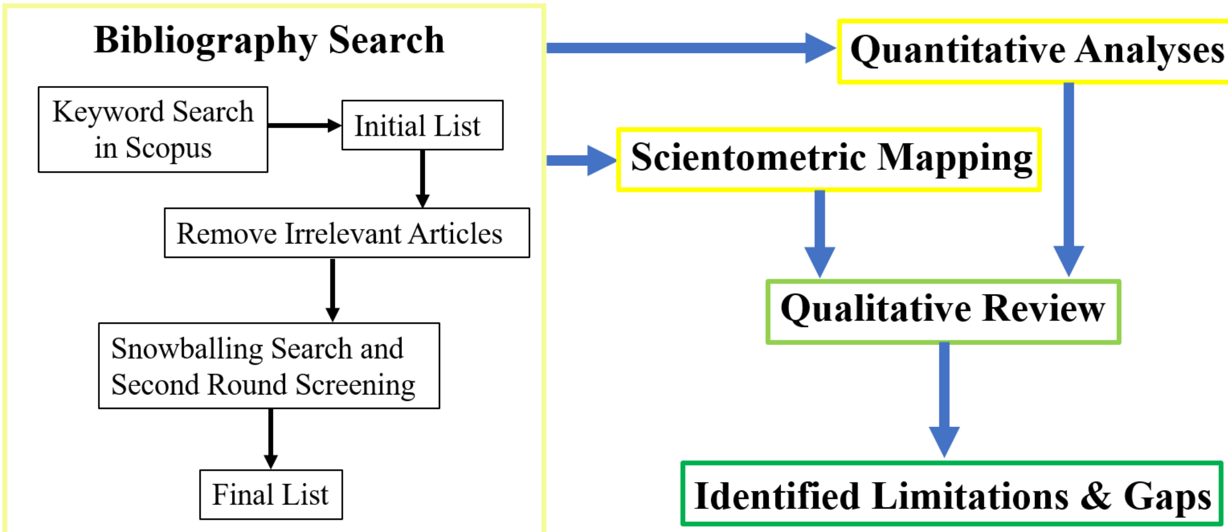


Figure 2 Workflow of the review in this paper.

The bibliometric search was conducted to produce a list of articles to be analyzed. The list was initially obtained from the Scopus search engine, which covered more publications than other sources [22]. The following combinations of keywords were implemented for the search:

TITLE-ABS-KEY((“leak” AND “acoustic” AND “localization”) OR ((“leakage” AND “acoustic” AND “localization”)) OR ((“leak” AND “acoustic” AND “detection”)) OR ((“leakage” AND “acoustic” AND “detection”)) OR ((“leak” AND “acoustic” AND “locating”)) OR ((“leakage” AND “acoustic” AND “locating”)))

Then the list was manually refined based on the following rules: (1) remove irrelevant articles; (2) limit the language to English only; (3) limit the document types to research articles and conference papers only; (4) remove articles earlier than 1990. A representative example of an irrelevant article is one that focused only on the detection of the leak without localizing the leak’s position. Finally, a so-called snowballing search was conducted to include the relevant articles from the “cited by” list of the obtained articles.

The software *VOSviewer* [23] was used to conduct the scientometric studies in this paper. It is a text-mining tool for constructing and visualizing bibliometric networks and has become increasingly popular for conducting a literature review in various fields [10, 11, 24]. Following the recommendation of a previous study [25], *VOSViewer* was adopted in this paper to (1) import the publication list from the Scopus database; (2) visualize the data of co-authorship analysis; and (3) visualize the data of co-keyword analysis.

2.2 Data Analyses and Discussions

2.2.1 Qualitative Analyses

By performing the above bibliometric study procedures, a total of 181 publications were identified. The number of publications per year was summarized and scientometric analyses were implemented. These analyses included science mapping of research keywords, active scholars, active countries, as well as influential publications. Figure 3 shows the number of publications per year in terms of leak localization technology. It can be observed that there is an increase in yearly publications, and this is more noticeable from the year 2010. The highest number of publications, 25, is seen in 2019. However, the number of relevant articles for 2020 is incomplete, as the article search was retrieved up to mid-May of 2020. According to this increasing trend, it is reasonable to surmise that the number of research outputs in leak localization field will continue to grow in the following years.

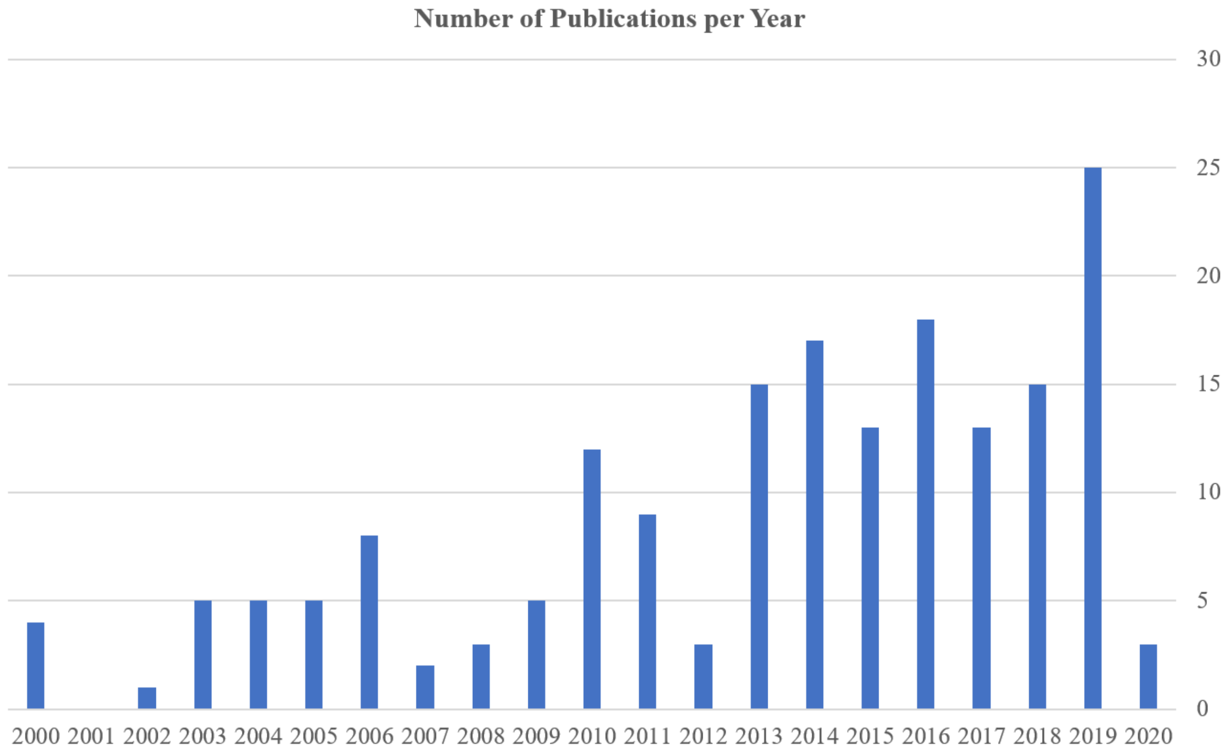


Figure 3 The number of publications since 2000.

Generally, the sources of publications in a certain area are concentrated in a series of popular journals. However, they are found to be fairly scattered for leak localization with acoustic techniques. Table 2 shows the top 10 journals with the number of publications since 2000.

Table 2 Top 10 sources with the highest number of publications

Source Title	**Number of Publications**
Journal of Sound and Vibration	15
Applied Acoustics	7
Journal Of Loss Prevention In The Process Industries	7
Sensors Switzerland	5
Journal of the Acoustical Society of America	4

Measurement Science and Technology	4
ASME International Mechanical Engineering Congress and Exposition Proceedings Imece	3
Applied Thermal Engineering	3
Measurement Journal of the International Measurement Confederation	3
Sensors and Actuators: A Physical	3

Table 3 lists the publication titles with the top 10 number of citations for reference. The effect of publication year on the citation number is not considered. An exception is made for the article "Acoustical characteristics of leak signals in plastic water distribution pipes". Although it was published in 1999, it is included in the list in Table 2 because it is the most cited article in this area. In Table 2, it is apparent that most of these papers focus on the theoretical modeling or analyses of the acoustic wave characteristic in pipes. The reason is that such a fundamental research generally has a great impact on subsequent works in the field. In Table 3, except for "Fiber optic in-line distributed sensor for detection and localization of the pipeline leaks", all other articles can be considered as correlation-based technology. This is the most applied method in locating leaks based on the acoustic theory. Details will be discussed in the following sections.

