Table S1: Summary of reviewed papers.

ID. *Authors (year)* *TDM/TRM/SRM/ITM* *Domain* *Title*	*Analysis approach* *Analysis technique* *System Response Type* *Optimization Technique* *Friction model* *Viscoelasticity* *Noise*	*Network/Pipeline* *Case Study* *Leak Unknowns* *(Number/Location/intensity)* *NO. Measurement Points* *Validation* *(Numerical/Lab/Field)*	*Brief Description and findings*
1. Jönsson and Larson (1992) TRM Domain: Time-Frequency Title: Leak Detection through Hydraulic Transient Analysis	Analysis approach: Hydraulic modeling Analysis technique: MOC System Response Type: N/A Optimization Technique: N/A Friction model: Friction in the pipe is neglected and it is assumed that no minor losses occur at the leak Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location NO. measurement Points**:** Single Validation: Numerical, Field	The paper begins by discussing the effect of a pressure wave propagating past a leak from a theoretical point of view, including the derivation of an analytic solution for the magnitude of the reflected wave for a simple configuration. • **Methodology:** o Numerical simulations using MOC employed to determine the effect of a leak on the pressure variation in simple hydraulic systems. o The spectral analysis used to analyze time series of pressure in order to detect reflected waves originating from a leak. • **Results:** The presented technique employed to field measurements carried out in a hydraulic system where a leak could be simulated. o Under field conditions this effect may be difficult to distinguish, as frictional attenuation of the transient pressure tends to exceed the friction estimated from steady-state models. o By applying spectral analysis to the measured pressure time series, it is easier to identify reflected waves in a hydraulic system. In the paper a number of examples of are presented where this technique is employed, encompassing both numerical simulations for sample cases as well as field measurements.
2. Liggett and Chen (1994) ITM Domain: Time Title: Inverse transient analysis in pipe networks	Analysis approach: Hydraulic modeling Analysis technique: MOC System Response Type: N/A Optimization Technique: Levenberg-Marquardt method	Network/Pipeline: Network Case Study: small pipe network with 11 pipes and 7 nodes Leak Unknowns: Number/Location/intensity NO. measurement Points**:** Multiple	This study proposes inverse transient analysis method to calibrate and determining leaks or unauthorized use in pipe networks. • **Methodology:** o The adjoint solution of the system to find gradient data and a Jacobian matrix is applied

	Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Validation: Numerical	to find a Hessian matrix, which is used in the Levenberg-Marquardt method to adjust parameters to minimize the difference between calculated and measured heads. o The adjoint method is also used to compute sensitivities, which are valuable in judging the quality of the solution. • **Results:** Transient calculations show much more promise, especially when used with inverse mathematics. In current systems the calibration is often poorly known. When using steady-state analysis, the friction factors become important quantities to know accurately, leading to large errors when friction is not accurately known. In the unsteady analysis, calibration is much easier and can be carried on simultaneously with the leak analysis.
3. Salvatore, Paolo et al. (1998) TRM Domain: Time Title: Leak detection in liquefied gas pipelines by artificial neural networks	Analysis approach: Hydraulic Modeling and AI-Enhanced Analysis technique: Solving Mass, Energy and Momentum conservation equations using Finite Difference Method, ANN System Response Type: N/A Optimization Technique: N/A Friction model: using energy conservation equilibrium including two-phase friction factor defined by Sintef-Ife (1990) Viscoelasticity: N/A Noise: Noise Characteristics for Transducers on the Reference Pipeline were considered	Network/Pipeline: Pipeline Case Study: a single pipeline Leak Unknowns: Number/Location/intensity NO. measurement Points**:** Multiple Validation: Numerical, Field	• **Description and methodology:** In this study, a leak detection system for pipelines was developed by using artificial neural networks (ANN) for leak sizing and location and by processing the field data. o A reference pipeline was considered for practical implementation of the package. The ability of the package to withstand spurious alarms in the event of operational transients was tested. • **Challenges and solutions:** o The compressibility effect, due to "packing" of the liquid in the pipeline, causes many such spurious alarms. o Adequate preprocessing of the data performed by using a computer code in conjunction with the ANN to compensate for the operational variations and to prevent spurious alarms. • **Results:** The package detects leaks as small as 1% of the inlet flow rate and correctly predicts the leaking segment of the pipeline with a probability of success that is greater than 50% for the smallest leak.
4. Liou (1998) SRM Domain: Time	Analysis approach: Hydraulic modeling, Signal Processing Analysis technique: MOC, Cross-Correlation Analysis	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/intensity	• **Methodology:** In this investigation, the impulse response is extracted by using cross-correlations between a low amplitude pseudo-random binary disturbance input and the system's

Title: Pipeline Leak Detection by Impulse Response Extraction	System Response Type: Impulse Response Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: using a pseudo-random binary signal to approximate the wide-band noise	NO. measurement Points: Multiple Validation: Numerical	output, and applied to pipeline hydraulics as a means of real-time non-interruptive integrity monitoring. o A method for generating pseudo random binary head signals, an explanation of their usefulness in impulse response extraction, and the theory on impulse response extraction by cross correlation are discussed. o Small-amplitude transient pipe flows are modeled numerically to generate surrogate "measured" head data. The impulse response to a unit head pulse, with and without a leak, is explained and the leak detection rationale established. o Valve modulation is used to generate the pseudo random binary head disturbances. o The adverse effect of additive data noise and how to minimize it are studied.
5. Brunone (1999) TRM Domain: Time Title: Transient test-based technique for leak detection in outfall pipes	Analysis approach: Hydraulic modeling Analysis technique: MOC System Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: A single pipeline Leak Unknowns: Location/intensity NO. measurement Points: Single Validation: Numerical, Lab	In this paper, a transient test-based technique is proposed for leak detection in outfall pipes. • **Methodology:** o First, numerical modeling of the effects of a leak on the propagation of a pressure wave is discussed. o Then, a first-order formula for the preliminary evaluation of the discharge behavior of the leak is given. Results of some laboratory tests carried out on a long pipe confirm the reliability and validity of the proposed technique, at least when a simple pipe system is considered. • **Results:** o Inverse transient calculations are proved to be able to provide precise information about the characteristics of the leak. o • **The special features of this application:** o The practicality of only onshore pressure control and measurement, as well as their importance from an environmental point of view, make this topic valuable. o The transient tests proposed do not require complex equipment to be carried out (in fact, pressure measurement at only one section is needed) and do not give rise to dangerous overpressures. The state of the outfall pipe can then be determined periodically by comparing the present pressure signal with the one recorded, as an

			example, just after the construction corresponding to an intact pipe.
6. Nash and Karney (1999) ITM Domain: Time Title: Efficient inverse transient analysis in series pipe systems	Analysis approach: Hydraulic modeling Analysis technique: MOC System Response Type: N/A Optimization Technique: Levenberg-Marquardt method Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: N/A NO. measurement Points: Single Validation: Numerical	This study considers a direct-equation implementation of inverse transient analysis using both perfect data and data with modeling and simulated measurement errors. Accuracy depends on both of these errors through a least-squares merit function. **Methodology:** • Measurement of the changes in heads initiated by a valve closure is used to calibrate the friction factors in a hydraulic system consisting of a series-connected pipeline and a downstream valve joining two reservoirs. • The calibration is performed by minimizing the inverse least-squares problem representing the difference between the measured and predicted transient response in the network. • Unlike previous approaches, the sensitivity information required for the minimization or error is obtained by direct differentiation of MOC equations and the valve equation with respect to the friction factors. • The sensitivity of the calibration results to the amount of data included in the analysis, the initial friction factor estimates, and modeling and simulated measurement errors is discussed. **Key finding:** The ultimate test of the method will involve the use of field collected data. Data of this type will provide a more rigorous test of the assumptions central to the solution of the forward problem. • It is expected that it will not be possible to continuously improve the results by extending the simulation time due to the increasing error caused by the standard assumption of quasi-steady friction.
7. Vitkovsky, Simpson et al. (2000) ITM Domain: Time Title: Leak Detection and Calibration Using Transients and Genetic Algorithms	Analysis approach: Hydraulic modeling Analysis technique: MOC System Response Type: N/A Optimization Technique: GA Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Network Case Study: small pipe network with 11 pipes and 7 nodes Leak Unknowns: Number/Location/intensity NO. measurement Points: Multiple Validation: Numerical	This paper uses the genetic algorithm (GA) technique in conjunction with the inverse transient method to detect leaks and friction factors in water distribution systems. **Methodology:** • A continuous variable representation has been developed for the GA coding scheme. • Two new GA operators for crossover and mutation are introduced. **Key findings and results:** • There is a trade-off between the fast speed of a derivative method of optimization and the slower but more robust and comprehensive GA search.

