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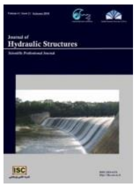

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Statistical Review of Major Standpoints in Hydraulic Transient-Based Leak Detection

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Abstract

Today, pipe systems are the most common facilities to convey various fluids from one place to another. In such facilities faults like leaks lead to advert consequences such as economic losses and social health threats. The fact that early detection of leaks can play a prominent role in reducing the amount of these undesired impacts has absorbed noticeable attention from researchers to this field of study. This paper presents a literature review on major aspects of hydraulic transient-based leak detection in pipe systems over the past three decades. The value of the present study is that an extensive database of peer-reviewed publications is brought together under a meticulous survey. It describes the trends, status and pinpoints the areas with a need for further investigation in the future. Uniquely, it contains information for over 95 publications in a tabular form, presenting domain type, analysis approach, optimization technique, topographic complexity of the case study, leak unknowns and validation approach.

Keywords: Hydraulic transient, Frequency Domain, Signal processing, Topographic complexity, Leak specifications.

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1. Introduction

In the modern world, pipe systems are the most popular means of fluid transportation. Such facilities suffer from various kinds of faults like leakage, blockage, etc. which can cause different sorts of costs ranges from economic loss to serious social health issues. An economic

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loss could be a result of fluid wastage that leads to a reduction in the quality of services to the consumers. Social health problems would emerge when an inverse flow forms at leak location and consequently hazardous pollutants in the environment around the pipe contaminate drinking water. In both cases, early detection of leaks can guarantee a noticeable decrease in the number of losses and threats. Due to such adverse consequences of leakages, leak detection has gained noticeable currency among researchers in recent years, and a variety of leak detection techniques has been developed.

Leak by nature is a hydraulic phenomenon that occurs in a certain location that its presence can affect the hydraulic condition of the system, therefore, could be detected hydraulically. Typically, such an aspect to leak detection requires a large quantity of data for accurate calculation, and the unsteady event like transient wave provides much more data than a steady event [1]. As an injected transient pressure wave travels throughout the pipe network, pipe features such as contractions, expansions, dead ends, branches, valves, junctions, bends, leaks, blockages, and deteriorations affect the input signal specifications. Generally, passing throughout the system, the transient wave is partially reflected, partially transmitted and some of it may be absorbed in a feature, thus altering in some way a system's flow and pressure response[2], and all these phenomena form some specific pattern changes in the original injected wave. In some sense, all transient-based leak detection techniques can be regarded as solving an inverse problem, in which the system state presented by analyzing the response signal in order to determine the unknown leaks and other features of the pipe network.

This paper aims to take a systematic survey throughout some major viewpoints in Hydraulic Transient-Based Leak detection literature to summarize the knowledge and prepare a comprehensive overview of conducted studies over the past three decades. A list of 95 peer-reviewed articles are considered, and a detailed analytical table of articles presents a thorough database that reflects discussed features. Behind the Introduction section, the current investigation consists of seven major parts. In section 2, Domain type is discussed in detail. In section 3, Analysis approach (Hydraulic Analysis/Signal Processing) is investigated to characterize previous works. Section 4 discusses Applied Optimization techniques. In section 5, the topographic complexity of the system (Network/Pipeline) is surveyed through the literature. Other two main aspects including Leak specifications and Results validation approach are considered in section 6 and 7, respectively. The conclusion and recommendations for future works are presented in section 8. In each section, analytical statistics concerning the frequency and trend of the discussed topic is presented in the form of illustrative charts and diagrams. It is worth mentioning that the focus of the present article is specifically on leakage and works that merely dedicated to other types of faults such as blockage are excluded.

2. Domain type (Time/Frequency)

The transient response of the hydraulic system is a set of data, which either could be acquired from hydraulic modeling of the system or measured using the transducers. In case of hydraulic modeling, depending on the applied methodology in solving the governing equations, response signals could be in time-domain [3-25] or frequency-domain [26-49], while the measured data from the sensors and transducers are generally in the form of time histories in time-domain. The later time histories could be applied in methods with Signal Processing approach (described in following sections) as system response to be interpreted for leak detection purposes [2, 50-58],or as a part of objective function to be minimized in Inverse Transient Methods (ITM) (also known as time domain reflectometry) or as a benchmark response in the validation of the novel pipe network analyzing techniques [3, 5, 6, 8-11, 13, 15, 17-20, 23, 24, 59, 60]. Besides, several studies taking the advantages of capabilities of both domains for further extension and justification of their proposed leak detection technique [30, 32, 37, 41, 61-68].

According to publications presented in appendix table, an equal percentage of 39 percent of studies has been performed in time and frequency domain, whereas roughly 21 percent have done in both domains. Figure 1 illustrates the variation of the researchers' attention to the different domain over the past three decades. The trend shows that before 2000, most of the investigations were performed in time domain, while after that, frequency domain methods have absorbed more attention to the extent that in recent six years the investigations mostly have done in the frequency domain.

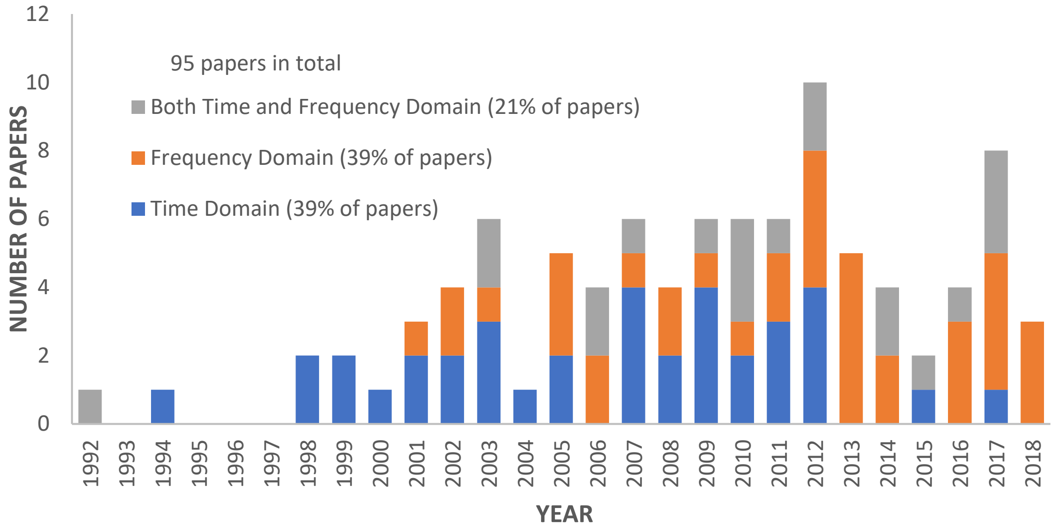

Figure 1: Papers (from Appendix table) by year and Domain Type

3. Analysis approach (Hydraulic Analysis/Signal Processing)

Regarding the standpoint in which transient wave response of a system is obtained and analyzed, two analysis approaches namely Hydraulic modeling (also known as model-based methods) and Signal processing are considered here.