Table 3 Top 10 publications with the highest number of citations

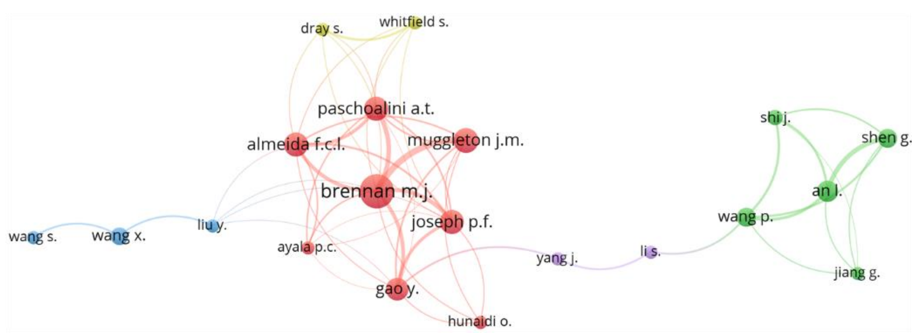
Article Title	**Number of Citation**
Acoustical characteristics of leak signals in plastic water distribution pipes	199
Detecting leaks in plastic pipes	138
A model of the correlation function of leak noise in buried plastic pipes	127

Wavenumber prediction of waves in buried pipes for water leak detection	122
A comparison of time delay estimators for the detection of leak noise signals in plastic water distribution pipes	117
On the selection of acoustic/vibration sensors for leak detection in plastic water pipes	112
Experimental study on leak detection and location for gas pipeline based on acoustic method	107
Leak detection in water-filled plastic pipes through the application of tuned wavelet transforms to Acoustic Emission signals	106
Fiber optic in-line distributed sensor for detection and localization of the pipeline leaks	102
Axisymmetric wave propagation in fluid-filled pipes: Wavenumber measurements in in vacuo and buried pipes	88

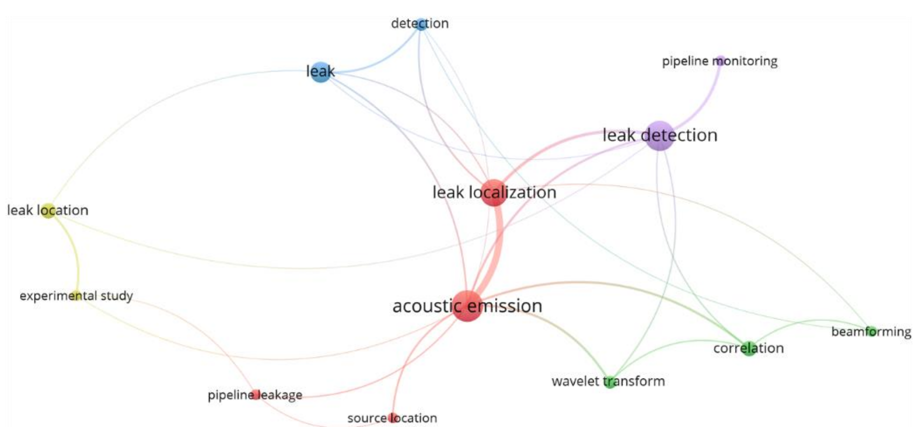
2.2.2 Scientometric Analyses

Collaboration networks in a certain field of research are of significant importance for a funding application, improving specialty and expertise, enhancing productivity, and preventing repetitive research [26]. Figure 4a shows the co-authorship cluster. The minimum numbers of publications and citations were set to 3 and 1, respectively. As a result, 20 out of a total of 160 authors are identified from the co-authorship analysis. Brennan's lab is the most active group in this area, whose name is on five different articles in Table 2. Additionally, the authors of 7 out of the 10 papers can be found in the cluster. This result demonstrates that the scientometric mapping analysis contributes to the bibliography study and emphasizes the value of co-authorship analysis.

Keywords play an important role in a research article because it represents the key contents of an article and summarizes the topics studied within a given discipline [27]. The co-occurrence of keywords is analyzed in this paper. Among the 181 selected articles, "Author Keywords" and "Fractional Counting" were set in *VOSviewer*, as suggested by Hosseini *et al* [26]. The inclusion and exclusion of keywords were manually conducted based on the following rules: (1) minimum number of occurrences of a keyword was set to 3; (2) general keywords such as "acoustic" and "pipe" were removed; (3) keywords with essentially identical meaning were combined, for example, "leak" and "leakage". Finally, the co-occurrence of the remaining 13 keywords is shown in Fig. 4b. This figure indicates that all the publications have concentrated on acoustic emission signals. Particularly, the green cluster in the right bottom corner identifies the research methods. Wavelet transformation, cross-correlation, and beamforming are the most frequently used methods to locate a leak in pipelines. Besides, the authors discovered several other methods during the review. However, due to the fewer occurrences counts of keywords, they do not show up in Fig. 4b and will be further reviewed in the following sections.



(a)



(b)

Figure 4 Scientometric mapping analysis: (a) co-authorship; (b) co-keyword.

3. REVIEW OF LOCALIZATION TECHNOLOGIES

A systematic and comprehensive classification of existing works will considerably facilitate and benefit the qualitative literature review. However, the rules for categorizing the articles are not unique because the relationships among different researches are not parallel or linearly connected. Figure 5 shows another four potential classifications. The fundamental study on wave propagation aims to foster a better understanding of the mechanism of the generation, transmission, and reflection of leak signals. It also involves the study of the interaction among pipe vibration, its surrounding, and inner mediums. Such a study provides a theoretical prediction of the wave velocity and attenuation properties, which enhances further cross-correlation analysis.

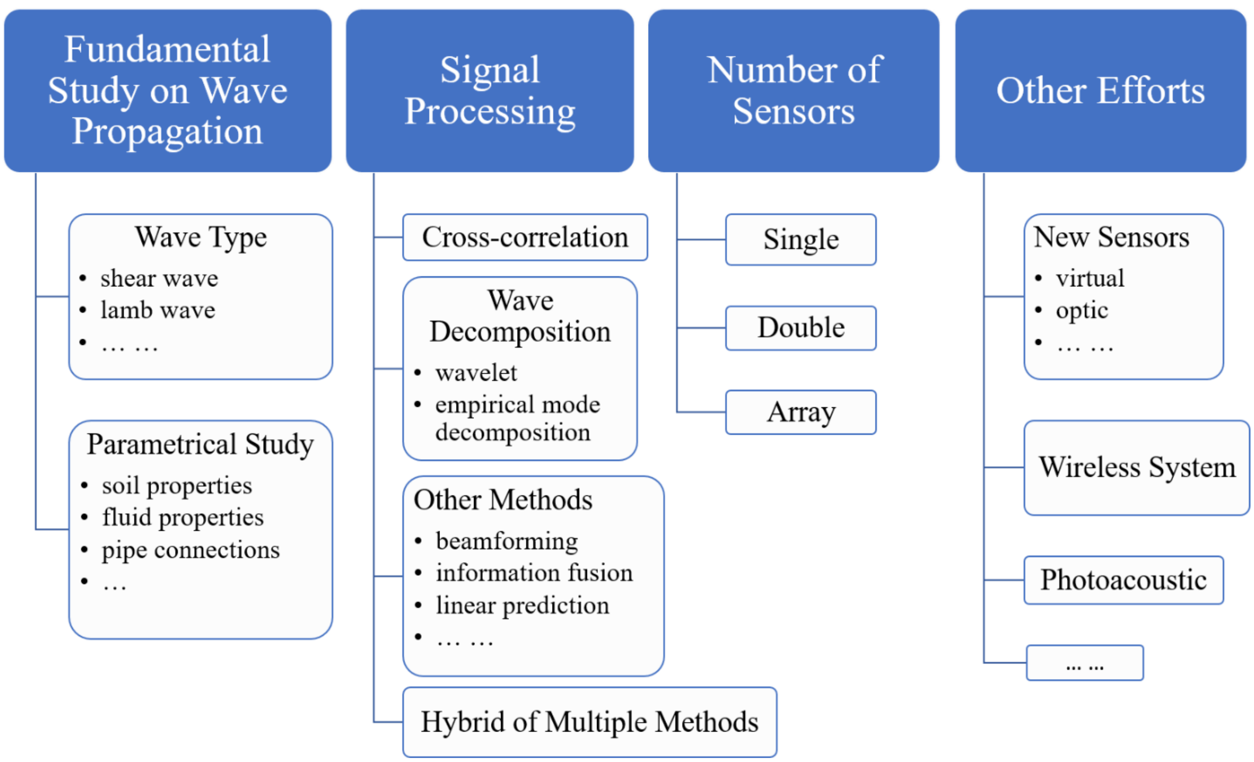


Figure 5 Possible classifications of the research topics.

The most significant step in any leak localization problem is signal processing, where the cross-correlation technique is the most frequently applied method. However, due to the complex environment of a practical leak situation, low Signal-to-Noise Ratio (SNR), and structural uncertainties, it is sometimes difficult to effectively extract the leak signal. Wave decomposition and transformation techniques are employed to reduce or eliminate the noise within the obtained leak signal. Hence, it improves the overall reliability and leak signal quality. Nevertheless, not all signal processing methods are correlation-based, which will be treated in detail in later sections. Other efforts devoted to leak localization include using a different number of sensors, developing new sensors, using a wireless system, etc. All these are aimed at enlarging the range of applicability of the various localization algorithms.