			• The GA has the ability to bound its search in the parameter space. This is a distinct advantage over gradient-based methods where bounding can cause the optimization method to fail.
8. Mpesha, Gassman Sarah et al. (2001) SRM Domain: Frequency Title: Leak Detection in Pipes by Frequency Response Method	Analysis approach: Hydraulic modeling Analysis technique: Transfer Matrix Method System Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: single, series, parallel branched RPV system Leak Unknowns: Number/Location/intensity NO. measurement Points: Single Validation: Numerical	In this paper, a method using the frequency response method is presented for detecting and locating leaks. This method has the potential to determine the location and magnitude of leaks in real-life pipe systems by comparing a computed no leak frequency response diagram to an experimentally derived frequency response diagram. This study considered the analysis of series and branching systems using periodic excitations. **Methodology:** • A steady-oscillatory flow, produced by the periodic opening and closing of a valve, is analyzed in the frequency domain by using the transfer matrix method, and a frequency response diagram at the valve is developed. **Key findings:** • For a system with leaks, Frequency response diagram has additional resonant pressure amplitude peaks (referred to as the secondary pressure amplitude peaks) that are lower than the resonant pressure amplitude peaks (called primary amplitude peaks) for the system with no leaks. **Limitations:** • The method is capable of detecting and locating individual leaks of up to 0.5% of the mean discharge **when uncertainties in system parameters are not considered**. • Leaks smaller than this that are distributed along a pipeline cannot be detected. **Future work:** • Additional investigations are needed for closed-loop networks and for nonperiodic excitations.
9. Brunone and Ferrante (2001) SRM Domain: Time Title: Detecting leaks in pressurized pipes by means of transients	Analysis approach: Hydraulic modeling Analysis technique: MOC System Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/intensity NO. measurement Points: Single Validation: Numerical, Lab	The aim of this paper is to show that the use of unsteady-state tests, which give rise to small overpressure, can be considered as an appropriate method. • During these tests, it is necessary to record the pressure-time history in just one section of the pipe. **Key findings:** • Based on a thorough laboratory investigation, the influence on the pressure signal of size and shape of

	Noise: N/A		small leaks, along with discharge conditions and initial flow regime, is analyzed. • Some remarks about the possible applicability of the obtained results to pipes of different material are presented. • A criterion is provided for a first-approximation estimation of leak size, based on the results of an inverse method procedure concerning pressure signals.
10. Covas and Ramos (2001) ITM Domain: Time Title: Hydraulic Transients used for Leakage Detection in Water Distribution Systems	Analysis approach: Hydraulic modeling Analysis technique: MOC System Response Type: N/A Optimization Technique: Levenberg-Marquardt method and GA Friction model: Steady State using Darcy Weisbach model/ Unsteady Brunone et al. 1991a, 1995 with improvements by Vitkovskey et al. (2000a) Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Network Case Study: A pipe network with six square loops Leak Unknowns: Location/intensity NO. measurement Points: Multiple Validation: Numerical, Lab	In this research, the ITM approach is presented conceptually and implemented in a software tool. **Methodology:** • The methodology of this paper is the identification of leaks location in pipe networks using observed pressure data, collected during the occurrence of transient events, and the minimization of the difference between observed and calculated parameters. **Results:** • The methodology is tested and verified with laboratory data collected in an experimental facility at Technical The University of Lisbon. • Based on preliminary data analysis, the main practical difficulties of the implementation of this methodology in field network systems are outlined.
11. Wang, Lambert Martin et al. (2002) TDM Domain: Frequency Title: Leak Detection in Pipelines using the Damping of Fluid Transients	Analysis approach: Hydraulic modeling Analysis technique: MOC, Fourier series analysis System Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model/ Unsteady the modified Brunone model (Vitkovskey´ 2001) Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: Location/intensity NO. measurement Points: Single Validation: Numerical, Lab	The paper presents a method of finding location and magnitude of leaks based on the fact that Leaks in pipelines contribute to damping of transient events. **Key finding:** • Because the problem of transient flow in pipes is nearly linear, the solution of the governing equations can be expressed in terms of a Fourier series. • All Fourier components are damped uniformly by steady pipe friction, but each component is damped differently in the presence of a leak. Thus, overall leak-induced damping can be divided into two parts. • The magnitude of the damping indicates the size of a leak, whereas different damping ratios of the various Fourier components are used to find the location of a leak. • This method does not require rigorous determination and modeling of boundary conditions and transient behavior in the pipeline.
12. Lee, Vítkovský et al. (2002) ITM Domain: Frequency	Analysis approach: Hydraulic modeling	Network/Pipeline: Pipeline Case Study: RPR	In this study, the frequency response to an oscillatory input, especially under resonant conditions, is used to describe leaks.

Title: Leak detection in pipelines using an inverse resonance method	Analysis technique: Transfer Matrix method System Response Type: N/A Optimization Technique: SCE Algorithm Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: Using peak resonant to reduce signal-to-noise ratio at any position on the amplitude response diagram	Leak Unknowns: Location/intensity NO. measurement Points: Single Validation: Numerical	• The method—used in the frequency domain—borrows from the inverse transient analysis in that it fits the measured frequency response to that caused by leaks, thus determining both location and size of a leak. **Key findings:** • Transient pressure fluctuation can be used as probe to locate and quantify leaks in pipelines • The response to such a probe contains properties that can be used to describe leaks. • A leak has an effect on the magnitude of the response.
13. Vitkovsky, Simpson et al. (2002) ITM Domain: Time Title: Minimization algorithms and experimental inverse transient leak detection	Analysis approach: Hydraulic modeling Analysis technique: MOC System Response Type: N/A Optimization Technique: A systematic approach to the application of the LevenbergMarquardt algorithm Friction model: Steady State using Darcy Weisbach model, For Unsteady Friction a variant of the Brunone et al. (1991) unsteady friction model introduced Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: Location/intensity NO. measurement Points: Multiple Validation: Numerical, Lab	This paper, verifies the inverse transient method for leak detection from a laboratory pipeline using a least-squares minimization. **Key findings:** • In the current experiment, the Levenberg-Marquardt algorithm yields incorrect leak locations and magnitudes. • The complexity of the objective function surface causes the Levenberg-Marquardt algorithm to fail. • The use of the shuffled complex evolution algorithm-a more global minimization algorithm-improves results, however, convergence is slow. • A systematic approach to the application of the Levenberg Marquardt algorithm determines the correct leak location and magnitude more efficiently.
14. Mpesha, Hanif Chaudhry et al. (2002) SRM Domain: Time, Frequency Title: Leak detection in pipes by frequency response method using a step excitation	Analysis approach: Hydraulic modeling Analysis technique: MOC, FFT System Response Type: Frequency Response Optimization Technique: N/A Friction model: steady-State using the Approximation equation for the friction-loss term Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: single pipe system/parallel pipe system/Branched pipe system Leak Unknowns: Number/Location/intensity NO. measurement Points: Single Validation: Numerical	This paper presents a new procedure utilizing transient state pressures to detect leakage in piping systems. **Methodology:** • Transient flow, produced by opening or closing a valve, is analyzed in the time domain by MOC and the results are transformed into the frequency domain by the fast Fourier transform. • In this method a frequency response diagram is developed at the valve end. **Key findings:** • The frequency response diagram of a system with leaks have additional resonant pressure amplitude peaks (called the secondary pressure amplitude peaks) that are lower than the resonant pressure amplitude peaks for the