Signal processing concerns the analysis, synthesis, and modification of signals, which are broadly defined as functions conveying "information about the behavior or attributes of some phenomenon" [69], such as sound, images, and biological measurements [70]. Some instances of signal-processing techniques applications are to improve signal transmission fidelity, storage efficiency, subjective quality, and to emphasize or detect components of interest in a measured signal [71]. On this basis, in signal processing, the system mostly is dealt with as a black box, and conventionally the unknowns of the system structure and configuration are neglected. In other words, here, the focus is on interpreting the output signal to obtain informative data about system condition and behavior. In transient-based leak detection, signal processing is utilized to extract information from measured data and to compare them with those from a fault-free flow or pressure benchmark signal to determine leak features.

Over the years, many researchers used several combinations of signal processing techniques in different fields as preprocessing, processing and post-processing tools. A number of common signal processing techniques that exploit in the literature are: Artificial Neural Network (ANN)

[72], Cross-Correlation Analysis [73, 74], Wavelet Analysis [50, 51, 55, 56, 75-81], Cepstrum Analysis [51, 52, 54, 58, 74, 82], Cumulative Sum change detection algorithm(CUSUM) [53], Gilbert Transform (HT) [2, 82], Hilbert-Huang Transform (HHT) [2], Normalized Hilbert transform (NHT)[82], Direct Quadrature (DQ) [82], Teager Energy Operator (TEO) [82], Maximum Likelihood Estimation (MLE) method [83, 84], Synchrosqueeze Wavelet Transform (SWT) [57], Principal Component Analysis (PCA) [58], Match Field Proccessing (MFP) [85].

In Hydraulic Modeling, the pipe systems' behavior is simulated using a set of nonlinear partial differential equations. Considering initial and boundary conditions, system response obtained by solving the continuity, motion and in some cases energy equations for unsteady pipe flow as the governing equations. Various researchers have proposed different solutions that vary in terms of precision, the amount of needed computational effort, simplicity and domain type. As for an instance a well-known method, namely Method Of Characteristics (MOC) is a high precision method with the considerable amount of computational cost while a frequency-domain method known as transfer matrix is far faster than MOC at the expense of losing the precision caused by considering a number of linearization assumptions in modeling some system components and characteristics.

A number of commonly used Hydraulic Modeling techniques from the literature are: MOC [1, 3-11, 13, 14, 18-20, 23, 59, 60, 64, 86, 87], Backward MOC [15], Transfer Matrix Method [27, 29, 32, 33, 38, 40, 41, 44-46, 48, 66, 67, 83, 88-91], Impedance Method [25, 39, 42, 43, 47, 61, 76], Finite Difference Method (FDM) [72], Transmission Line Modeling (TLM) [66, 75, 81], Standing Wave Difference Method (SWDM) [30], Admittance Matrix Method [34, 84], Impulse Response [25, 28, 53, 92], Orthogonal Collocation Model (OCM) [16].

Figure 2. illustrates the popularity of each analysis approach over the studied period. Data manifests that almost over the whole period; hydraulic analysis methods receive noticeable attention of 72 percent from researchers that implies that more investigation in the application of signal processing methods is still required.

4. Applied Optimization techniques

Over the studied period, Inverse Transient Methods (ITM) of fault detection achieve noticeable currency from the researchers because of their specific advantages such as the capability of simultaneous fault diction and calibration of parameters. In this category of methods, an optimization problem emerges through solving an inverse problem and consequently utilizing an optimization technique is inevitable. Various ITM methods have proposed and applied variety of optimization means to address this issue such as Levenberg-Marquardt method [3, 5, 8, 9, 17, 19], Genetic Algorithms [1, 6, 24, 25, 39, 43, 44, 61, 62, 67, 93], Shuffled Complex Evolution (SCE) [27, 31, 59], Model parsimony approach-Model error compensation [11], PSO [14, 45], Sequential Quadratic Programming Method [15, 18, 20, 37, 87], CFO [60], SA (Simulated Annealing) [21, 23]. The frequency of various optimization technique is presented in Figure 3 that implies GA is the most frequent method among all others.