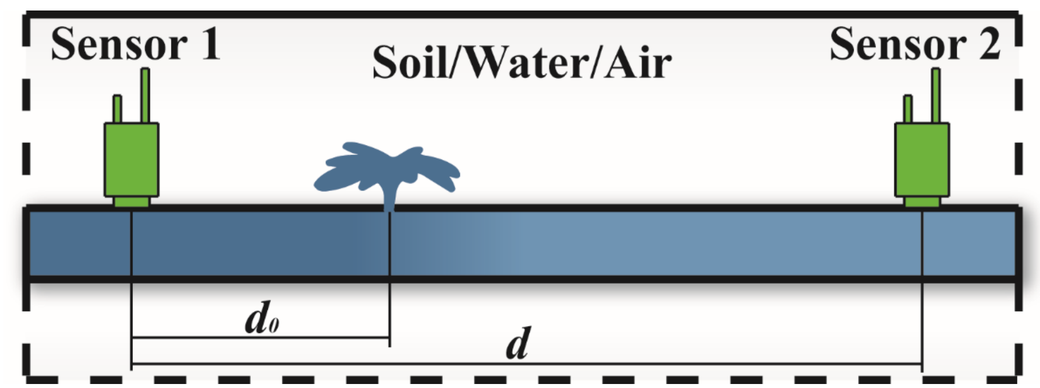
The review below will be structured as follows. Section 3.1 will review the researches related to cross-correlation methods in two groups: (1) fundamental researches on wave propagations, which implementations the cross-correlation techniques; (2) study on cross-correlation methods. Section 3.2 focuses on the enhanced cross-correlation methods along with other signal processing techniques. Section 3.3 presents a review of other methods that literally do not involve cross-correlation analysis. However, one should notice that the classification made in this paper is not a unique and absolute one. Some articles may be classified into more than one different sections.

3.1 Cross-correlation Based Methods

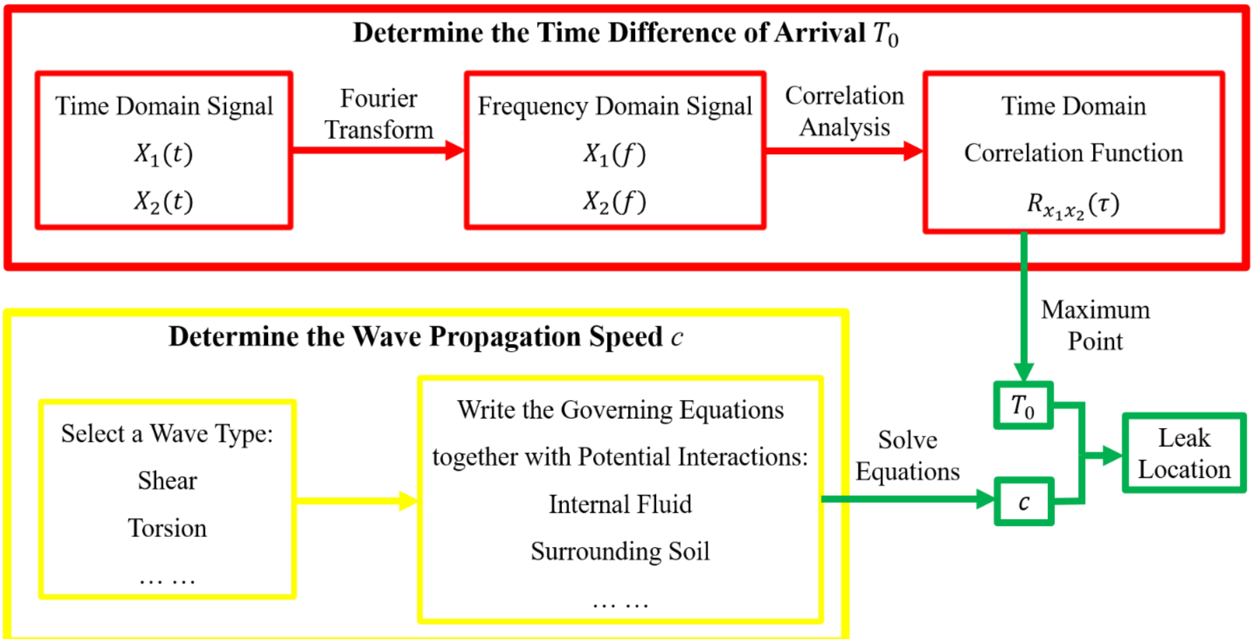
The cross-correlation analysis aims at determining the leak location between two sensors. A typical illustration is shown in Fig. 6a. The leak location d_0 is given by

$$d_0 = \frac{d - cT_0}{2}, \tag{1}$$

where c is the speed of propagation of the leak noise, d is the total distance between the sensors, and T_0 is the time delay, which is the difference in arrival times between the signals generated by the leak and received at the sensors. Apparently, in Eq. 1, the unknown factors are c and T_0, requiring further analyses. The wave speed c can be solved from the governing equations of the pipe, depending on the type of wave (torsion, shear, etc.) received by the sensor, while the Time Difference of Arrival (TDOA) T_0 of the two sensors can be obtained from the peak location in the correlation function of the two signals. A flow chart is shown in Fig. 6b to illustrate the procedure for implementing the cross-correlation analysis.



(a)



(b)

Figure 6 (a) An illustration for the configuration of a water pipe; (b) A flow chart for the classical cross-correlation method.

As observed in Eq. 1, the accuracy level of the obtained leak position depends on the effectiveness level of c and T_0. Therefore, the predictions of the wave propagation speed and the estimation of TDOA are of vital importance for accurately locating the leak position. In what follows, Section 3.1.1 will focus on the basic investigations on the leak signal, i.e. wave propagations within the pipe, mainly including the wave speed and the wave attenuation function. Section 3.1.2 reviews the traditional application of the cross-correlation method. The improved cross-correlation methods, which involve various signal processing techniques, are presented in Section 3.1.3.

3.1.1 Basic Investigations on Wave Propagation Models

To help establish and improve the cross-correlation methods in leak localization, fundamental researches have been conducted to study wave propagation properties along a pipe [28-39]. As one of the earliest researches on the acoustical characteristics of pipes, Hunaidi and Chu study the signals from different types of leaks in a laboratory environment. The characterization of the frequency content of leak signals is studied as a function of leak type, flow rate, pipe pressure, etc. Muggleton, Brennan, and Pinnington propose a model to predict the wavenumber of waves in a buried pipe [29], as shown in Fig. 7. A semi-infinite pipe of thickness h and radius r is investigated by considering its coupling with the surrounding soil and internal fluid. The governing equations of the pipe are solved for two different wave types, of which the complex wavenumbers are given. The model has been experimentally validated in a subsequent work [30].

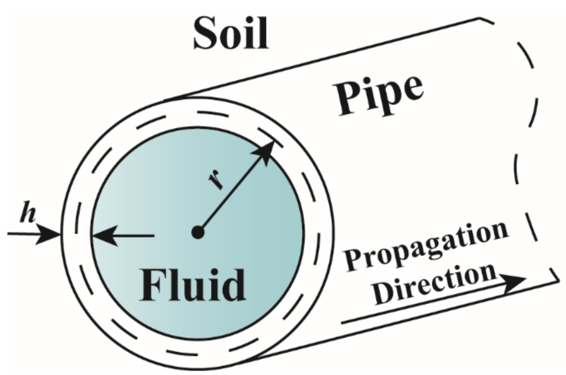


Figure 7 Illustration of the modeled configuration.

Based on this model, further developments are made to study different pipe conditions. These include submerging the pipe in water [31], studying the effect of wall discontinuity due to a change in thickness, elasticity, or internal radius change of the pipe [32], and analyzing the effect of shear coupling at the soil-pipe interface [33]. A similar model has also been developed using the Boundary Element Method (BEM) [34]. The dispersive acoustic wave and wave propagation in a fluid-filled pipe are studied. Experimental investigations conducted in a laboratory environment highlight some of the features of the measured signals in gas pipes. For buried pipelines, the effect of soil cannot be neglected. Brennan, Karimi, and Muggleton study the effect of soil on the propagation of leak signal in buried plastic pipes by analytical, numerical, and experimental ways [38]. It is shown that the wave speed can be affected by the stiffness of the pipe hoop and the soil shear stiffness. The attenuations of different wave types rely on the detailed arrangement of pipelines. Amplitude distortion caused by instrumentation is another factor that influences the reliability of the cross-correlation method. A study has also shown that the time delay can be accurately estimated even if the signals are severely distorted by external interactions [39].

Besides the numerical techniques, experimental approaches are also considered, which even become necessary in some practical problems [40]. Scussel, Brennan, and Muggleton estimate the bulk and shear moduli of the soil surrounding a plastic water pipe through experiments [35]. The predominant fluid wave, which carries the leak noise, is measured. An optimizing algorithm is, then, adopted to determine the properties of the soil. Findings reveal that the bulk and shear modulus can be obtained in sandy soil, while only shear modulus is available in clay soil. Almeida, Brennan, and Joseph *et al* obtain the wave propagation velocity by *in-situ* measurements in buried water distribution pipes [36]. The wave-speed is measured by exciting the pipe with a shaker at one position and measuring the time delay between the acceleration at that position and another position 50 m away. Although the accelerometers are found to be the best sensor, hydrophones are suggested in long-distance measurements due to the relatively lower attenuation.