			system if there were no leaks (called primary amplitude peaks). • The location of a leak is determined from frequencies of the primary and secondary pressure amplitude peaks and the leak discharge is determined from the maximum and minimum discharge amplitudes. • This method is applicable for practical values of the friction factor over the range 0.01 to 0.025 and can be used to detect leaks in real-life pipe systems
15. Vitkovsky, Lee et al. (2003) SRM Domain: Time Title: Leak and blockage detection in pipelines via an impulse response method	Analysis approach: Hydraulic modeling Analysis technique: Transfer Matrix, MOC for verification System Response Type: Impulse Response Optimization Technique: N/A Friction model: Steady State using the Darcy Weisbach model, Unsteady using Vardy-Brown 1996 model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: Number/Location/intensity NO. measurement Points: Single Validation: Numerical	This paper presents a method for the detection and location of leaks and blockages, using the impulse response function. **Methodology:** • A pseudo-random binary signal is an input into the pipeline system using an oscillating valve. • A measured pressure response is compared to the leak and blockage-free calculation. • An extra spike in the impulse response identifies the presence of a leak or blockage. • The position of the extra spike in time determines the location of the leak or blockage and its size determines its magnitude.
16. Kapelan, Savic et al. (2003) ITM Domain: Time Title: A hybrid inverse transient model for leakage detection and roughness calibration in pipe networks	Analysis approach: Hydraulic modeling Analysis technique: MOC System Response Type: N/A Optimization Technique: A new hybrid genetic algorithm (HGA) Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: Normally distributed noise (zero mean and certain standard deviation) is added to the perfect observed data	Network/Pipeline: Network Case Study: Small pipe network with 11 pipes and 7 nodes Leak Unknowns: Number/Location/intensity NO. measurement Points: Multiple Validation: Numerical	This work introduces an inverse transient model based on a hybrid search technique. **Methodology:** • The inverse transient procedure is formulated as a constrained optimization problem of weighted least-squares type. • Two optimization techniques are tested: the genetic algorithm (GA) and the Levenberg-Marquardt (LM) method. • A new hybrid genetic algorithm (HGA) is developed to exploit the advantages of combining the two methods. **Results:** • The HGA-based inverse transient model proved to be more stable than the LM-based model and it is more accurate and much faster than the GA-based inverse transient model.
17. Vitkovsky, Liggett et al. (2003) ITM Domain: Time	Analysis approach: Hydraulic modeling Analysis technique: MOC System Response Type: N/A	Network/Pipeline: Network Case Study: Two small and large networks	This paper presents an approach for **determining the configuration of measurement sites** that produces optimal results for quality **of leak detection and quantification** and **calibration for friction coefficients** in **networks**.

Title: Optimal Measurement Site Locations for Inverse Transient Analysis in Pipe Networks	Optimization Technique: GA with a new crossover operator Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Leak Unknowns: Number/Location/intensity NO. measurement Points: Multiple (to be estimated based on this paper results) Validation: Numerical	**Methodology and key findings:** • Three performance indicators, two that are based on A- and D-optimality criteria and one that is based on the sensitivities of the heads with respect to the parameters, show which configurations are superior. • These are illustrated by two case studies, the first of which is a small pipe network in which all configurations are considered directly (fully enumerable) and the second is a larger pipe network in which statistics are drawn from a sampling of configurations. • For the large network, a genetic algorithm, with a new crossover operator, performs a search of possible measurement site configurations to determine the optimal measurement locations. • The **number of sites**, as well as **time length of data at each site**, are also considered.
18. Al-Shidhani, Beck et al. (2003) SRM Domain: Time-Frequency Title: Leak monitoring in pipeline networks using wavelet analysis	Analysis approach: Hydraulic modeling, Signal Processing Analysis technique: Time domain-based transmission line modeling technique, Wavelet System Response Type: Frequency Response Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: The authors believe that considering Signal-to-Noise Ratio, the wavelet analyses implemented in this paper is at least as effective (and simpler to use) than the correlation method to find numerous reflections in real pipe systems.	Network/Pipeline: Pipeline Case Study: RPVR Leak Unknowns: Location/intensity NO. measurement Points: Single Validation: Numerical	This work shows applications of wave reflections identified from the water hammer tests in leak monitoring. **Methodology:** • A wavelet-based procedure for leak severity monitoring is proposed. • The method detects singularities in reflected pressure waves. • Pressure waves are simulated using time domain-based transmission line modeling techniques. **Results:** • The study shows good potential for this method of leak severity identification.
19. Ferrante and Brunone (2003) SRM Domain: Frequency Title: Pipe system diagnosis and leak detection by unsteady-state tests. 1. Harmonic analysis	Analysis approach: Hydraulic modeling Analysis technique: impulse response via transfer function System Response Type: Impulse response Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: simple pipeline Leak Unknowns: Location/intensity NO. measurement Points: Single Validation: Numerical	In this paper and in the companion paper it is shown that unsteady-state tests can be used to pipe diagnosis and leak detection. **Methodology and key findings:** • The governing equations for transient flow in pressurized pipes are solved directly in the frequency domain by means of the impulse response method.

			• The analytical expression of the piezometric head spectrum at the downstream end section of a single pipe system during transients is then derived. • It is shown that the **piezometric head spectrum is the product of two terms**: the former related only to the maneuver characteristics, the latter depending only on the characteristics of the system. • **In the case of fast linear closure maneuvers**, the analytical expression of both terms is also given. • The derived **analytical solution of the pressure signal in the frequency domain**, allow us to interpret the data acquired in a single pipe system to have information on its state. • Experimental data are compared to the analytic solution.
20. Ferrante and Brunone (2003) SRM Domain: Time-Frequency Title: Pipe system diagnosis and leak detection by unsteady-state tests. 2. Wavelet analysis	Analysis approach: Signal processing Analysis technique: Wavelet Response Type: Frequency Response Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: Unavoidable noise is present in the experimental signal. In addition, Variations due to noise or small discontinuities are present in the pressure signal, giving rise to other local maxima in the wavelet transform.	Network/Pipeline: Pipeline Case Study: RPVR Leak Unknowns: Number/Location/intensity NO. measurement Points: Single Validation: Numerical/Lab	The paper work on the limitations caused by moving from time to frequency domain. During this transform, important information about the arrival time of pressure waves is lost. **Methodology and solutions:** • To overcome this limitation and to widen the applicability of transient-test based methodologies for leak detection, the wavelet transform of laboratory experimental data is used. • The wavelet transform is used to detect local singularities in the pressure time history due to the presence of a leak. • The discontinuity occurrence in time reveals the arrival time of the leak reflected pressure wave and is the basis for leak location.
21. Brunone and Ferrante (2004) SRM Domain: Time-Frequency Title: Pressure waves as a tool for leak detection in closed conduits	Analysis approach: Hydraulic modeling, Signal processing Analysis technique: impedance method, wavelet analysis, using Fourier transform Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV and wastewater outfall system (WOS) Leak Unknowns: Location/intensity NO. measurement Points: Single Validation: Lab	This article briefly outlines the **properties of pressure waves in closed single pipe systems**. • Past findings from the analysis of pressure signals within the time domain framework are reviewed and time series of pressure variations acquired in laboratory experiments at one measurement section is examined. • Emphasis is placed on the analysis of transient test results in the frequency domain and the use of the wavelet transform for interpreting pressure signals. • Both a single pipe system and a wastewater outfall system are examined and discussed.
22. Stephens, Lambert et al. (2004) ITM Domain: Time Title: Field Tests for Leakage, Air Pocket, and Discrete	Analysis approach: Hydraulic modeling Analysis technique: MOC Response Type: N/A	Network/Pipeline: Pipeline Case Study: Kookaburra Court (KCRT) and St Johns Terrace (STJT) pipelines after the streets	This paper presents preliminary results for the implementation of ITA in a field environment aiming to address some **complexities involved in the application** of **ITA to the field**.