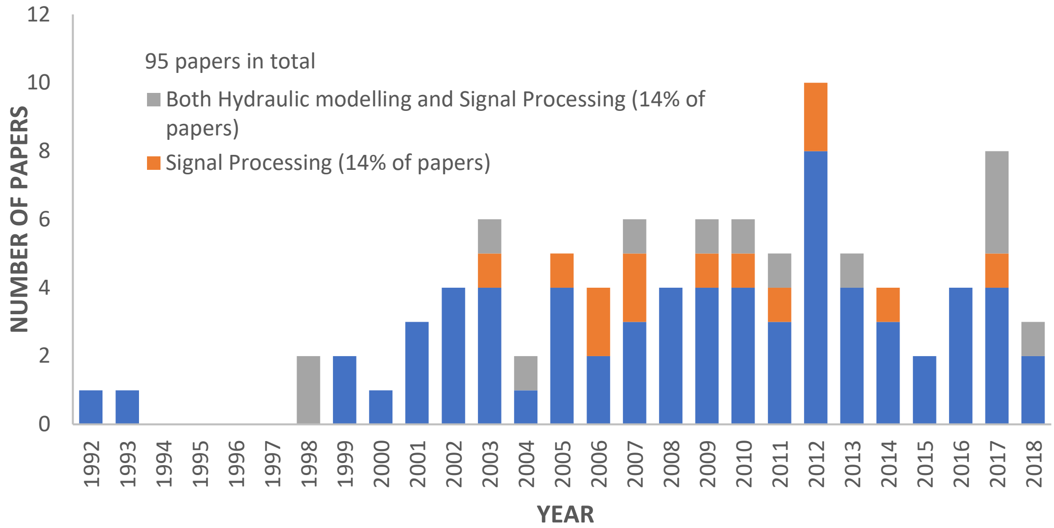

Figure 2. Papers (from Appendix table) by year and Analysis Approach

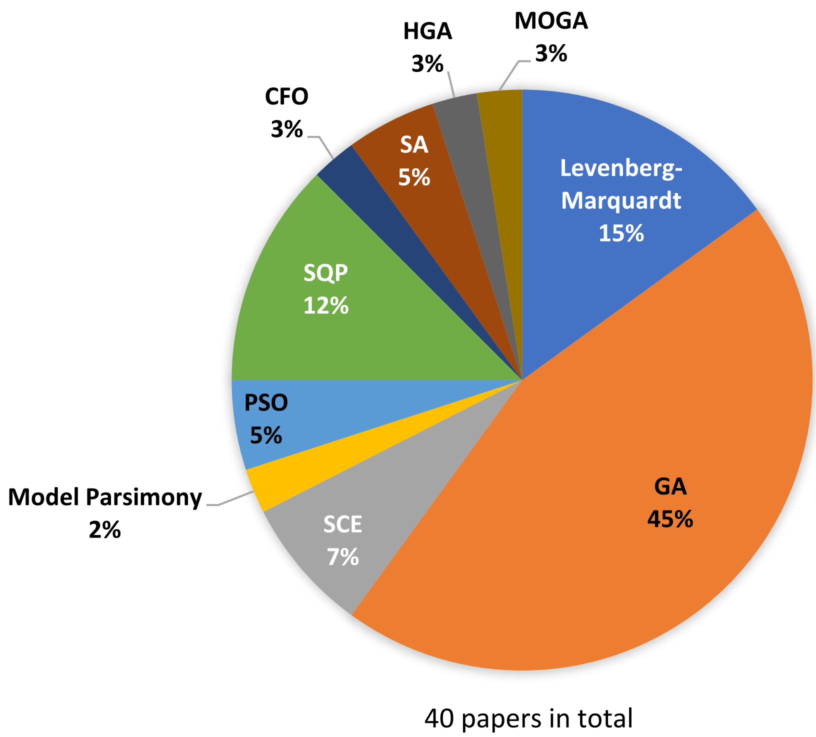

Figure 3. The frequency of utilization of optimization techniques in Papers from Appendix table.

5. The topographic complexity of the system (Network/Pipeline)

From the geometric complexity viewpoint, papers could be categorized into three main groups. The first group concerns the leak detection issues in pipelines that mainly consider a simple pipeline with a certain upstream and downstream boundary condition. The most popular configurations in this group are RPV (Reservoir-Pipe-Valve), RPR (Reservoir-Pipe-Reservoir) and RPVR (reservoir-Pipe-Valve-Reservoir). Hydraulically, such systems are more convenient to deal with because their simple geometry leads to no interaction between hydraulic responses of various pipes. On the other hand, the second group includes studies that work on systems consist of more than a simple pipe ranges from the pipeline with a single branch or loop to complex pipe networks with arbitrary layouts. Additionally, there exists a third group consisting of both pipeline and network case studies. Figure 4. represents papers (from Appendix table) by year and topographic complexity. Statistics reveal that although most facilities are in the form of complex networks with mixed layouts in practice, almost a quarter of researches have been dedicated to such geometries and lack of sufficient investigations in this field is still a matter of concern.

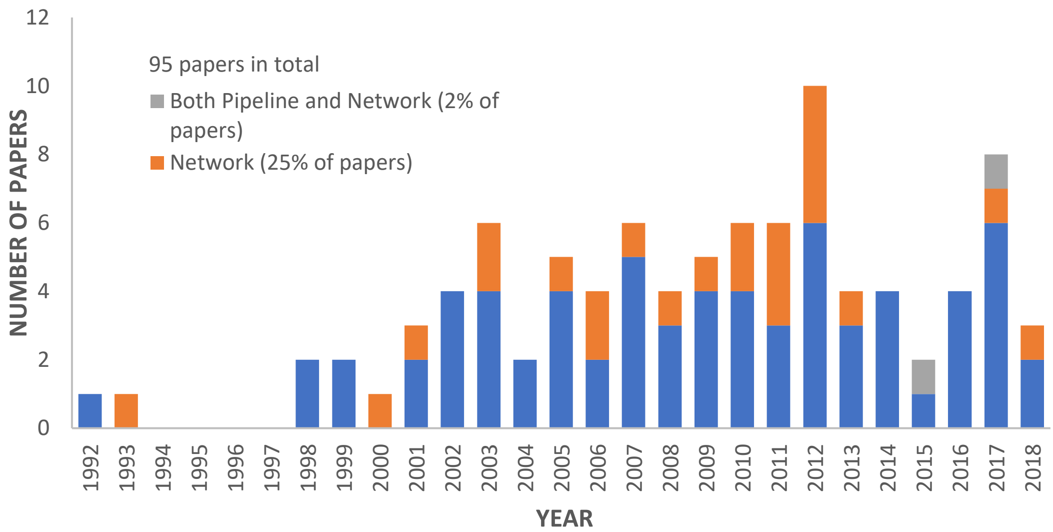

Figure 4. Papers (from Appendix table) by year and topographic complexity

6. Leak specifications: single leak or multiple leaks/location/size

Verbally, leak detection means to discover the existence of leaks in a pipe system. However, inherently, leaks could be characterized by several specifications such as number, location, and intensity of leaks. Although all these features are typical unknowns to be solved in a leak detection problem, only 39 percent of previously performed investigations take all of them into consideration. Almost 39 percent of studies present methods to find just Location and intensity and only roughly 21 percent (mostly ones with signal processing approach) are only capable of finding the location of the leak. The major motivation of works that exclude one or two of Leak specifications in their research is to decrease the number of decision variables so that reduces the dimension of the problem. Figure 5. shows the trend which describes the frequency of the various combination of leak features in papers from the appendix table over the past three decades.