3.1.2 Cross-correlation Methods

Based on the models of wave propagation in pipes, cross-correlation methods can be implemented in a pipeline system for leak localization purposes. Gao, Brennan, and Joseph *et al* propose an analytical model of the cross-correlation function for wave propagation in buried plastic water pipes [41]. It is found that the most valuable signals are concentrated within 5 – 50 Hz. Additional peaks may come up due to longitudinal resonances of the water pipe, soil resonance, or fundamental frequencies of rotating machinery on the test site, etc. Based on this model, the effects of sensor types [42], time delay estimator types [43], and reflections [44] have been studied. Particularly in Ref. [43], Comprehensive comparisons are made between pressure, velocity, and acceleration sensors, and between impulse response (proposed by Peter Roth), smoothed coherence transform (SCOT), WIENER (after its inventor Norbert Wiener), phase transform (PHAT) and the maximum likelihood (ML) estimators. The causes of reflections can be changes in section, resistance such as valves, and pipe junctions.

Besides the leak localization in water distribution pipes, acoustic cross-correlation technology has been applied to other areas as well. These comprise the gas pipeline [45, 46] and nuclear plant [47]. An approach based on cross-time-frequency spectrum (CTFS) has been proposed to deal with the frequency-dependent wave speed [45]. This is determined in real time to significantly minimize the error due to constant speed assumption. Shimanskiy, Iijima, and Naoi propose a method for leak detection and localization using high-temperature resistant microphones in Fugen nuclear plant [47]. The sensitivity of the method is investigated, including both the detection and localization of a small leak.

3.1.3 Improved Cross-correlation Methods

Owing to background noise and other uncertainties during measurement, the reliability of correlation-based methods requires technical enhancement. Decomposition techniques, which can denoise and extract useful components from the original signal, can be used to improve the performance of the cross-correlation methods. Wavelet Decomposition (WD) has a similar function shape as the leak signal. Hence, it is one of the most frequently used decomposition techniques [48]. For instance, based on a previous correlation-based article [47], an improvement on the method suggested by Shimanskiy, Iijima, and Naoi utilizes WD to extract the short-term spectral fluctuations of the leak signals [49]. Meng, Li, and Wang *et al* de-noise the leak signal with WD to eliminate background noises [50]. A time-frequency analysis is then implemented to analyze the signal characteristics in the frequency domain. Again, this paper [50]confirms that the leak signals are mainly concentrated below 100 Hz, which is consistent with the conclusion of a previous work [41]. The relative error in leak localization has been experimentally shown to be within 0.01% and 1.37%. Davoodi and Mostafapour [51] develop an analytical model of the acoustic emission of a leak using the traditional correlation-based Galerkin method. Then, the majority of the noise is removed with the wavelet transformation and filtering techniques. The proposed model is well validated by experimental results. This method is later improved by combining the WD, filtering, and cross-correlation techniques [52]. Experiments are conducted by changing the distance from the sensor to leak position and the relative errors are shown to be less than 3%.

In the work of Ozevin and Harding, the TDOA is determined using a correlation function for a pipeline system spreading in a two-dimensional configuration [53]. To improve the localization performance for long-range pipelines, Xu, Gong, and Xie *et al* conduct a cross-correlation analysis to the leak signal component obtained from the wavelet packet decomposition (WPD) [54]. The localization algorithm is developed based on the attenuation properties of the signal. Similarly, based on the wave attenuation properties, Liu, Li, and Yan *et al* conduct a wavelet transformation of the acoustic signal of a leak to determine its location without considering its velocity and time difference [55]. For a buried pipeline system with a continuous leak, the prediction performance is experimentally proven to be better than the traditional wave-attenuation-based methods. The extracted spectral components are shown to be less influenced by signal distortion. Thus it provides a larger correlation value and it is capable of leak localization under lower signal-to-noise ratios. This model is later modified to better adapt the detection and localization of leak in natural gas pipelines [56].

The principle and idea of using functions that are similar to that of the leak signal can be extended beyond the wavelet-based methods. Gao, Brennan, and Liu *et al* optimize the shape of the correlation function and this results in an accurate estimation of the time delay. A similar idea has also been proposed by Li, Zhang, and Yan *et al* [57]. By applying a weighing window that is tuned based on the wavenumber of a particular mode, different mode components of a leak signal can be individually extracted. This leads to a reduction in detection uncertainty and location error. The method has been applied to a gas pipeline and the relative localization errors are shown to be reduced by more than 7% on average.

Another popular decomposition technique is the Empirical Mode Decomposition (EMD). Bakhti, Bentoumi, and Harrag *et al* decompose the measured acoustic signal using the EMD. Then the leak location is determined by the cross-correlation analysis of the decomposed signal. Experimental tests have shown the high accuracy of this method. Liu, Li, and Fang *et al* propose a de-noising system to improve the performance of the traditional cross-correlation method [58]. The de-noising process is designed to adapt to the properties of the amplitude frequency spectrum. To facilitate the parametrical investigation of correlation-based methods, Brennan, Lima, and Almeida *et al* recommend a proof-of-concept virtual pipe test-rig to simulate pipe vibration due to *in-situ* water leaks [59]. System parameters can be modified including pipe material and size, measurement positions, and leak strength.

3.2 Signal Processing Based Methods

Compared with correlation-based methods, which usually refer to physical characteristics like wave speed and attenuation function, the signal processing based methods rely more on mathematical manipulations and algorithms. In this section, the articles reviewed are classified into three categories. Section 3.2.1 summarizes the localization approaches based on various signal processing techniques. Two categories of methods, statistical-based and beamforming, are identified to be more frequently and widely applied. These will be individually discussed in Sections 3.2.2 and 3.2.3, respectively.

3.2.1 Solutions with Signal Processing Techniques

The purposes of implementing signal processing techniques for leak localization are to achieve denoising and extract useful components from the originally obtained leak signal. Due to space limitations, only part of the identified articles will be reviewed in this section [60-72]. Cui, Yan, and Guo propose a hybrid method based on EMD, signal reconstruction, and data fusion method to tackle attenuation and dispersion of the received acoustic signal [60]. To locate the leak in underwater gas pipelines, Mahmutoglu and Turk propose a passive acoustic method based on the received signal strength (RSS) [61]. The authors show that the leak position can be determined from several kilometers away with a relatively low average error. The amplitude, however, depends on background noise, number of sensors, source strength, etc. A technique based on linear prediction (LP) has also been presented by Cody, Dey, and Narasimhan to be employed along with the traditional cross-correlation method [62]. It is shown that the LP is effective in extracting the composite spectrum effects of radiation, pipe system, and leak-induced excitation of the pipe system, with and without leaks.

Lang, Li, and Cao *et al* propose a localization method for small leaks based on information fusion, which makes use of the wave velocity and flow rate signals [63]. It is shown that the change of the information fusion signal is larger than that of the wave velocity and pressure signal. Experimental results also show that small leaks in a pipe can be effectively located with the proposed method. To filter the noise and achieve a better localization performance, Yu, Liang, and Zhang propose a method based on a dual-tree complex wavelet transform (DTCWT) and a singular value decomposition (SVD) [64]. the DTCWT is implemented to filter the noise and preserve the characteristic frequency band, while the SVD eliminates noises in the non-characteristic bands. Both theoretical analyses and experiments indicate that the DTCWT-SVD method is effective for signal noise reduction.

3.2.2 Solutions with Statistical Based Techniques

A statistical based technique solves the leak location problem from a relatively larger number of data sets than the traditional signal processing and wave propagation methods. It requires more existing signals to extract and analyze the features so as to locate the leak in future cases. On the contrary, statistical based methods do not rely on the wave propagation model. This is because the wave speed or attenuation function is no longer a condition for leak detection. Han, Zhao, and Cui *et al* develop a leak localization method [73], which combines the WP algorithm and radial basis function network (RBFN). The selected input feature vectors include WP energy and its maximum value, and TDOA obtained from the cross-correlation function. Experiments present a relative error of less than 2%.

Jin, Zhang, and Liang *et al* have also proposed an improved wavelet double-threshold de-noising optimization method [74]. The leak condition is determined by the least squares support vector machine (LS-SVM). Experimental validations illustrate that the model can effectively improve the accuracy of leak detection and localization. Sun, Xiao, Wen *et al* present another method based on root mean square (RMS) entropy of local mean deposition (LMD) and Wigner-Ville time-frequency analysis [75]. The wavelet energy packet analysis and support vector machine are used during the signal processing procedures. Experiments demonstrate that the method can identify leak apertures of different types and outperforms the direct cross-correlation method.

Research on the application of the neural network is becoming increasingly popular in recent years. Following the flow chart in Fig. 8, EI-abbasy, Mosleh, and Senouci et al develop an Artificial Neural Network (ANN) [76] to detect and locate leaks in a pipeline system. The noise logger mounted on the test rig provides 140 sets of data, of which 80% are used for training the algorithm and 20% are used for validation. The ANN outperforms a regression model during the validation process. Later on, the ANN model is applied in a case study of the Qatar University water network, where a 99.5% relative accuracy is achieved. Wu and Lee propose a leak localization method based on the generalized cross-correlation method and the attenuation-based multilayer perceptron neural networks (MLPNN) [77]. The averaged relative errors are reduced by 14% compared to the traditional cross-correlation methods.