Blockage Detection Using Inverse Transient Analysis in Water Distribution Pipes	Optimization Technique: Shuffled Complex Evolution (SCE) global search algorithm Friction model: Steady State model Viscoelasticity: N/A Noise: N/A	where they are located within the township of Willunga. Leak Unknowns: Number/Location/intensity NO. measurement Points: Single Validation: Numerical/Field	• Leaks, air pockets and discrete blockages with defined characteristics are introduced into two single branch pipelines in a "controlled manner" and their effects on an induced transient are measured. • Findings are made regarding the sensitivity of each type of pipeline phenomena to detection and, where possible, ITA is also used to locate and size leaks and air pockets.
23. Beck, Curren et al. (2005) TRM Domain: Time Title: Pipeline Network Features and Leak Detection by Cross-Correlation Analysis of Reflected Waves	Analysis approach: Signal Processing Analysis technique: Cross-Correlation Analysis Response Type: N/A Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: To reduce the noise, the solenoid actuation and data acquisition were repeated a number of times and the average pressure measurement obtained.	Network/Pipeline: Network Case Study: T-junction pipe network Leak Unknowns: Location/intensity NO. measurement Points: Multiple Validation: Numerical/Lab	This paper describes progress on a new technique to detect pipeline features and leaks using signal processing of a pressure wave measurement through using an enhanced signal processing technique to improve the detection of leaks. **Results:** • It is shown experimentally that features/ leaks can be detected around a sharp bend, and up to seven reflections from features/leaks can be detected, by which time the wave has traveled over 95 m. • The testing determined the position of a leak to within an accuracy of 5%, even when the location of the reflection from a leak is itself dispersed over a certain distance and, therefore, does not cause an exact reflection of the wave.
24. Lee, Vítkovský et al. (2005) SRM Domain: Frequency Title: Leak location using the pattern of the frequency response diagram in pipelines: a numerical study	Analysis approach: Hydraulic modeling Analysis technique: Transfer Matrix Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady State using the Darcy Weisbach model, Unsteady (Vardy-Brown 1996) and numerically derived scaling factors Viscoelasticity: N/A Noise: Taking the advantage of Frequency Response Function, for Frequency Response Diagram extraction, the correlation process actively reduces the effect of random background noise from the data	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: Number/Location/intensity NO. measurement Points: Single Validation: Numerical	The paper presents a method of leak detection in a single pipe where the behavior of the system frequency response diagram (FRD) is used as an indicator of the pipe integrity. **Key finding:** • The presence of a leak in a pipe imposes a pattern on the resonance peaks of the FRD that can be used as a clear indication of leakage. • Analytical expressions describing the pattern of the resonance peaks are derived. • Illustrations of how this pattern can be used to individually locate and size multiple leaks within the system are presented. • Practical issues with the technique, such as the procedure for frequency response extraction, the impact of measurement position, noise- and frequency-dependent friction are also discussed.
25. Kim (2005) SRM Domain: Time Title: Extensive development of leak detection algorithm by impulse response method	Analysis approach: Hydraulic modeling Analysis technique: Impedance Method Response Type: Impulse Response Optimization Technique: GA	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: Number/Location/intensity NO. measurement Points: Single Validation: Numerical	This work analyzes the oscillatory flows in pipeline systems due to excitation by valve operation by the **impulse response method**. **Methodology:**

	Friction model: Steady State using the Darcy Weisbach model, unsteady friction modeled by the improved version of the Brunone's formula for turbulent flows by Vitkovskey (Bergant et al. 2001) Viscoelasticity: N/A Noise: N/A		• The impact of leakage is incorporated into the transfer functions of the complex head and discharge. • **Frequency-dependent friction** is used to consider the impact of unsteady friction on the laminar condition. • Extensive development of the impulse response method was made by considering the sources of friction associated with the local and convective acceleration of velocity for turbulent flow. • The genetic algorithm was integrated into the impulse response method to calibrate the location and the quantity of leakage. **Key findings and results:** • The calibration function for leakage detection can be made using the pressure-head response at the valve, or the pressure-head and flow response at the section upstream from the valve. • The proposed leak detection algorithm shows the potentials for being applied to a simple pipeline system with a **single leak or multiple leaks**.
26. Covas, Ramos et al. (2005) SRM Domain: Frequency Title: Standing wave difference method for leak detection in pipeline systems	Analysis approach: Hydraulic modeling Analysis technique: Standing wave difference method Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: infinite pipeline-RPV-RLPV (loop) Leak Unknowns: Location NO. measurement Points: Single Validation: Numerical	This work focuses on leakage detection in pipe systems by means of the standing wave difference method SWDM used for cable fault location in electrical engineering. **Methodology:** • This method is based on the generation of a steady-oscillatory flow in a pipe system, by the sinusoidal maneuver of a valve, and the analysis of the frequency response of the system for a certain range of oscillatory frequencies. **Key findings:** • A leak creates a resonance effect in the pressure signal with a secondary superimposed standing wave. • The pressure measurement and the spectral analysis of the maximum pressure amplitude at the excitation site enable the identification of the leak frequencies and, consequently, the estimation of the leak approximate location.
27. Lee, Vítkovský et al. (2005) SRM-ITM Domain: Frequency Title: Frequency Domain Analysis for Detecting Pipeline Leaks	Analysis approach: Hydraulic modeling Analysis technique: Transfer Matrix Response Type: Frequency Response Optimization Technique: shuffled complex evolution (SCE) algorithm	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical	This paper proposes two methods of leak detection using the frequency response of the pipeline. • First method: The **inverse resonance method** involves matching the modeled frequency responses to those observed to determine the leak parameters.

	Friction model: Steady State using the Darcy Weisbach model, Unsteady-state modeling: scaling factors derived numerically for a leak-free case between steady friction and unsteady friction results by means of Vítkovský et al. (2003) model . Viscoelasticity: N/A Noise: Previous publications, such as Liou (1998), indicate that the extraction procedure for the FRD will result in the removal of noise of a different structure to that of the input signal. This technique is commonly known as match filtering.		• Second method: The **peak-sequencing method** determines the region in which the leak is located by comparing the relative sizes between peaks in the frequency response diagram. **Key findings:** • It was found that a unique pattern was induced on the peaks of the frequency response for each specific location of the leak within the pipeline. • The leak location can be determined by matching the observed pattern to patterns generated numerically within a lookup table. • The procedure for extracting the linear frequency response diagram, including the optimum measurement position, the effect of unsteady friction, and the way in which the technique can be extended into pipeline networks, are also discussed.
28. Lee, Lambert et al. (2006) SRM Domain: Frequency Title: Experimental verification of the frequency response method for pipeline leak detection	Analysis approach: Hydraulic modeling Analysis technique: MOC and Transfer Matrix method Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: The proposed FRD method of leak detection is robust with respect to background noise than conventional time domain methods of leak detection due to some its intrinsic properties that are disscussed in the article	Network/Pipeline: Pipeline Case Study: A symmetric and antisymmetric pipeline including two reservoir and a side discharge valve Leak Unknowns: Number/Location/Intensity NO. measurement Points: Single Validation: Numerical/Lab/Field	This paper presents an experimental validation of the frequency response method for pipeline leak detection. **Methodology:** • The presence of a leak within the pipe imposes a periodic pattern on the resonant peaks of the frequency response diagram. • This pattern can be used as an indicator of leaks **without requiring the "no-leak" benchmark** for comparison. • **Important issues**, such as the procedure for frequency response extraction and methods for dealing with frequency-dependent friction are considered. • **Transient signal generation:** a side-discharge solenoid valve generates transient signals. Non-linearity errors associated with large valve movements can be prevented by a change in the input parameter to the system. • **The optimum measuring and generating position** for two different system boundary configurations—a symmetric and an antisymmetric system—are discussed in the paper and the analytical expression for the leak-induced pattern in these two cases is derived.
29. Nixon, Ghidaoui et al. (2006) TDM Domain: Frequency-Laplace Title: Range of Validity of the Transient Damping Leakage Detection Method	Analysis approach: Hydraulic modeling Analysis technique: One-Dimensional Linearized Model and two-Dimensional Linearized Model	Network/Pipeline: Pipeline Case Study: RPR, RPV Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical/Lab	The proposed method in this paper exploits the fact that friction and leakage damp the modes of transient waves in a different manner. **Methodology:**