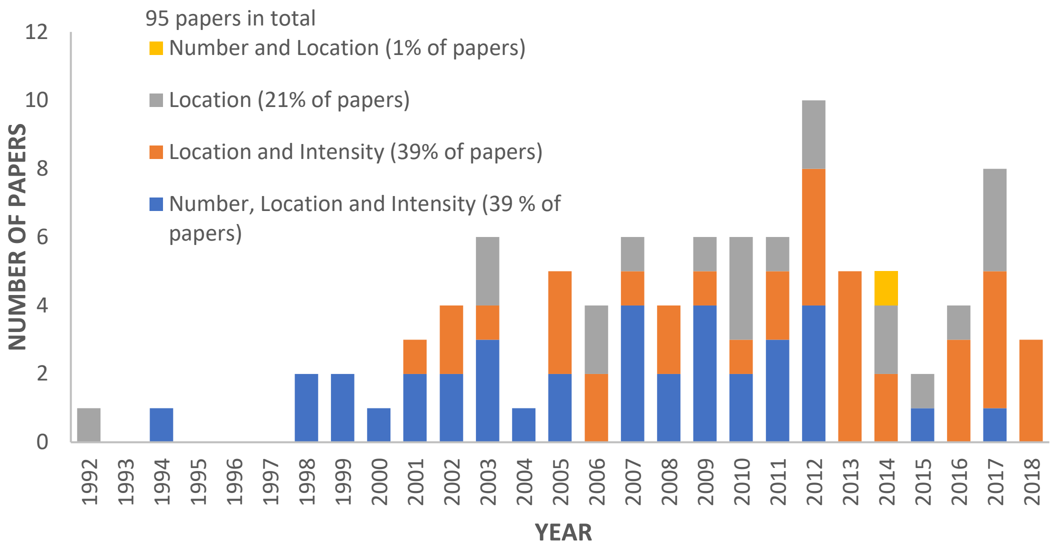

Figure 5. Papers (from Appendix table) by year and unknown leak specifications to detect

7. Results validation approach

The assessment of scientific knowledge involves a controversial issue namely validation that serves improving its generalization and reliability. The same as many investigations in engineering fields, Numerical simulations, Laboratory experiments, and Field application are the three most common validation approaches in leak detection studies.

Regarding economic issues in the development of laboratory experiments and real field application, the numerical simulations have gained wide currency among many researchers. However, most numerical models include a range of ideal assumptions in boundary conditions, initial conditions and the governing equations, which can leads to some levels of inaccuracies in results. In this condition, performing some laboratory modeling can provide researchers with rather reliable benchmarks to justify the results and avoid imprecisions. Despite all the advantages of the laboratory tests, it should be noted that tests often perform in a highly controlled laboratory circumstance to discover and decrease the undesired impacts of the unknown sources of uncertainties in real field application. Therefore, the most comprehensive validation approach to justify the reliability and robustness of a method is to consider all three approaches simultaneously. Figure 6. presents Papers from Appendix table by year and validation type. Regarding the information from the appendix table and Figure 6, only 3 percent of papers have used all three methods of validation, and a considerable amount of papers only focus on numerical simulations as a validation methodology and studies applying numerical and laboratory results are at a second place (with about 35% of papers). Also, the trend tells us that most researches of the current five years have merely preferred numerical methods that highlight the need for further investigation using laboratory and field approaches.

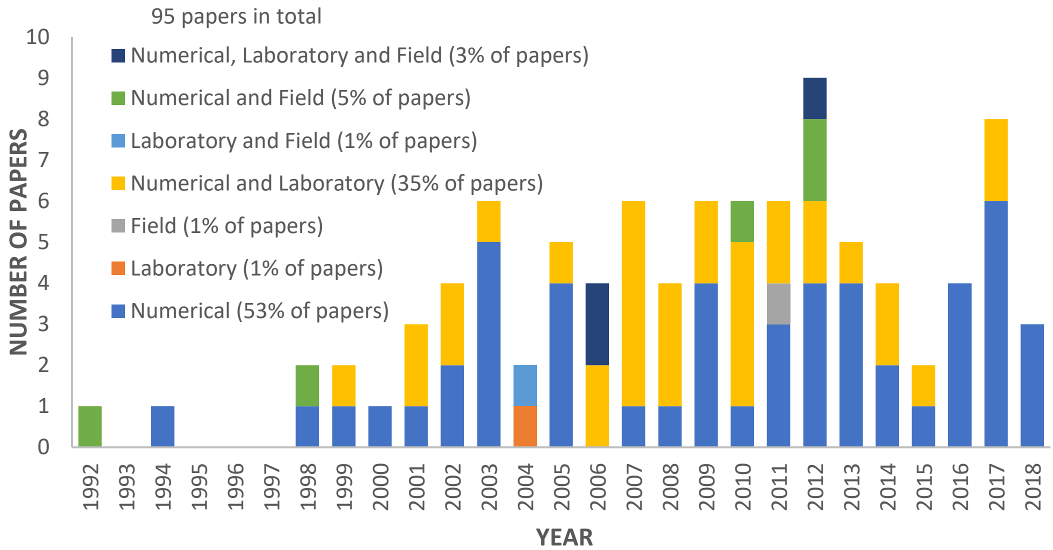

Figure 6. Papers (from Appendix table) by year and validation type

8. Conclusion

This paper presented a literature review of some major standpoints in hydraulic transient-based leak detection of pipe systems from 1992 to 2018. The papers concerning the detection of other kinds of faults were excluded from this study. The merit of the paper is that it brings together the majority of 95 peer-reviewed publications for hydraulic transient-based leak detection, which have been published over the past three decades. It describes the status and pinpoints the areas with a need for further investigation. Uniquely, it contains information for over 95 publications in a tabular form, presenting domain type, analysis approach, optimization technique, topographic complexity of case study, leak unknowns, and validation approach.