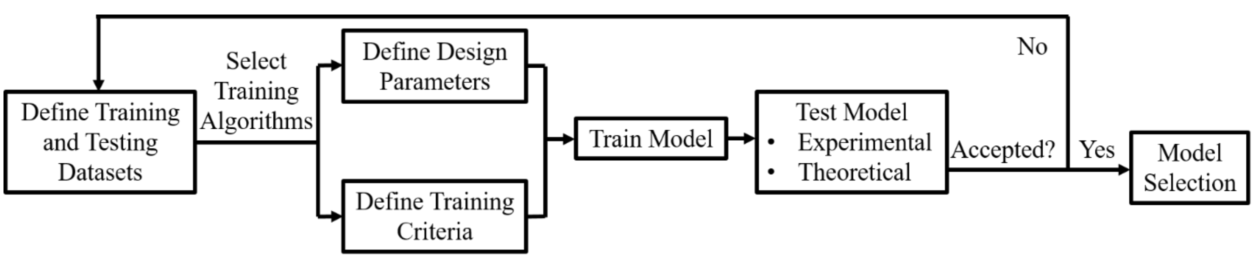


Figure 8 The ANN model building framework.

3.2.3 Solutions with Beamforming

Beamforming is a popular signal processing technique used in directional signal transmission or reception obtained from sensor arrays. It can be applied in leak source detection and localization problems, where a sensor array is available. Compared with the traditional TDOA and cross-correlation methods, beamforming can improve the accuracy of localization by analyzing the signal received from multiple sensors. This is achievable through delaying, summing, and weighting algorithms. It can be applied to the traditional vibroacoustic analysis. Likewise, Moriot, Maxit, and Guyader *et al* develop a beamforming-based method to locate a source within a cylindrical elastic shell [78]. It is applied to the radial velocities of the fluid-loaded shell, which is obtained from a developed vibroacoustic model. Parametric studies on the influence of sensor distance, radial location of the source, system damping loss factor, and fluid properties can be conveniently investigated. Li, Yang, and Bian *et al* present a virtual linear ultrasonic sensor array, which is aimed at localizing the leakage in gas pipelines with high-resolution results [79]. A virtual beamforming algorithm is applied to locate the leak position. Experimental validations are presented along with the numerical analyses.

Cui, Yan, and Hu *et al* propose a near-field beamforming-based method on a flat-surface structure [80]. The authors compare the performances of different configurations of the sensor array in terms of the localization of a gas leakage. It is found that the L-shaped array is the most competitive arrangement. Experimental results have shown that the L-shaped array can localize the leak on a surface with satisfactory performance. Wang and Ghidaoui recommend an Interative Beamforming (IB) model for the detection and localization of multiple leaks in a pipeline system [81]. The method is developed based on the hydraulic pressure of a fluid, rather than the acoustic waves. However, it provides a valuable reference for the potential development of acoustic-based methods. The proposed IB model has been experimentally validated [82].

3.3 Investigations on Sensor

3.3.1 Studies on Sensor Numbers

The studies on sensors mainly focus on two aspects, numbers and types. An apparent conclusion is that more sensors can always lead to better performance. However, the number of sensors is limited by the practical environment and economic reasons. Even two sensors may not be available for use in some extreme cases. However, one choice is to install the two sensors extremely close to each other, which can be considered as a single point compared to the whole length of the pipe. Ozevin and Yalcinkaya propose an approach which can detect and locate the leak from a single point measurement with two sensors [83]. The wave motions are received at two orthogonal directions (radial and axial) of the pipe. The approach is validated in a laboratory environment with steel pipes, compared with the conventional two-neighbor sensor approach. The other solution is to use only one sensor, where the reflected signals exist. Cross-correlation can be conducted between the propagating and reflected signals. Liu, Fan, and Wu suggest a localization technology for downhole tubing leaks requiring only one sensor [84]. The acoustic wave will be reflected at the medium interface because the pipeline is surrounded by different fluid mediums. The model is developed by analyzing the time difference of reflections and the acoustic velocity in the pipeline. Feld test shows the relative location error can be less than 1% for the proposed method.

On the contrary, a sensor array is considered when two sensors cannot satisfy the requirements [85-88]. Wang, Wang, and Pei *et al* propose a method involving multiple ultrasonic transducers at equal intervals and using small variations in acoustic intensity to detect and preliminarily locate the leak [85]. A TDOA algorithm is implemented to determine the accurate position of the leak. More applications of the sensor array are targeted at localizing the leak on a surface or whole space. Cui, Yan, and Guo *et al* develop a circular sensor array to achieve a continuous leak localization on the surface of a storage vessel [86]. EMD is used to reduce the background noise in the signal. The time difference between the signals from two neighbor sensors is obtained from the cross-correlation analysis. The method shows a good performance in the experiment.

3.3.2 Studies on Sensor Types and Systems

By providing more or extra signal information, specified sensors may achieve better accuracy than the traditional accelerators and loggers. For example, optic sensor is a feasible choice to improve the performance of correlation. Due to the distributed character of the fiber-optic sensor, the acceleration of the system can be measured in a more detailed manner. Stajanca, Chruscicki, and Homann explore the potential of using a Fiber-Optic Distributed Acoustic Sensing (DAS) system to detect and locate the leak in a pipeline system. It is shown that the DAS system is capable of monitoring pipeline vibrations due to the contained leak fluid. However, detailed localization strategies are not proposed.

In the work of Hussels, Chruscicki, and Arndt [89] *et al*, optic fiber sensors are used to localize the transient impacts. Additionally, the group velocities of different acoustic modes can be identified, which are consistent with theoretical predictions. Also, Zuo, Zhang, and Xu *et al* apply the optic fiber sensor to develop a wavelet and EMD based algorithm. The algorithm analyzes the characteristics of the time domain signal to detect leaks and locate the leak position with frequency domain analyses [90]. The SNR and correlation are improved to 18.28 and 0.75, respectively. The leak location is determined by the average of the frequency domain accumulation. The effectiveness of the method has been proven by experimental works. With an in-line distributed fiber sensor, Huang, Lin, and Tsai *et al* propose a hybrid Mach-Zehnder and Sagnac interferometer [91]. The acoustic leak signal deforms the fiber and changes the refractive index of the fiber core hence, the total length of the optical path is altered. Then, the position of the leak is determined from the null frequency of the obtained spectrum, as in previous works [92, 93].

Yönak and Dowling work on a photoacoustic based method to detect and locate leaks [94]. From the recorded signals, the existence of a leak can be determined by comparing it with the background noise level. A simple model is developed, based on the acoustic environment and matched field processing (MFP), to locate the leak position. This work has been extended by using more frequency components and conducting parametric studies on laser scan rates. Further improvements include examining mismatch between the practical environment and the propagation model, and locating the leak on a curved surface [95-97]. For some extreme environments where traditional sensing configuration is not applicable, special treatment needs to be adopted. To achieve remote real-time monitoring, Hieu, Choi, and Kim *et al* develop a wireless system to achieve a cross-correlation analysis [98]. The authors analyze the underground wireless sensor nodes, for which a potential structure is proposed. Experimental results show that the communication limits are 10 m in the horizontal direction and 30 cm in the vertical direction.

4. DISCUSSIONS ON LIMITATIONS AND GAPS

Besides the progress reviewed in previous sections, limitations, and gaps that require further investigations still exist. Figure 9 summarizes the topics where the current authors identify some research limitations and potential future research directions. These include experimental studies, algorithm developments, etc. On the other hand, according to the review of the existing works, many pieces of research have been conducted under various backgrounds. Consequently, a direct comparison in terms of advantages and disadvantages may not be completely fair. Therefore, this section will only focus on those widely used methods like cross-correlation and wavelet analysis.