	solved by Fourier–Bessel Series and also Laplace Transform Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model, unsteady (wang et al 2002 in laplace domain) and Quasi-steady assumption Viscoelasticity: N/A Noise: N/A		• The method involves **six major assumptions**: 1.the periodic motion in time of each mode is linearly independent of all other modes; 2. the amplitude of the induced transient is small; 3. the magnitude of the leak is small in comparison with the flow rate; 4 the wall friction can be represented by the Darcy–Weisbach equation; 5. the transient is initiated by an instantaneous small amplitude disturbance; and 6. the pipe system is a simple reservoir–pipe–valve type system or reservoir–pipe–reservoir type system. • These six assumptions are relaxed and the validity of the transient damping method is assessed. **Results:** • The analysis shows that the first four assumptions do not pose any serious restriction to the applicability of the damping rate method provided that the mathematical model, used to generate the transient head trace in the leak-free pipe, accurately represents the frictional damping in the system. • Assumptions 5 and 6 restrict the applicability of the method to systems that do not involve internal boundary conditions, such as junctions and pumps, and to transients triggered by impulses whose duration is smaller than the wave travel time. • The general framework used to derive the damping rate method has led to an efficient and direct algorithm for identifying leaks and future research should seek ways to adapt this framework to more complex pipe systems. **Future work:** • Extension of this method to complex pipe systems requires that the linearized water hammer equations are solved under more general initial and boundary conditions.
30. Beck, Foong et al. (2006) SRM Domain: Time-Frequency Title: Wavelet and Cepstrum Analyses of Leaks in Pipe Networks	Analysis approach: Signal Processing Analysis technique: wavelet and Cepstrum analysis Response Type: N/A Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: Using Wavelet analysis to filter the data	Network/Pipeline: Network Case Study: A simple T-shaped network Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical/Lab/Field	In this study, Cepstrum techniques is used to find the common pipe leaks in the network. • Latterly, this has been used in conjunction with wavelet analysis to filter the data. • Finally, continuous wavelets are being used to explain many of the results that have previously been produced. **Results:** • The results show that wavelet analysis, without extensive modification, is unsuitable for finding features in pipeline networks.

			• Cepstrum analysis method is capable of extracting useful information from real experimental networks with a high degree of accuracy. **Future work:** • Further work is required to improve the method and test it on more complicated and longer circuits using a variety of fluids.
31. Taghvaei, Beck et al. (2006) SRM Domain: Time-Frequency Title: Leak detection in pipelines using Cepstrum analysis	Analysis approach: Signal Processing Analysis technique: wavelet and Cepstrum analysis Response Type: N/A Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: Using Wavelet analysis to filter the data	Network/Pipeline: Network Case Study: A simple T-shaped network Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical/Lab	This paper shows that Cepstrum analysis is a viable approach to leak detection and location in pipeline networks. **Methodology:** • Pressure signals were first filtered using discrete wavelets to remove the dc offset, and the low and high frequencies. • Then they analyzed using a Cepstrum method which identified the time delay between the initial wave and its reflections. **Key findings:** • There were some features in the processed results that can be ascribed to features in the pipeline network such as junctions and pipe ends. • When holes were drilled in the pipe, new peaks occurred which identified the presence of a leak in the pipeline network. • When tested with holes of different sizes, the amplitude of the processed peak was seen to increase as the cube root of the leak diameter. • Using this method, it is possible to identify leaks that are small in comparison with the flow through the pipe.
32. Lee, Lambert et al. (2007) TRM-SRM Domain: Time Title: Leak location in single pipelines using transient reflections	Analysis approach: Signal Processing Analysis technique: Cumulative sum change detection algorithm (CUSUM) Response Type: Impulse Response Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: Include suggestions to reduce background noise	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: Location NO. measurement Points: Multiple Validation: Numerical/Lab	This paper discusses possible solutions to a number of **practical issues** associated with leak detection methods of the time domain reflectometry type, including **the impact of the system configuration** and **methods for detecting leak reflected signals within a transient trace**. • A set of equations has been derived to locate leaks in a pipeline for all locations of the transient source and measurement stations, and is essential for an automated monitoring system that uses more than one simultaneous measurement of the transient signal. • A change detection algorithm is used in this paper to provide an automated approach for detecting leak reflections, which can reduce the ambiguity associated with simple visual inspection of the transient trace.

33. Vitkovsky John, Lambert Martin et al. (2007) ITM Domain: Time Title: Experimental Observation and Analysis of Inverse Transients for Pipeline Leak Detection	Analysis approach: Hydraulic modeling Analysis technique: MOC Response Type: N/A Optimization Technique: Model parsimony approach, Model error compensation Friction model: Steady State using Darcy Weisbach model, Unsteady (Vardy-Brown 1996) Viscoelasticity: N/A Noise: Savitsky-Golay smoothing filter	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: Number/Location/Intensity NO. measurement Points: Multiple Validation: Numerical/Lab	This paper presents further development of ITA and experimental observations for leak detection in a laboratory pipeline. **Key findings:** • The effects of data and model error on ITA results have been explored including strategies to minimize their effects using model error compensation techniques and ITA implementation approaches. • A rapid input transient that may be of small magnitude contains maximum system response information, thus improving the uniqueness and quality of the ITA solution. • The effect of using head measurements as boundary conditions for ITA has been shown to significantly reduce sensitivity, making both detection and quantification problematic. • Model parsimony is used to limit the number of unknown leak candidates in ITA, thus reducing the minimization problem complexity.
34. Ferrante, Brunone et al. (2007) TRM Domain: Time-Frequency Title: Wavelets for the Analysis of Transient Pressure Signals for Leak Detection	Analysis approach: Hydraulic modeling, Signal Processing Analysis technique: MOC, Wavelet Analysis Response Type: N/A Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: Using Wavelet analysis to filter the data Based on the properties of the random noise wavelet transform, chains attributed to "false alarms" are filtered.	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical/Lab	This study considers both continuous and discrete wavelet transforms and compares different mother wavelets for the analysis of transient pressure signals for leak detection. **Results:** • The reliability of the technique with respect to the noise effects is tested on numerically simulated and experimental pressure signals. • It is shown that the wavelet analysis of numerical signals, with and without superimposed white noise, facilitates testing the ability of this tool to recognize small step variation—corresponding to small leaks—using low-cost transducers.
35. Lee, Vítkovský et al. (2007) SRM Domain: Time Title: Leak location in pipelines using the impulse response function	Analysis approach: Hydraulic modeling Analysis technique: impulse response function Response Type: impulse response Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: Location NO. measurement Points: Single Validation: Numerical/Lab	This paper uses the impulse response function (IRF) as a means of leak detection. **Key findings:** • The IRF provides a unique a relationship based on the physical characteristics of the system between an injected transient event and a measured pressure response from a pipeline and is useful in determining its integrity as well.