Based on the reviewed literature, the following areas of study are recommended for future research:

- More investigation in the application of signal processing methods is still required.
- Despite the importance and popularity of water distribution networks, only roughly 25% of works includes networks as a case study. It means that network transient analysis of the networks is still in its infancy and special attention should be dedicated to pipe networks for the future.
- In case of leak unknows only about 40% of papers consider detection of a leak in its full specifications, and more studies on leak full specifications including number, location, and intensity of leaks are advantageous.
- Only 3 percent of papers have used all three methods of validation and a considerable amount of papers only focus on numerical simulations as a validation methodology. Due to the importance of field and laboratory verification of the results, further investigation using laboratory and field approaches is highly recommended.

- Regarding the higher efficiency of frequency domain analysis of pipe networks, the exploitation of FRF in ITM process is proposed to reduce the computational cost in ITM. In this condition, special attention should be paid into extensive investigations on the accuracy of frequency domain modeling of transients, and its application in case of pipelines and networks.

Appendix Table. Analytical information about reviewed papers

ID.	*Authors* *Title*	*Analysis approach* *Optimization Technique* *Domain Type*	*Network/Pipeline* *Leak Unknowns* *(Number/Location/intensity)* *Validation* *(Numerical/Lab/Field)*
1.	Jönsson and Larson [86] Title: Leak Detection through Hydraulic Transient Analysis	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location Validation: Numerical, Field
2.	Liggett James and Chen [3] Title: Inverse transient analysis in pipe networks	Analysis approach: Hydraulic modeling Optimization Technique: Levenberg-Marquardt method Domain: Time	Network/Pipeline: Network Leak Unknowns: Number/Location/intensity Validation: Numerical
3.	Salvatore, Paolo [72] Title: Leak detection in liquefied gas pipelines by artificial neural networks	Analysis approach: Hydraulic Modeling, Signal Processing Optimization Technique: N/A Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/intensity Validation: Numerical, Field
4.	Liou [73] Title: Pipeline Leak Detection by Impulse Response Extraction	Analysis approach: Hydraulic Modeling, Signal Processing Optimization Technique: N/A Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Location/intensity Validation: Numerical
5.	Brunone [4] Title: Transient test-based technique for leak detection in outfall pipes	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Location/intensity Validation: Numerical, Lab
6.	Nash and Karney [5] Title: Efficient inverse transient analysis	Analysis approach: Hydraulic modeling	Network/Pipeline: Pipeline Leak Unknowns: N/A

	in series pipe systems	Optimization Technique: Levenberg-Marquardt method Domain: Time	Validation: Numerical
7.	Vítkovský John, Simpson Angus [6] Title: Leak Detection and Calibration Using Transients and Genetic Algorithms	Analysis approach: Hydraulic modeling Optimization Technique: GA Domain: Time	Network/Pipeline: Network Leak Unknowns: Number/Location/intensity Validation: Numerical
8.	Mpesha, Gassman Sarah [26] Title: Leak Detection in Pipes by Frequency Response Method	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/intensity Validation: Numerical
9.	Brunone and Ferrante [7] Title: Detecting leaks in pressurized pipes by means of transients	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Location/intensity Validation: Numerical, Lab
10.	Covas [8] Title: Hydraulic Transients used for Leakage Detection in Water Distribution Systems	Analysis approach: Hydraulic modeling Optimization Technique: Levenberg-Marquardt method and GA Domain: Time	Network/Pipeline: Network Leak Unknowns: Location/intensity Validation: Numerical, Lab
11.	Wang, Lambert Martin [63] Title: Leak Detection in Pipelines using the Damping of Fluid Transients	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: Location/intensity Validation: Numerical, Lab
12.	Lee, Vítkovský [27] Title: Leak detection in pipelines using an inverse resonance method	Analysis approach: Hydraulic modeling Optimization Technique: SCE Algorithm Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/intensity Validation: Numerical
13.	Vítkovský, Simpson [9] Title: Minimization algorithms and experimental inverse transient leak detection	Analysis approach: Hydraulic modeling Optimization Technique: A systematic approach to the application of the Levenberg-Marquardt algorithm Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Location/intensity Validation: Numerical, Lab
14.	Mpesha, Hanif Chaudhry [94] Title: Leak detection in pipes by	Analysis approach: Hydraulic modeling	Network/Pipeline: Pipeline eak Unknowns:

frequency response method using a step excitation	Optimization Technique: N/A Domain: Time, Frequency	Number/Location/intensity Validation: Numerical
15. Vitkovsky, Lee [88] Title: Leak and blockage detection in pipelines via an impulse response method	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/intensity Validation: Numerical
16. Kapelan, Savic [10] Title: A hybrid inverse transient model for leakage detection and roughness calibration in pipe networks	Analysis approach: Hydraulic modeling Optimization Technique: A new hybrid genetic algorithm (HGA) Domain: Time	Network/Pipeline: Network Leak Unknowns: Number/Location/intensity Validation: Numerical
17. Vitkovsky , Liggett [1] Title: Optimal Measurement Site Locations for Inverse Transient Analysis in Pipe Networks	Analysis approach: Hydraulic modeling Optimization Technique: GA with a new crossover operator Domain: Time	Network/Pipeline: Network Leak Unknowns: Number/Location/intensity Validation: Numerical
18. Al-Shidhani, Beck [75] Title: Leak monitoring in pipeline networks using wavelet analysis	Analysis approach: Hydraulic Modeling, Signal Processing Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/intensity Validation: Numerical
19. Ferrante and Brunone [28] Title: Pipe system diagnosis and leak detection by unsteady-state tests. 1. Harmonic analysis	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/intensity Validation: Numerical
20. Ferrante and Brunone [50] Title: Pipe system diagnosis and leak detection by unsteady-state tests. 2. Wavelet analysis	Analysis approach: Signal processing Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/intensity Validation: Numerical/Lab
21. Brunone and Ferrante [76] Title: Pressure waves as a tool for leak detection in closed conduits	Analysis approach: Hydraulic modeling, Signal processing Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/intensity Validation: Lab
22. Stephens, Lambert [59] Title: Field Tests for Leakage, Air	Analysis approach: Hydraulic modeling	Network/Pipeline: Pipeline Leak Unknowns:

	Pocket, and Discrete Blockage Detection Using Inverse Transient Analysis in Water Distribution Pipes	Optimization Technique: Shuffled Complex Evolution (SCE) global search algorithm Domain: Time	Number/Location/intensity Validation: Numerical/Field
23.	Beck, Curren [95] Title: Pipeline Network Features and Leak Detection by Cross-Correlation Analysis of Reflected Waves	Analysis approach: Signal Processing Optimization Technique: N/A Domain: Time	Network/Pipeline: Network Leak Unknowns: Location/intensity Validation: Numerical/Lab
24.	Lee, Vítkovský [29] Title: Leak location using the pattern of the frequency response diagram in pipelines: a numerical study	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/intensity Validation: Numerical
25.	Kim [25] Title: Extensive development of leak detection algorithm by impulse response method	Analysis approach: Hydraulic modeling Optimization Technique: GA Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/intensity Validation: Numerical
26.	Covas, Ramos [30] Title: Standing wave difference method for leak detection in pipeline systems	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location Validation: Numerical
27.	Lee, Vítkovský [31] Title: Frequency Domain Analysis for Detecting Pipeline Leaks	Analysis approach: Hydraulic modeling Optimization Technique: shuffled complex evolution (SCE) algorithm Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical
28.	Lee, Lambert [32] Title: Experimental verification of the frequency response method for pipeline leak detection	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/Intensity Validation: Numerical/Lab/Field
29.	Nixon, Ghidaoui [96] Title: Range of Validity of the Transient Damping Leakage Detection Method	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical/Lab
30.	Beck, Foong [51] Title: Wavelet and Cepstrum Analyses of Leaks in Pipe Networks	Analysis approach: Signal Processing Optimization Technique:	Network/Pipeline: Network Leak Unknowns: Location/Intensity

	N/A Domain: Time-Frequency	Validation: Numerical/Lab/Field
31. Taghvaei, Beck [52] Title: Leak detection in pipelines using cepstrum analysis	Analysis approach: Signal Processing Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: Network Leak Unknowns: Location/Intensity Validation: Numerical/Lab
32. Lee, Lambert [53] Title: Leak location in single pipelines using transient reflections	Analysis approach: Signal Processing Optimization Technique: N/A Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Location Validation: Numerical/Lab
33. Vítkovský John, Lambert Martin [11] Title: Experimental Observation and Analysis of Inverse Transients for Pipeline Leak Detection	Analysis approach: Hydraulic modeling Optimization Technique: Model parsimony approach, Model error compensation Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/Intensity Validation: Numerical/Lab
34. Ferrante, Brunone [77] Title: Wavelets for the Analysis of Transient Pressure Signals for Leak Detection	Analysis approach: Hydraulic Modeling, Signal Processing Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical/Lab
35. Lee, Vítkovský [92] Title: Leak location in pipelines using the impulse response function	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Location Validation: Numerical/Lab
36. Nixon and Ghidaoui Mohamed [12] Title: Numerical Sensitivity Study of Unsteady Friction in Simple Systems with External Flows	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: N/A Validation: Numerical
37. Taghvaei, Beck [54] Title: Leak detection in pipeline networks using low-profile piezoceramic transducers	Analysis approach: Signal Processing Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Network Leak Unknowns: Number/Location/Intensity Validation: Numerical/Lab
38. Al-Khomairi [13] Title: Leak detection in long pipelines using the least squares method	Analysis approach: Hydraulic modeling Optimization Technique: N/A	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical/Lab

		<u>Domain:</u> Time	
39.	Jung and Karney [14] <u>Title:</u> Systematic exploration of pipeline network calibration using transients	<u>Analysis approach</u>: Hydraulic modeling <u>Optimization Technique:</u> GA and PSO <u>Domain:</u> Time	<u>Network/Pipeline:</u> Network <u>Leak Unknowns:</u> Number/Location <u>Validation:</u> Numerical/Lab
40.	Lee Pedro, Vítkovský John [89] <u>Title:</u> Valve Design for Extracting Response Functions from Hydraulic Systems Using Pseudorandom Binary Signal	<u>Analysis approach</u>: Hydraulic modeling <u>Optimization Technique:</u> N/A <u>Domain:</u> Frequency	<u>Network/Pipeline:</u> Pipeline <u>Leak Unknowns:</u> N/A <u>Validation:</u> Numerical/Lab
41.	[33] <u>Title:</u> Leak detection in pipelines by frequency response method	<u>Analysis approach</u>: Hydraulic modeling <u>Optimization Technique:</u> N/A <u>Domain:</u> Frequency	<u>Network/Pipeline:</u> Pipeline <u>Leak Unknowns:</u> Location/Intensity <u>Validation:</u> Numerical
42.	Ferrante, Brunone [55] <u>Title:</u> Leak detection in branched pipe systems coupling wavelet analysis and a Lagrangian model	<u>Analysis approach</u>: Signal Processing <u>Optimization Technique:</u> N/A <u>Domain:</u> Time	<u>Network/Pipeline:</u> Network <u>Leak Unknowns:</u> Location <u>Validation:</u> Numerical/Lab
43.	Shamloo and Haghighi [15] <u>Title:</u> Leak detection in pipelines by inverse backward transient analysis	<u>Analysis approach</u>: Hydraulic modeling <u>Optimization Technique:</u> Sequential Quadratic Programming Method <u>Domain:</u> Time	<u>Network/Pipeline:</u> Pipeline <u>Leak Unknowns:</u> Number/Location/Intensity <u>Validation:</u> Numerical
44.	Ferrante, Brunone [78] <u>Title:</u> Leak-edge detection	<u>Analysis approach</u>: Signal Processing, Hydraulic modeling <u>Optimization Technique:</u> N/A <u>Domain:</u> Time	<u>Network/Pipeline:</u> Pipeline <u>Leak Unknowns:</u> Location/Intensity <u>Validation:</u> Numerical/Lab
45.	Zecchin Aaron, Simpson Angus [34] <u>Title:</u> Transient Modeling of Arbitrary Pipe Networks by a Laplace-Domain Admittance Matrix	<u>Analysis approach</u>: Hydraulic modeling <u>Optimization Technique:</u> N/A <u>Domain:</u> Frequency	<u>Network/Pipeline:</u> Network <u>Leak Unknowns:</u> N/A <u>Validation:</u> Numerical
46.	Bartecki [90] <u>Title:</u> Frequency-and time-domain analysis of a simple pipeline system	<u>Analysis approach</u>: Hydraulic modeling <u>Optimization Technique:</u> N/A <u>Domain:</u> Time-Frequency	<u>Network/Pipeline:</u> Pipeline <u>Leak Unknowns:</u> N/A <u>Validation:</u> Numerical