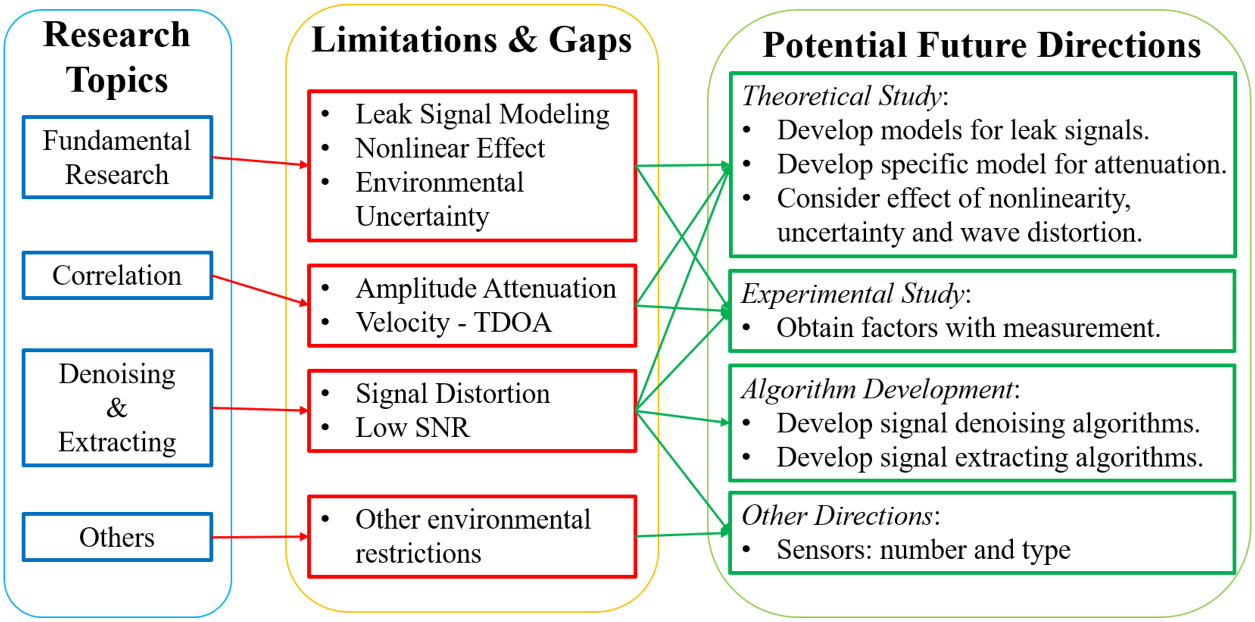


Figure 9 Summary of limitations and gaps, and potential future directions

The first topic listed in Fig. 9 is a fundamental study, which mainly involves the modeling of wave propagation along a pipe. The wave propagation in a pipeline is governed by a fluid-pipe-soil coupling process. Soil may also change to air or water depending on the location of the pipeline system. For predicting the wave speed, traditional methods assume that the wave velocity is constant in all pipelines. This, however, neglects the effect of the temperature of the surrounding medium. Additionally, the flow speed of the fluid within the pipes, which can be larger than 10 m/s for high-pressure pipelines (pressure up to 10 MPa), has a significant impact on the wave propagation, as well. These factors must be considered in the model, especially for long-distance pipelines, to avoid misleading output errors.

Other challenges include the effect of nonlinearity and uncertainty. Although they can be neglected in most low-frequency cases, evaluations should be more careful when the distance between the sensors is large. In addition to more specific modeling of the pipe system, Brennan et al emphasize the significance of in-situ measurement [40]. However, evident inaccuracies caused by resonances and reflections are observed. These difficulties call for attention from the scholars.

As reviewed in Section 3.1, correlation-based techniques are either the most frequently applied methods or play a key role in most methods. These techniques are implemented based on either the amplitude attenuation or the propagation velocity of the leak signal. The accuracy of the obtained leak position remarkably relies on the measured time difference and the employed prediction model. The application of the attenuation-based model is costly because of the complex attenuation function. This, in turn, depends on both the frequency and surrounding environment of the pipeline. Hence, it cannot be universally applied to all cases. Therefore, the correlation-based methods are more frequently used together with the arrival time difference. In contrast to the laboratory environment, measurement in practical cases usually involves multiple acoustic emission sources placed beside the leakage. Examples include vibrations at pipe joint and external random excitations. All these waves propagate in dispersive modes. Thus, the signal obtained at the measurement point is a superposition of all the different components of the propagating waves. Moreover, the acoustic oscillation caused by leaks, which can also be referred to as leak condition, can produce acoustic signals of various shapes. Some of these signals are quite similar to normal signals and are therefore difficult to extract. These problems all add difficulties to the application of correlation-based methods.

Wavelet decomposition and empirical mode decomposition are the two most frequently used tools in signal extraction and noise elimination. However, the measured signals at the sensors are already distorted by both wave attenuation and interferences in the propagation path. This problem becomes more serious when the leak position is far from the sensors or the leak signals are apt to be attenuated in the pipe material. Either developing a novel signal processing method or theoretically modeling the distortion process is a potential solution. Another problem is that small leak signals tend to be drowned in background noise so that the SNR of most pipeline leak signals is low. The denoising and extraction of low SNR signals is a topic that has plagued scholars for decades. Therefore, developing an efficient signal processing technique will benefit not only leak localization but more research areas. Other efforts can be concentrated on the types and numbers of sensors where environmental restrictions exist. Typical examples include the localization technique as reviewed in Section 3.3.1.

5. CONCLUDING REMARKS

A comprehensive review of the studies on pipeline leak localization with acoustic-based methods is conducted. The review is based on a systematical bibliography searching scheme. Both quantitative and scientometric analyses are presented, including annual publication numbers, co-authorship analysis, co-keyword analysis, etc. It is found that the number of research outcomes increases fast in the last decade. Most research has focused on or applied the cross-correlation method. Wavelet decomposition and empirical mode decomposition are two popular tools in eliminating noise signals during the extraction of leak signals. Localization methods can be conducted with either single or multiple sensors. Besides these efforts, beamforming is a feasible choice when a sensor array is applicable. Research limitations and gaps are summarized following the reviews. Potential future directions are also proposed as a reference for readers and researchers.

Generally, this study provides a reference for both industrial engineers and scholars working on fundamental research in wave propagations, developing new signal processing algorithms, and for use in practical applications. Additionally, one should notice that although the selected articles can reflect the current statues of leak localization research with acoustic techniques, not all relevant studies are covered in this paper.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support from the Innovation and Technology Fund (Innovation and Technology Support Programme (ITSP)) under grant number ITS/067/19FP, and the Water Supplies Department of Hong Kong.

REFERENCES

[1] J. Chepkemoi. *Top 20 Countries By Length Of Pipeline*. 2017 [cited 2020 May, 25th]; Available from: https://www.worldatlas.com/articles/top-20-countries-by-length-of-pipeline.html.

[2] O. Hunaidi, W. Chu, A. Wang, and W. Guan, "Detecting leaks in plastic pipes," Journal / American Water Works Association **92**(2), 82-94 (2000).

[3] W. Li, W. Ling, S. Liu, J. Zhao, R. Liu, Q. Chen, Z. Qiang, and J. Qu, "Development of systems for detection, early warning, and control of pipeline leakage in drinking water distribution: A case study," Journal of Environmental Sciences **23**(11), 1816-1822 (2011).

[4] S. Perdikou, K. Themistocleous, A. Agapiou, and D.G. Hadjimitsis, *Introduction—The problem of water leakages*, in *Integrated Use of Space, Geophysical and Hyperspectral Technologies Intended for Monitoring Water Leakages in Water Supply Networks*. 2014, IntechOpen.

[5] K. Vairavamoorthy and J. Lumbers, "Leakage reduction in water distribution systems: optimal valve control," Journal of hydraulic Engineering **124**(11), 1146-1154 (1998).

[6] C. Cities. *Tokyo, World Leader in Stopping Water Leakage*. 2012 [cited 2020 May, 25]; Available from: https://www.c40.org/case_studies/tokyo-world-leader-in-stopping-water-leakage.

[7] P.-S. Murvay and I. Silea, "A survey on gas leak detection and localization techniques," Journal of Loss Prevention in the Process Industries **25**(6), 966-973 (2012).

[8] Y. LI and C. LIU, "Advances in leak detection and location based on acoustic wave for gas pipelines," Chinese Science Bulletin **62**(7), 650-658 (2016).

[9] C.C. Tsai and M. Lydia Wen, "Research and trends in science education from 1998 to 2002: A content analysis of publication in selected journals," International journal of science education **27**(1), 3-14 (2005).

[10] J. Song, H. Zhang, and W. Dong, "A review of emerging trends in global PPP research: analysis and visualization," Scientometrics **107**(3), 1111-1147 (2016).

[11] X. Zhao, "A scientometric review of global BIM research: Analysis and visualization," Automation in Construction **80**(37-47 (2017).

[12] H. Lu, T. Iseley, S. Behbahani, and L. Fu, "Leakage detection techniques for oil and gas pipelines: State-of-the-art," Tunnelling and Underground Space Technology **98**(103249 (2020).

[13] R. Li, H. Huang, K. Xin, and T. Tao, "A review of methods for burst/leakage detection and location in water distribution systems," Water Science and Technology: Water Supply **15**(3), 429-441 (2015).

[14] S. El-Zahab and T. Zayed, "Leak detection in water distribution networks: an introductory overview," Smart Water **4**(1), 5 (2019).

[15] Y. Liu, D. Habibi, D. Chai, X. Wang, H. Chen, Y. Gao, and S. Li, "A comprehensive review of acoustic methods for locating underground pipelines," Applied Sciences **10**(3), 1031 (2020).

[16] P.J. Lee, M.F. Lambert, A.R. Simpson, J.P. Vítkovský, and J. Liggett, "Experimental verification of the frequency response method for pipeline leak detection," Journal of Hydraulic Research **44**(5), 693-707 (2006).

[17] S. El-Zahab, A. Asaad, E. Mohammed Abdelkader, and T. Zayed, "Development of a clustering-based model for enhancing acoustic leak detection," Canadian Journal of Civil Engineering **46**(6), 278-286 (2019).

[18] S. El-Zahab, E.M. Abdelkader, and T. Zayed, "An accelerometer-based leak detection system," Mechanical Systems and Signal Processing **108**(276-291 (2018).

[19] Y. Ke, S. Wang, A.P. Chan, and E. Cheung, "Research trend of public-private partnership in construction journals," Journal of construction engineering and management **135**(10), 1076-1086 (2009).

[20] Z. Li, G.Q. Shen, and X. Xue, "Critical review of the research on the management of prefabricated construction," Habitat international **43**(240-249 (2014).