	Noise: Using match filter to increase noise tolerance		• Transient responses of completely different shapes can be directly compared using the IRF. • The IRF refines all system reflections to sharp pulses, thus promoting greater accuracy in leak location, and allowing leak reflections to be detected without a leak-free benchmark, even when complex signals such as pseudo-random binary signals are injected into the system.
36. Nixon and Ghidaoui (2007) N/A Domain: Time Title: Numerical Sensitivity Study of Unsteady Friction in Simple Systems with External Flows	Analysis approach: Hydraulic modeling Analysis technique: The quasi-2D, unsteady friction, transient flow model Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model, for Unsteady friction utilizes the scheme that is based on an original model developed by Vardy the efficient scheme developed by Zhao and Ghidaoui 2003 and Hwang 1991, but with greatly improved efficiency Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: N/A NO. measurement Points: Single Validation: Numerical	This paper investigates the importance of unsteady friction effects when performing water hammer analyses for pipe systems with external fluxes due to demands, leaks, and other system elements. **Methodology:** • The transient energy equation for a system containing an orifice-type external flow is derived from the two-dimensional, axial momentum equation. • A quasi-two-dimensional flow model is used to evaluate the relative energy contribution of total friction, unsteady friction, and the external flow **Results:** • It is found that for initial lateral flows larger than around 30% of the mean flow, unsteady friction effects can probably be neglected, whereas for external flows smaller than this, unsteady friction should generally be considered. • Overall, the relative role of unsteady friction is found to diminish as the external flux increases, implying that unsteady friction is not critical for systems with large external flows. • Results imply that unsteady friction may have a significant impact on the validity of transient leak detection techniques that have been derived assuming quasi-steady friction. • To demonstrate this point, an existing transient leak detection method, originally derived under quasi-steady conditions, is tested with unsteady friction included.
37. Taghvaei, Beck et al. (2007) SRM Domain: Frequency Title: Leak detection in pipeline networks using low-profile piezoceramic transducers	Analysis approach: Signal Processing Analysis technique: Cepstrum analysis Response Type: Frequency Response Optimization Technique: N/A Friction model: N/A	Network/Pipeline: Network Case Study: A T-shape network Leak Unknowns: Number/Location/Intensity NO. measurement Points: Single Validation: Numerical/Lab	This study involves an experiment with a simple fluid filled pipeline network. **Methodology:** • A solenoid valve is used to introduce a pressure wave into the network by periodically opening and closing the

	Viscoelasticity: N/A Noise: Using Wavelet for denoising		valve. A low-profile piezoceramic transducer then senses the pressure wave. A conventional pressure transducer is also used for comparative studies. • The experiment is performed for different pipe lengths and severities of leakage. **Results:** • This work shows that while the piezoceramic transducer is poor at recording accurate pressure histories, it is perfectly acceptable for this type of condition monitoring, being able to identify the position and severity of leaks and other features in the pipeline network.
38. Al-Khomairi (2008) ITM Domain: Time Title: Leak detection in long pipelines using the least squares method	Analysis approach: Hydraulic modeling Analysis technique: MOC Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity NO. measurement Points: Multiple Validation: Numerical/Lab	This investigation proposes a new computer-based real-time technique to detect and locate leaks in long pipelines conveying liquids. **Methodology:** • The method utilizes a deterministic trial and error scheme to minimize squares of deviations between measured and computed quantities. • The deviations would be minimal if an agreement is achieved between a leak in the actual system and a numerically simulated trial leak imposed by the RTM with as close a discharge, location and time of occurrence as possible to the actual leak. • The advantage of the proposed method is that **the model works in parallel with the actual system** to make use of the first leak impact on boundary quantities. • An experimental work using a 300 m pipe was carried out to verify the applicability of the approach. **Results:** • The technique produced a fairly accurate estimation of the leak location and size even during severe transient flow conditions.
39. Jung and Karney (2008) ITM Domain: Time Title: Systematic exploration of pipeline network calibration using transients	Analysis approach: Hydraulic modeling Analysis technique: MOC Response Type: N/A Optimization Technique: GA and PSO Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A	Network/Pipeline: Network Case Study: Small pipe network with 11 pipes and 7 nodes Leak Unknowns: Number/Location NO. measurement Points: Multiple Validation: Numerical/Lab	This paper investigates quantitatively how inaccuracies values such as diameter, wave speed and the water demand at the time of the tests invariably deteriorate the performance of calibration approaches. Thus, the paper argues that a systematic calibration should explicitly include these additional uncertainties during the ITA process. **Methodology:** Two evolutionary approaches of Genetic Algorithms and Particle Swarm Optimization, are applied

	Noise: N/A		and are both compared and contrasted during the ITA iterations. **Results:** The evolutionary algorithms help the search escape from poor local optima in multifaceted and complex problems and thus assist in locating global (or near-global) optima. **Challenges:** Current approaches are shown to converge poorly as the full scale of the typical field problems is progressively reflected in the search space.
40. Lee Pedro, Vítkovský John et al. (2008) SRM Domain: Frequency Title: Valve Design for Extracting Response Functions from Hydraulic Systems Using Pseudorandom Binary Signal	Analysis approach: Hydraulic modeling Analysis technique: Transfer Matrix Method Response Type: Frequency Response Optimization Technique: N/A Friction model: The original transfer matrix model in Chaudhry 1987 was improved to incorporate both steady and unsteady friction effects in this paper. Viscoelasticity: N/A Noise: To minimize the presence of electronic noise caused by earth loops when main power is used, 24 V DC batteries power the pressure transducers.	Network/Pipeline: Pipeline Case Study: RPVR Leak Unknowns: N/A NO. measurement Points: Single Validation: Numerical/Lab	This paper presents the design for a side discharge valve for generating a pseudorandom binary sequence of pressure changes that are of a small magnitude in relation to the steady state head of the pipeline. **Methodology:** • The pseudorandom pressure sequence is used to provide an estimate of the system response function. • The continuous form of the signal allows the amplitude of each individual pulse within the signal to be small while maintaining the same signal bandwidth. **Results:** • The valve has been tested experimentally and was found to provide a good match with the theoretical response of the pipeline. • The method provides a practical alternative to frequency sweeping using sinusoidal signals or sharp valve closures for the extraction of the response functions.
41. (Sattar and Chaudhry 2008) SRM Domain: Frequency Title: Leak detection in pipelines by frequency response method	Analysis approach: Hydraulic modeling Analysis technique: Transfer Matrix Method Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model, Unsteady model by Vitkovskey et al., 2003 Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical	The paper presents a technique for the detection of leaks in a pipeline is presented utilizing its frequency response. **Methodology:** • In the system frequency response, a leak increases the amplitude of pressure oscillations at the even harmonics. Such an increase in amplitude has an oscillatory pattern; the frequency and amplitude of this pattern may be utilized to predict the location and discharge of a leak. • In this technique, the pressure transient history at one location is sufficient and the history of the transient in the pipe prior to leak is not needed; this makes it advantageous over a number of other existing techniques, and to being simpler to use as well. **Results:**

			• It is shown that the technique successfully detects the location of a leak in a number of simple systems with leak discharge as low as 0.2% of the steady discharge. • The technique is verified by comparing the results with those computed by using MOC.
42. Ferrante, Brunone et al. (2009) TRM Domain: Time Title: Leak detect ion in branched pipe systems coupling wavelet analysis and a Lagrangian model	Analysis approach: Signal Processing Analysis technique: Wavelet analysis, utilizing the Lagrangian model Response Type: N/A Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: Using Wavelet for denoising	Network/Pipeline: Network Case Study: A Y-shape network Leak Unknowns: Location NO. measurement Points: Multiple Validation: Numerical/Lab	The present work extends ITM approach to more complex systems than a simple pipeline, that is, those with at least one junction. **Methodology:** • To accomplish this, the pressure signal is analyzed using wavelet analysis. • The analysis of the pressure signals is generalized by means of a Lagrangian model, which directly simulates the pressure waves' generations and movements in the system. **Key findings:** • Coupling wavelet analysis with the Lagrangian model allows to associate singularities pointed out in pressure signals to singularities in the system. • In order to better ascertain the applicability of the method, tests were carried out on both a laboratory installation and a real system.
43. Shamloo and Haghighi (2009) ITM Domain: Time Title: Leak detection in pipelines by inverse backward transient analysis	Analysis approach: Hydraulic modeling Analysis technique: Backward MOC Response Type: N/A Optimization Technique: Sequential Quadratic Programming Method Friction model: Steady State using Darcy Weisbach model, using quasi-steady friction loss modeling to consider the energy losses due to viscosity Viscoelasticity: N/A Noise: To eliminate undesirable noisy and uncertainties due to the valve modeling, a method independent of valve type, closure duration and valve operation was considered.	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Number/Location/Intensity NO. measurement Points: Single Validation: Numerical	This work introduces a method of leak detection in pipelines based on the inverse transient analysis. **Methodology:** • The duration of valve closure is considered long enough to minimize effects of the friction factor and of water hammer. • The numerical modeling of transient analysis in time domain uses the backward MOC. • An inverse problem is applied for leak detection by defining the least-squares criterion objective function. • The leak areas at characteristic nodes are considered as decision variables. • Leak parameters are determined using the Sequential Quadratic Programming (SQP) method. • To eliminate undesirable noisy and uncertainties due to the valve modeling, a method independent of valve type, closure duration and valve operation is considered. **Results:**