47. Torres, Besançon [16] Title: Multi-leak estimator for pipelines based on an orthogonal collocation model	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/Intensity Validation: Numerical
48. Covas and Ramos [17] Title: Case Studies of Leak Detection and Location in Water Pipe Systems by Inverse Transient Analysis	Analysis approach: Hydraulic modeling Optimization Technique: Levenberg-Marquardt method, GA Domain: Time	Network/Pipeline: Network Leak Unknowns: Number/Location/Intensity Validation: Lab/Field
49. Shamloo and Haghighi [18] Title: Optimum leak detection and calibration of pipe networks by inverse transient analysis	Analysis approach: Hydraulic modeling Optimization Technique: Sequential Quadratic Programming(SQP), GA Domain: Time	Network/Pipeline: Network Leak Unknowns: Number/Location/Intensity Validation: Numerical
50. Duan, Ghidaoui [97] Title: Unsteady friction and visco-elasticity in pipe fluid transients	Analysis approach: Hydraulic Modeling, Signal Processing Optimization Technique: N/A Domain: Time, Frequency	Network/Pipeline: Pipeline Leak Unknowns: N/A Validation: Numerical/Lab
51. Duan, Lee [64] Title: Essential system response information for transient-based leak detection methods	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Time, Frequency	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/Intensity Validation: Numerical/Lab
52. Lee Pedro and Vítkovský John [35] Title: Quantifying Linearization Error When Modeling Fluid Pipeline Transients Using the Frequency Response Method	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: N/A Validation: Numerical
53. Ghazali, Staszewski [2] Title: Instantaneous phase and frequency for the detection of leaks and features in a pipeline system	Analysis approach: Signal Processing Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location Validation: Numerical/Lab
54. Duan, Lee [36] Title: Leak detection in complex series pipelines by using the system frequency response method	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/Intensity Validation: Numerical
55. Soares, Covas [19] Title: Leak detection by inverse	Analysis approach: Hydraulic modeling	Network/Pipeline: Network Leak Unknowns: Location

transient analysis in an experimental PVC pipe system	Optimization Technique: Levenberg-Marquardt method, GA Domain: Time	Validation: Numerical/Lab
56. Haghighi and Shamloo [87] Title: Transient generation in pipe networks for leak detection	Analysis approach: Hydraulic modeling Optimization Technique: SQP, GA Domain: Time	Network/Pipeline: Network Leak Unknowns: Number/Location/Intensity Validation: Numerical
57. Vítkovský John, Lee Pedro [37] Title: Head- and Flow-Based Formulations for Frequency Domain Analysis of Fluid Transients in Arbitrary Pipe Networks	Analysis approach: Hydraulic modeling Optimization Technique: SQP, GA Domain: Frequency	Network/Pipeline: Network Leak Unknowns: N/A Validation: Numerical
58. Hu, Zhang [79] Title: Detection of small leakage from long transportation pipeline with complex noise	Analysis approach: Signal Processing Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/Intensity Validation: Field
59. Meniconi, Brunone [80] Title: Small Amplitude Sharp Pressure Waves to Diagnose Pipe Systems	Analysis approach: Hydraulic Modeling, Signal Processing Optimization Technique: N/A Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical/Lab
60. Haghighi, Covas [20] Title: Direct backward transient analysis for leak detection in pressurized pipelines: from theory to real application	Analysis approach: Hydraulic modeling Optimization Technique: SQP Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/Intensity Validation: Numerical/Field
61. Haghighi and Keramat [21] Title: A fuzzy approach for considering uncertainty in transient analysis of pipe networks	Analysis approach: Hydraulic modeling Optimization Technique: SA (Simulated Annealing) Domain: Time	Network/Pipeline: Network Leak Unknowns: N/A Validation: N/A
62. Haghighi and Ramos [60] Title: Detection of Leakage Freshwater and Friction Factor Calibration in Drinking Networks Using Central Force Optimization	Analysis approach: Hydraulic modeling Optimization Technique: CFO Domain: Time	Network/Pipeline: Network Leak Unknowns: Number/Location/Intensity Validation: Numerical
63. Duan, Ghidaoui [98] Title: Relevance of Unsteady Friction to Pipe Size and Length in Pipe Fluid Transients	Analysis approach: Hydraulic modeling Optimization Technique: N/A	Network/Pipeline: Pipeline Leak Unknowns: N/A Validation: Numerical/Lab/Field

	Domain: Frequency	
64. Duan, Lee Pedro [38] Title: System Response Function–Based Leak Detection in Viscoelastic Pipelines	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location Validation: Numerical
65. Guo, Yang [39] Title: Leak detection in pipelines by exclusively frequency domain method	Analysis approach: Hydraulic modeling Optimization Technique: GA Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical/Lab
66. Kashima, Lee [65] Title: Numerical errors in discharge measurements using the KDP method	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: N/A Validation: Numerical
67. Zecchin Aaron, Lambert Martin [22] Title: Inverse Laplace Transform for Transient-State Fluid Line Network Simulation	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Time	Network/Pipeline: Network Leak Unknowns: N/A Validation: Numerical
68. Ghazali, Beck [82] Title: Comparative study of instantaneous frequency-based methods for leak detection in pipeline networks	Analysis approach: Signal Processing Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical/Field
69. Srirangarajan, Allen [56] Title: Wavelet-based Burst Event Detection and Localization in Water Distribution Systems	Analysis approach: Signal Processing Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: network Leak Unknowns: Location Validation: Numerical/Lab
70. Gong, Lambert Martin [40] Title: Single-Event Leak Detection in Pipeline Using First Three Resonant Responses	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical/Lab
71. Gong, Simpson [91] Title: Determination of the linear frequency response of single pipelines using persistent transient excitation: a numerical investigation	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical
72. Lee [41] Title: Energy analysis for the illustration of inaccuracies in the linear modeling of	Analysis approach: Hydraulic modeling Optimization Technique:	Network/Pipeline: Pipeline Leak Unknowns: N/A Validation: Numerical