[21] C.M. Mak and Z. Wang, "Recent advances in building acoustics: An overview of prediction methods and their applications," Building and Environment **91**(118-126 (2015).

[22] A. Aghaei Chadegani, H. Salehi, M. Yunus, H. Farhadi, M. Fooladi, M. Farhadi, and N. Ale Ebrahim, "A comparison between two main academic literature collections: Web of Science and Scopus databases," Asian Social Science **9**(5), 18-26 (2013).

[23] N. Van Eck and L. Waltman, "Software survey: VOSviewer, a computer program for bibliometric mapping," scientometrics **84**(2), 523-538 (2010).

[24] Q. He, G. Wang, L. Luo, Q. Shi, J. Xie, and X. Meng, "Mapping the managerial areas of Building Information Modeling (BIM) using scientometric analysis," International Journal of Project Management **35**(4), 670-685 (2017).

[25] J.Y. Park and Z. Nagy, "Comprehensive analysis of the relationship between thermal comfort and building control research-A data-driven literature review," Renewable and Sustainable Energy Reviews **82**(2664-2679 (2018).

[26] M.R. Hosseini, I. Martek, E.K. Zavadskas, A.A. Aibinu, M. Arashpour, and N. Chileshe, "Critical evaluation of off-site construction research: A Scientometric analysis," Automation in Construction **87**(235-247 (2018).

[27] H.-N. Su and P.-C. Lee, "Mapping knowledge structure by keyword co-occurrence: a first look at journal papers in Technology Foresight," Scientometrics **85**(1), 65-79 (2010).

[28] O. Hunaidi and W.T. Chu, "Acoustical characteristics of leak signals in plastic water distribution pipes," Applied Acoustics **58**(3), 235-254 (1999).

[29] J.M. Muggleton, M.J. Brennan, and R.J. Pinnington, "Wavenumber prediction of waves in buried pipes for water leak detection," Journal of Sound and Vibration **249**(5), 939-954 (2003).

[30] J.M. Muggleton, M.J. Brennan, and P.W. Linford, "Axisymmetric wave propagation in fluid-filled pipes: Wavenumber measurements in in vacuo and buried pipes," Journal of Sound and Vibration **270**(1-2), 171-190 (2004).

[31] J. Muggleton and M. Brennan, "Leak noise propagation and attenuation in submerged plastic water pipes," Journal of Sound and Vibration **278**(3), 527-537 (2004).

[32] J.M. Muggleton and M.J. Brennan, "Axisymmetric wave propagation in buried, fluid-filled pipes: Effects of wall discontinuities," Journal of Sound and Vibration **281**(3-5), 849-867 (2005).

[33] J.M. Muggleton and J. Yan, "Wavenumber prediction and measurement of axisymmetric waves in buried fluid-filled pipes: Inclusion of shear coupling at a lubricated pipe/soil interface," Journal of Sound and Vibration **332**(5), 1216-1230 (2013).

[34] M.S. Kim and S.K. Lee, "Detection of leak acoustic signal in buried gas pipe based on the time-frequency analysis," Journal of Loss Prevention in the Process Industries **22**(6), 990-994 (2009).

[35] O. Scussel, M.J. Brennan, J.M. Muggleton, F.C.L. Almeida, and A.T. Paschoalini, "Estimation of the bulk and shear moduli of soil surrounding a plastic water pipe using measurements of the predominantly fluid wave in the pipe," Journal of Applied Geophysics **164**(237-246 (2019).

[36] F.C.L. Almeida, M.J. Brennan, P.F. Joseph, S. Dray, S. Whitfield, and A.T. Paschoalini, "Towards an in-situ measurement of wave velocity in buried plastic water distribution pipes for the purposes of leak location," Journal of Sound and Vibration **359**(40-55 (2015).

[37] J. Muggleton, M. Kalkowski, Y. Gao, and E. Rustighi, "A theoretical study of the fundamental torsional wave in buried pipes for pipeline condition assessment and monitoring," Journal of Sound and Vibration **374**(155-171 (2016).

[38] M.J. Brennan, M. Karimi, J.M. Muggleton, F.C.L. Almeida, F. Kroll de Lima, P.C. Ayala, D. Obata, A.T. Paschoalini, and N. Kessissoglou, "On the effects of soil properties on leak noise propagation in plastic water distribution pipes," Journal of Sound and Vibration **427**(120-133 (2018).

[39] M.J. Brennan, Y. Gao, P.C. Ayala, F.C.L. Almeida, P.F. Joseph, and A.T. Paschoalini, "Amplitude distortion of measured leak noise signals caused by instrumentation: Effects on

leak detection in water pipes using the cross-correlation method," Journal of Sound and Vibration **461**((2019).

[40] M.J. Brennan, F.L.C. de Almeida, F.K. de Lima, P.C.A. Castillo, and A.T. Paschoalini, "Measurement of the speed of leak noise propagation in buried water pipes: Challenges and difficulties," Lecture Notes in Mechanical Engineering **PartF6**(511-522 (2018).

[41] Y. Gao, M.J. Brennan, P.F. Joseph, J.M. Muggleton, and O. Hunaidi, "A model of the correlation function of leak noise in buried plastic pipes," Journal of Sound and Vibration **277**(1-2), 133-148 (2004).

[42] Y. Gao, M.J. Brennan, P.F. Joseph, J.M. Muggleton, and O. Hunaidi, "On the selection of acoustic/vibration sensors for leak detection in plastic water pipes," Journal of Sound and Vibration **283**(3-5), 927-941 (2005).

[43] Y. Gao, M.J. Brennan, and P.F. Joseph, "A comparison of time delay estimators for the detection of leak noise signals in plastic water distribution pipes," Journal of Sound and Vibration **292**(3-5), 552-570 (2006).

[44] Y. Gao, M.J. Brennan, and P.F. Joseph, "On the effects of reflections on time delay estimation for leak detection in buried plastic water pipes," Journal of Sound and Vibration **325**(3), 649-663 (2009).

[45] S. Li, Y. Wen, P. Li, J. Yang, X. Dong, and Y. Mu, "Leak location in gas pipelines using cross-time–frequency spectrum of leakage-induced acoustic vibrations," Journal of Sound and Vibration **333**(17), 3889-3903 (2014).

[46] C. Liu, Z. Cui, L. Fang, Y. Li, and M. Xu, "Leak localization approaches for gas pipelines using time and velocity differences of acoustic waves," Engineering Failure Analysis **103**(1-8 (2019).

[47] S. Shimanskiy, T. Iijima, and Y. Naoi, "Development of microphone leak detection technology of fugen NPP," Progress in Nuclear Energy **43**(1-4 SPEC), 357-364 (2003).

[48] M. Ahadi and M.S. Bakhtiar, "Leak detection in water-filled plastic pipes through the application of tuned wavelet transforms to Acoustic Emission signals," Applied Acoustics **71**(7), 634-639 (2010).

[49] S. Shimanskiy, T. Iijima, and Y. Naoi, "Development of acoustic leak detection and localization methods for inlet piping of fugen nuclear power plant," Journal of Nuclear Science and Technology **41**(2), 183-195 (2004).

[50] L. Meng, L. Yuxing, W. Wuchang, and F. Juntao, "Experimental study on leak detection and location for gas pipeline based on acoustic method," Journal of Loss Prevention in the Process Industries **25**(1), 90-102 (2012).

[51] S. Davoodi and A. Mostafapour, "Modeling acoustic emission signals caused by leakage in pressurized gas pipe," Journal of Nondestructive Evaluation **32**(1), 67-80 (2013).

[52] S. Davoodi and A. Mostafapour, "Gas leak locating in steel pipe using wavelet transform and cross-correlation method," International Journal of Advanced Manufacturing Technology **70**(5-8), 1125-1135 (2014).

[53] D. Ozevin and J. Harding, "Novel leak localization in pressurized pipeline networks using acoustic emission and geometric connectivity," International Journal of Pressure Vessels and Piping **92**(63-69 (2012).

[54] C. Xu, P. Gong, J. Xie, H. Shi, G. Chen, and G. Song, "An acoustic emission based multi-level approach to buried gas pipeline leakage localization," Journal of Loss Prevention in the Process Industries **44**(397-404 (2016).

[55] C.W. Liu, Y.X. Li, Y.K. Yan, J.T. Fu, and Y.Q. Zhang, "A new leak location method based on leakage acoustic waves for oil and gas pipelines," Journal of Loss Prevention in the Process Industries **35**(236-246 (2015).

[56] L. Cui-Wei, L. Yu-Xing, F. Jun-Tao, and L. Guang-Xiao, "Experimental study on acoustic propagation-characteristics-based leak location method for natural gas pipelines," Process Safety and Environmental Protection **96**(43-60 (2015).

[57] S. Li, J. Zhang, D. Yan, P. Wang, Q. Huang, X. Zhao, Y. Cheng, Q. Zhou, N. Xiang, and T. Dong, "Leak detection and location in gas pipelines by extraction of cross spectrum of single non-dispersive guided wave modes," Journal of Loss Prevention in the Process Industries **44**(255-262 (2016).

[58] C. Liu, Y. Li, L. Fang, and M. Xu, "Experimental study on a de-noising system for gas and oil pipelines based on an acoustic leak detection and location method," International Journal of Pressure Vessels and Piping **151**(20-34 (2017).