			• A step-by-step application indicates the capability and flexibility of the method to deal with single or multiple leaks, large scale problems, and various sampling frequencies. • It was shown that the presented method is capable to calibrate a pipe for the friction factor in addition to leak parameters simultaneously. • Due to use of the MOC to transient analysis, the proposed method can be developed for more complicated systems including various equipment, boundary conditions and multi branches such as water supply networks.
44. Ferrante, Brunone et al. (2009) TRM Domain: Time Title: Leak-edge detection	Analysis approach: Signal Processing, Hydraulic modeling Analysis technique: Wavelet Analysis, MOC Response Type: N/A Optimization Technique: N/A Friction model: The paper stated that since the times in Eq. (7) (leak position estimation equation) occur in the very first phase of the transient, the effect of friction—either steady or unsteady—on the leak location is negligible. Viscoelasticity: N/A Noise: Taking the advantage of Wavelet analysis for filtering the noise effect at higher scales while retaining the precision in finding discontinuities at the lowest scales	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical/Lab	In this study an edge detection technique is applied to improve leak detection for pressurized pipe flow, based on wavelet and transient test analysis. **Methodology:** • The information contained in a signal is interpreted, especially when it is sharp and isolated: The sudden brightness changes an image and the pressure variations due to a pressure wave trespassing the measurement section. • Herein, the analogy between edge and leak detections is further developed. • The multi-scale product of the wavelet transform is used to detect sharp pressure variations. • Both numerical and experimental pressure signals were used to evaluate the effects of the noise and the test conditions. **Key findings:** • Both the simplicity and the reliability of this technique as compared to others make it suitable to develop a rational and automatic procedure. • It is demonstrated that the wavelet analysis of numerical signals facilitates to recognize small step variations, i.e. small leaks, using low-cost transducers. The experimental tests corroborate the numerical results.
45. Zecchin Aaron, Simpson Angus et al. (2009) SRM Domain: Frequency Title: Transient Modeling of Arbitrary Pipe Networks by a	Analysis approach: Hydraulic modeling Analysis technique: Laplace-domain network admittance matrix Response Type: Frequency Response Optimization Technique: N/A	Network/Pipeline: Network Case Study: Two networks: a) A 6 nodes, 7 pipes network; b) A 35 nodes, 51 pipes from Vitkovskey 2001 Leak Unknowns: N/A NO. measurement Points: N/A	This study introduces an alternative method based on Laplace transform techniques to the modeling of the transient behavior of pipeline systems in the time-domain. • The method **addresses a limitation with almost all frequency-domain methods** for pipeline networks is that they are only able to deal with systems of a certain

Laplace-Domain Admittance Matrix	Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Validation: Numerical	class of configuration, namely, networks not containing second-order loops. • This paper addresses this limitation by utilizing graph theoretic concepts to derive a **Laplace-domain network admittance matrix** relating the nodal variables of pressure and demand for a network comprised of pipes, junctions, and reservoirs. • The adopted framework allows complete flexibility with regard to the topological structure of a network and, as such, it provides an extremely useful general basis for modeling the frequency-domain behavior of pipe networks.
46. Bartecki (2009) SRM Domain: Time-Frequency Title: Frequency-and time-domain analysis of a simple pipeline system	Analysis approach: Hydraulic modeling Analysis technique: Transfer matrix using Laplace transform Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: N/A NO. measurement Points: N/A Validation: Numerical	In this paper, a mathematical model of a simple pipeline system is considered. • Pipeline **frequency and time responses** are determined and presented in the form of two and three-dimensional plots, taking into account spatially distributed nature of the process. • Owing to the transcendental form of the obtained pipeline transfer function, these responses reveal certain peculiarities, closely associated with wave phenomena taking place inside the pipe.
47. Torres, Besançon et al. (2009) SRM Domain: Time Title: Multi-leak estimator for pipelines based on an orthogonal collocation model	Analysis approach: Hydraulic modeling Analysis technique: Orthogonal collocation method (OCM) to solve water hammer equations Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model, Unsteady friction using Vitkovskey et al 2006 model Viscoelasticity: N/A Noise: Noise has been added to the outputs to represent the measurement noise of instruments.	Network/Pipeline: Pipeline Case Study: simple pipeline Leak Unknowns: Number/Location/Intensity NO. measurement Points: Multiple Validation: Numerical	In this study, the **orthogonal collocation method** (OCM) is used to obtain an approximate solution of the water hammer equations which represent one-phase water flow transients in pipeline systems. • The OCM provides solutions over the entire spatial domain, therefore it can be used to obtain an accurate model with possible leaks spatially distributed. • An estimator can be designed based on the spatially-discretized model in order to detect multiple leaks by identifying their positions and leak coefficients.
48. Covas and Ramos (2010) ITM Domain: Time Title: Case Studies of Leak Detection and Location in Water Pipe Systems by Inverse Transient Analysis	Analysis approach: Hydraulic modeling Analysis technique: Forward Transient Solver (FTS) Response Type: N/A Optimization Technique: Levenberg-Marquardt method, GA	Network/Pipeline: Network Case Study: Complex pipe system Leak Unknowns: Number/Location/Intensity NO. measurement Points: Single Validation: Lab/Field	The paper aims at the assessment of the effectiveness of inverse transient analysis for leak detection in water pipe systems using physical data. **Methodology:** • Data were collected from two pipe systems made of polyethylene.

	Friction model: The description of unsteady friction losses consists of the incorporation of an additional term in the momentum equation. Three unsteady friction formulations were included in the model: formulations by Trikha 1975, Vardy et al. 1993, and Vitkovskey et al. 2000a. Viscoelasticity: The viscoelastic effect is described by an additional term in the continuity equation Covas et al. 2005c. The viscoelastic component is described by a creep function that can be estimated by a creep or a dynamic test of a pipe sample, or by inverse transient calculations. Noise: The success of ITA depends on the noise observed and on the multiple reflections e.g., different pipe materials, diameters and air bubbles observed in the pressure signal and on the accuracy of the transient solver.		• A hydraulic transient solver especially developed for viscoelastic pipes typically made of polyethylene and an optimization algorithm for the simultaneous creep calibration and leak location have been developed for the application of this technique. • The evaluation of the presence, location, and size of leaks was carried out using collected data. **Key findings:** • ITA allowed for the identification of the approximate location of leaks as long as the physical characteristics of the pipeline are well known, the transient is generated by a fast change of flow conditions, the leak has a "reasonable size," and the transient solver is accurate enough to describe the transient event.
49. Shamloo and Haghighi (2010) ITM Domain: Time Title: Optimum leak detection and calibration of pipe networks by inverse transient analysis	Analysis approach: Hydraulic modeling Analysis technique: MOC Response Type: N/A Optimization Technique: Sequential Quadratic Programming (SQP), GA Friction model: Steady State using Darcy Weisbach model Viscoelasticity: limited by considering upper and lower permissible bounds for pressure variations throughout the network. Noise: N/A	Network/Pipeline: Network Case Study: A small pipe network with 11 pipes and 7 nodes Leak Unknowns: Number/Location/Intensity NO. measurement Points: The Optimum site design is performed Validation: Numerical	This work aims to introduce new features to enhance the efficiency of leak detection and calibration of pipe networks by inverse transient analysis **Methodology:** • An optimization programming is developed to generate transients in the network optimally, and then pressure fluctuations are sampled at a few optimum measurement sites. • Criteria are introduced for optimum site design. • A non-linear programming with the least squares criterion is defined and then the unknown parameters of leaks and friction factors are inversely sought using sequential quadratic programming. **Results:** • The obtained results show how the proposed new features make the process of leak detection more effective.