	pipe fluid transients	N/A Domain: Frequency	
73.	Lee, Duan [66] Title: The effect of time-frequency discretization on the accuracy of the transmission line modeling of fluid transients	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: N/A Validation: Numerical
74.	Zecchin, White [84] Title: Parameter identification of fluid line networks by frequency-domain maximum likelihood estimation	Analysis approach: Hydraulic Modeling, Signal Processing Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Network Leak Unknowns: N/A Validation: Numerical
75.	Kim [61] Title: Inverse Transient Analysis for a Branched Pipeline System with Leakage and Blockage Using Impedance Method	Analysis approach: Hydraulic modeling Optimization Technique: GA Domain: Time-Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical
76.	Gong, Zecchin Aaron [42] Title: Frequency Response Diagram for Pipeline Leak Detection: Comparing the Odd and Even Harmonics	Analysis approach: Hydraulic modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical
77.	Kim Sang, Zecchin [43] Title: Diagnosis of a Pipeline System for Transient Flow in Low Reynolds Number with Impedance Method	Analysis approach: Hydraulic modeling Optimization Technique: GA Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical/Lab
78.	Amin, Hadi [57] Title: Leakage Detection in Pipeline Using Synchrosqueeze Wavelet Transform	Analysis approach: Signal Processing Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: Pipeline Leak Unknowns: Number/Location Validation: Numerical/Lab
79.	Huang, Lin [23] Title: An Optimization Approach to Leak Detection in Pipe Networks Using Simulated Annealing	Analysis approach: Hydraulic Modeling Optimization Technique: SA (Simulated Annealing) Domain: Time	Network/Pipeline: Pipeline and Network Leak Unknowns: Number/Location/Intensity Validation: Numerical
80.	Lee Pedro, Duan [62] Title: Numerical and Experimental Study on the Effect of Signal Bandwidth on Pipe Assessment Using Fluid Transients	Analysis approach: Hydraulic Modeling Optimization Technique: GA Domain: Time-Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical/Lab
81.	Duan [67]	Analysis approach:	Network/Pipeline: Pipeline

Title: Transient frequency response based leak detection in water supply pipeline systems with branched and looped junctions	Hydraulic Modeling Optimization Technique: GA Domain: Frequency	Leak Unknowns: Location/Intensity Validation: Numerical
82. Duan and Lee [44] Title: Transient-Based Frequency Domain Method for Dead-End Side Branch Detection in Reservoir Pipeline-Valve Systems	Analysis approach: Hydraulic Modeling Optimization Technique: GA is used in an inverse problem of solving the analytical equations Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: N/A Validation: Numerical
83. Ranginkaman, Haghighi [45] Title: Inverse Frequency Response Analysis For Pipelines Leak Detection Using The Particle Swarm Optimization	Analysis approach: Hydraulic Modeling Optimization Technique: PSO Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Number/Location/Intensity Validation: Numerical
84. Ferrante, Capponi [68] Title: Numerical transient analysis of random leakage in time and frequency domain	Analysis approach: Hydraulic Modeling Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: Pipeline Leak Unknowns: N/A Validation: Numerical
85. Rubio Scola, Besançon [46] Title: Blockage and Leak Detection and Location in Pipelines Using Frequency Response Optimization	Analysis approach: Hydraulic Modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical
86. Hanafi.M.Yusop, M.F.Ghazali [58] Title: Improvement of Cepstrum Analysis for the Purpose to Detect Leak, Feature and Its Location in Water Distribution System based on Pressure Transient Analysis	Analysis approach: Signal Processing Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location Validation: Numerical/Lab
87. Motazedi and Beck [74] Title: Leak detection using cepstrum of cross-correlation of transient pressure wave signals	Analysis approach: Hydraulic Modeling, Signal Processing Optimization Technique: N/A Domain: Time-Frequency	Network/Pipeline: Pipeline and Network Leak Unknowns: Location/Intensity Validation: Numerical
88. Rahmanshahi, Fathi-Moghadam [24] Title: Leak Detection in Viscoelastic Pipeline using Inverse Transient Analysis	Analysis approach: Hydraulic Modeling Optimization Technique: GA Domain: Time	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity Validation: Numerical/Lab
89. Hamat, Ghazali [81] Title: The Use of Transmission Line	Analysis approach: Hydraulic Modeling,	Network/Pipeline: Pipeline Leak Unknowns: Location

Modeling for Detection of Leakage in Pipeline	Signal Processing Optimization Technique: N/A Domain: Time-Frequency	Validation: Numerical
90. Kim [47] Title: Multiple Leakage Function for a Simple Pipeline System	Analysis approach: Hydraulic Modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity/Intensity Validation: Numerical
91. Wang and Ghidaoui [85] Title: Pipeline leak detection using the matched-field processing method	Analysis approach: Hydraulic Modeling, Signal Processing Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity/Intensity Validation: Numerical
92. Ranginkaman, Haghighi [48] Title: Application of the Frequency Response Method for Transient Flow Analysis of Looped Pipe Networks	Analysis approach: Hydraulic Modeling Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Network Leak Unknowns: N/A Validation: Numerical
93. Kim [93] Title: Development of Multiple Leakage Detection Method for a Reservoir Pipeline Valve System	Analysis approach: Hydraulic Modeling Optimization Technique: GA Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity/Intensity Validation: Numerical
94. Wang and Ghidaoui [83] Title: Identification of multiple leaks in pipeline: Linearized model, maximum likelihood, and super-resolution localization	Analysis approach: Hydraulic Modeling, Signal processing Optimization Technique: N/A Domain: Frequency	Network/Pipeline: Pipeline Leak Unknowns: Location/Intensity/Intensity Validation: Numerical
95. Sabzkouhi and Haghighi [49] Title: Uncertainty Analysis of Transient Flow in Water Distribution Networks	Analysis approach: Hydraulic Modeling Optimization Technique: MOGA Domain: Frequency	Network/Pipeline: Network Leak Unknowns: N/A Validation: Numerical

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