[59] M. Brennan, F.K. De Lima, F. De Almeida, P. Joseph, and A. Paschoalini, "A virtual pipe rig for testing acoustic leak detection correlators: Proof of concept," Applied Acoustics **102**(137-145 (2016).

[60] X. Cui, Y. Yan, Y. Ma, L. Ma, and X. Han, "Localization of CO2 leakage from transportation pipelines through low frequency acoustic emission detection," Sensors and Actuators, A: Physical **237**(107-118 (2016).

[61] Y. Mahmutoglu and K. Turk, "A passive acoustic based system to locate leak hole in underwater natural gas pipelines," Digital Signal Processing: A Review Journal **76**(59-65 (2018).

[62] R.A. Cody, P. Dey, and S. Narasimhan, "Linear Prediction for Leak Detection in Water Distribution Networks,″ Journal of Pipeline Systems Engineering and Practice **11**(1), (2020).

[63] X. Lang, P. Li, J. Cao, Y. Li, and H. Ren, "A small leak localization method for oil pipelines based on information fusion,″ IEEE Sensors Journal **18**(15), 6115-6122 (2018).

[64] X. Yu, W. Liang, L. Zhang, H. Jin, and J. Qiu, "Dual-tree complex wavelet transform and SVD based acoustic noise reduction and its application in leak detection for natural gas pipeline,″ Mechanical Systems and Signal Processing **72-73**(266-285 (2016).

[65] A. Mostafapour and S. Davoodi, "Leakage locating in underground high pressure gas pipe by acoustic emission method,″ Journal of Nondestructive Evaluation **32**(2), 113-123 (2013).

[66] M. Shehadeh, J.A. Steel, and R.L. Reuben, "Acoustic emission source location for steel pipe and pipeline applications: The role of arrival time estimation,″ Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering **220**(2), 121-133 (2006).

[67] P. Stajanca, S. Chruscicki, T. Homann, S. Seifert, D. Schmidt, and A. Habib, "Detection of leak-induced pipeline vibrations using fiber—Optic distributed acoustic sensing,″ Sensors (Switzerland) **18**(9), (2018).

[68] C. Liu, Y. Li, L. Fang, and M. Xu, "New leak-localization approaches for gas pipelines using acoustic waves,″ Measurement: Journal of the International Measurement Confederation **134**(54-65 (2019).

[69] W. Liang, L. Zhang, Q. Xu, and C. Yan, "Gas pipeline leakage detection based on acoustic technology,″ Engineering Failure Analysis **31**(1-7 (2013).

[70] A. Mostafapour and S. Davoudi, "Analysis of leakage in high pressure pipe using acoustic emission method,″ Applied Acoustics **74**(3), 335-342 (2013).

[71] C. Clark, L. Labonte, J. Castro, A. Abedi, and V. Caccese, "Wireless leak detection using airborne ultrasonics and a fast-Bayesian tree search algorithm with technology demonstration on the ISS C3 - IEEE International Conference on Wireless for Space and Extreme Environments, WiSEE 2015," (2016).

[72] J. Sumners and K.D. Chamraigne, "Wireless data acquisition system for impact detection and structural monitoring C3 - Structural Health Monitoring 2007: Quantification, Validation, and Implementation - Proceedings of the 6th International Workshop on Structural Health Monitoring, IWSHM 2007," **1**(211-221 (2007).

[73] X. Han, S. Zhao, X. Cui, and Y. Yan, "Localization of CO2 gas leakages through acoustic emission multi-sensor fusion based on wavelet-RBFN modeling," Measurement Science and Technology **30**(8), (2019).

[74] H. Jin, L. Zhang, W. Liang, and Q. Ding, "Integrated leakage detection and localization model for gas pipelines based on the acoustic wave method," Journal of Loss Prevention in the Process Industries **27**(1), 74-88 (2014).

[75] J. Sun, Q. Xiao, J. Wen, and Y. Zhang, "Natural gas pipeline leak aperture identification and location based on local mean decomposition analysis," Measurement **79**(147-157 (2016).

[76] M.S. El-Abbasy, F. Mosleh, A. Senouci, T. Zayed, and H. Al-Derham, "Locating leaks in water mains using noise loggers," Journal of Infrastructure Systems **22**(3), 04016012 (2016).

[77] Q. Wu and C.M. Lee, "A modified leakage localization method using multilayer perceptron neural networks in a pressurized gas pipe," Applied Sciences (Switzerland) **9**(9), (2019).

[78] J. Moriot, L. Maxit, J.L. Guyader, O. Gastaldi, and J. Périsse, "Use of beamforming for detecting an acoustic source inside a cylindrical shell filled with a heavy fluid," Mechanical Systems and Signal Processing **52-53**(645-662 (2015).

[79] L. Li, K. Yang, X. Bian, Q. Liu, Y. Yang, and F. Ma, "A gas leakage localization method based on a virtual ultrasonic sensor array," Sensors (Switzerland) **19**(14), (2019).

[80] X. Cui, Y. Yan, Y. Hu, and M. Guo, "Performance comparison of acoustic emission sensor arrays in different topologies for the localization of gas leakage on a flat-surface structure," Sensors and Actuators, A: Physical **300**((2019).

[81] X. Wang and M.S. Ghidaoui, "Identification of multiple leaks in pipeline II: Iterative beamforming and leak number estimation," Mechanical Systems and Signal Processing **119**(346-362 (2019).

[82] X. Wang, M.S. Ghidaoui, and J. Lin, "Identification of multiple leaks in pipeline III: Experimental results," Mechanical Systems and Signal Processing **130**(395-408 (2019).

[83] D. Ozevin and H. Yalcinkaya, "New leak localization approach in pipelines using single-point measurement," Journal of Pipeline Systems Engineering and Practice **5**(2), (2014).

[84] D. Liu, J. Fan, and S. Wu, "Acoustic wave-based method of locating tubing leakage for offshore gas wells," Energies **11**(12), (2018).

[85] W. Tao, W. Dongying, P. Yu, and F. Wei, "Gas leak localization and detection method based on a multi-point ultrasonic sensor array with TDOA algorithm," Measurement Science and Technology **26**(9), (2015).

[86] X. Cui, Y. Yan, M. Guo, X. Han, and Y. Hu, "Localization of CO2 leakage from a circular hole on a flat-surface structure using a circular acoustic emission sensor array," Sensors (Switzerland) **16**(11), (2016).

[87] S. Zhang, G. Shen, and L. An, "Leakage location on water-cooling wall in power plant boiler based on acoustic array and a spherical interpolation algorithm," Applied Thermal Engineering **152**(551-558 (2019).

[88] S.D. Holland, D.E. Chimenti, R. Roberts, and M. Strei, "Locating air leaks in manned spacecraft using structure-borne noise," Journal of the Acoustical Society of America **121**(6), 3484-3492 (2007).

[89] M.T. Hussels, S. Chruscicki, D. Arndt, S. Scheider, J. Prager, T. Homann, and A.K. Habib, "Localization of transient events threatening pipeline integrity by fiber-optic distributed acoustic sensing," Sensors (Switzerland) **19**(15), (2019).

[90] J. Zuo, Y. Zhang, H. Xu, X. Zhu, Z. Zhao, X. Wei, and X. Wang, "Pipeline Leak Detection Technology Based on Distributed Optical Fiber Acoustic Sensing System," IEEE Access **8**(30789-30796 (2020).

[91] S.C. Huang, W.W. Lin, M.T. Tsai, and M.H. Chen, "Fiber optic in-line distributed sensor for detection and localization of the pipeline leaks," Sensors and Actuators, A: Physical **135**(2), 570-579 (2007).

[92] J.P. Kurmer, S.A. Kingsley, J.S. Laudo, and S.J. Krak. *Distributed fiber optic acoustic sensor for leak detection*. in *Distributed and Multiplexed Fiber Optic Sensors*. 1992. International Society for Optics and Photonics.

[93] J.P. Kurmer, S.A. Kingsley, J.S. Laudo, and S.J. Krak, "Distributed fiber optic acoustic sensor for leak detection C3 - Proceedings of SPIE - The International Society for Optical Engineering," **1586**(117-128 (1991).

[94] S.H. Yönak and D.R. Dowling, "Photoacoustic detection and localization of small gas leaks," Journal of the Acoustical Society of America **105**(5), 2685-2694 (1999).

[95] S.H. Yönak and D.R. Dowling, "Parametric dependencies for photoacoustic leak localization," Journal of the Acoustical Society of America **112**(1), 145-155 (2002).

[96] E. Huang, D.R. Dowling, T. Whelan, and J.L. Spiesberger, "High-sensitivity photoacoustic leak testing," Journal of the Acoustical Society of America **114**(4 I), 1926-1933 (2003).

[97] S.H. Yönak, D.R. Dowling, and D.P. Gravel, "Photoacoustic assembly line leak testing," AutoTechnology **4**(APR.), 58-61 (2004).

[98] B. Van Hieu, S. Choi, Y.U. Kim, Y. Park, and T. Jeong, "Wireless transmission of acoustic emission signals for real-time monitoring of leakage in underground pipes," KSCE Journal of Civil Engineering **15**(5), 805-812 (2011).