50. Duan, Ghidaoui et al. (2010) N/A Domain: Time, Frequency Title: Unsteady friction and visco-elasticity in pipe fluid transients	Analysis approach: Hydraulic modeling, Signal Processing Analysis technique: MOC, FT Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model, Unsteady friction models by Zielke 1968, Trikha 1975, Vardy and Brown 1995 Viscoelasticity: Kelvin–Voigt visco-elastic model Noise: N/A	Network/Pipeline: Pipeline Case Study: Two RPV systems used by Covas et al. (2005) Leak Unknowns: N/A NO. measurement Points: Single Validation: Numerical/Lab	This study discussed the effects of Unsteady friction and visco-elasticity in pipe fluid transients **Key aspects:** • The current water hammer models coupled with friction models cannot adequately represent the pressure wave attenuation observed in real-world pipe systems, because additional effects not accounted for affect the pressure wave damping. • One such effect is pipe visco-elasticity from the material behavior of pipe-wall. **Key findings:** • The numerical results indicate that the pressure head attenuation attributable to unsteady friction is comparable to the visco-elastic effect during the initial transient stage, while the visco-elastic effect becomes dominant both in terms of damping and phase shift at later stages. • An analytical analysis shows that the visco-elastic effect is more critical if the visco-elastic retardation time is less than the wave travel time along the entire pipeline length. • It is demonstrated that the visco-elastic term in water hammer models is wrongly referred to in the literature as energy dissipation instead of energy transfer between fluid and pipe-wall by the work done by the pressure force.
51. Duan, Lee et al. (2010) All Four methods Domain: Time, Frequency Title: Essential system response information for transient-based leak detection methods	Analysis approach: Hydraulic modeling Analysis technique: MOC, SRFM Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: the additional reflections (considered as "noise" in the data) was added to the original signal to illustrates their consequence effect	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Number/Location/Intensity NO. measurement Points: Single Validation: Numerical/Lab	This work investigates the relative importance of the **damping and reflective** effects from the leak to the leak detection methods with the importance of both effects tested **using four representative methods**, which vary significantly in their modes of operation. **Key findings:** • It was found that all transient-based methods are unable to detect and locate the leak in the absence of the **leak-reflected signal**, whereas the leak is detected and located even in the absence of **leak-induced damping**. • The results indicate that the information previously thought to be contained in the damping of slow transients was found to be **low frequency reflections** from the leak.
52. Lee Pedro and Vitkovsky John (2010) SRM	Analysis approach: Hydraulic modeling Analysis technique: MOC	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: N/A	This paper investigates and quantifies the **linearization error in the frequency-domain method**, via comparison to a highly discretized time-domain model that uses MOC, and

Domain: Frequency Title: Quantifying Linearization Error When Modeling Fluid Pipeline Transients Using the Frequency Response Method	Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	NO. measurement Points: Single Validation: Numerical	describes situations where the frequency response method can be used with accurate results. **Key findings:** • The error consists of errors from two sources: the linear approximations of the steady friction and the steady orifice equations. • The unsteady mass and momentum equations for pipe flow can be solved in the frequency domain and provides additional insight into the behavior of fluid transients. • This approach has significant **computational advantages compared to MOC** because it is not based on a rigid time-space grid. • **Despite its advantages**, the frequency domain approach must be used with care as **it uses linearized forms of the steady friction and orifice equations**—which can deviate significantly from the true nonlinear solution. • The conditions in which the frequency response method can be accurately used are currently unknown. • The frequency response method is shown to produce identical results to MOC when these two sources of error are minimized. • The **error in the frequency-domain model** is quantified as **functions of the perturbation magnitude, frequency, and system parameters.** • The results indicate that errors are significant when the perturbation size is more than 25% of the steady-state condition and this error is frequency dependent with the largest errors occurring at the harmonic peaks of the system.
53. Ghazali, Staszewski et al. (2010) SRM Domain: Time-Frequency Title: Instantaneous phase and frequency for the detection of leaks and features in a pipeline system	Analysis approach: Signal Processing Analysis technique: Hilbert transform (HT) and the Hilbert–Huang transform (HHT) Response Type: Frequency Response Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: By removing some of the intrinsic mode function (IMF) corresponded to highest frequencies and summing the rest of IMF, a pressure signal without noise was generated and when compared with	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location NO. measurement Points: Single Validation: Numerical/Lab	This work focuses on the progress of a new analysis technique to detect pipeline leaks and features based on analysis of a pressure transient. **Methodology:** • The measured time domain signals of transients are obtained using a single pressure transducer. • The instantaneous phase and frequency of the signals are analyzed using the Hilbert transform (HT) and the Hilbert–Huang transform (HHT). • Both simulated and experimental pressure signals are used to evaluate the performance of these transforms. **Key findings:**

	original signal, it looks like similar but cleaner.		• The analysis of simulated signals allowed features in the pipeline network such as leaks and pipe ends to be ascribed to features in the signals. • Analysis of the experimental tests corroborates the simulated test results when the HT and the HHT analysis are used.
54. Duan, Lee et al. (2011) SRM Domain: Frequency Title: Leak detection in complex series pipelines by using the system frequency response method	Analysis approach: Hydraulic modeling Analysis technique: Transfer Matrix Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: Two pipe systems consisting of 3-series pipes and 10-series pipes in RPR configuration Leak Unknowns: Number/Location/Intensity NO. measurement Points: Single Validation: Numerical	This research investigates the applicability of the transient-based frequency-response function (FRF) method for detecting leaks in complex series pipelines. **Methodology:** • The behavior of transient waves in complex series pipelines with internal series junctions indicates that junction reflections modify the system resonant frequencies but have a small effect on the leak-induced information contained within the system frequency responses. • The analogous method previously developed for single pipelines is extended to complex series pipe systems by using the analytical transfer matrix method herein and the extended method is validated by two simple numerical experimental cases. **Key findings:** • The applied results indicate that the extended FRF method can be applied to detect single and multiple leaks in complex series pipelines as long as the location and size of the resonant peaks of system frequency responses are accurately determined.
55. Soares, Covas et al. (2011) ITM Domain: Time Title: Leak detection by inverse transient analysis in an experimental PVC pipe system	Analysis approach: Hydraulic modeling Analysis technique: MOC Response Type: N/A Optimization Technique: Levenberg-Marquardt method, GA Friction model: Steady State using Darcy Weisbach model Viscoelasticity: Kelvin–Voigt mechanical model of a viscoelastic solid is applied. This model is a combination of elements (springs and dashpots) that numerically describe the rheological response of viscoelastic solids (Aklonis & MacKnight 1983)	Network/Pipeline: Network Case Study: Complex PVC pipe system Leak Unknowns: Location NO. measurement Points: Single Validation: Numerical/Lab	In this research work, the association of hydraulic transient analysis with an optimization model, through inverse transient analysis (ITA), has been used for leak detection and its location in an experimental facility containing PVC pipes. **Methodology:** • Observed transient pressure data have been used for testing ITA. • A key factor for the success of the leak detection technique used is the accurate calibration of the transient solver, namely adequate boundary conditions and the description of energy dissipation effects since PVC pipes are characterized by a viscoelastic mechanical response. **Results:**

	Noise: In this research, leaks can be located with an accuracy corresponding to 4% of the total length of the discharge line, despite measurement errors that stems from the noise in the pressure signal.		• Results have shown that leaks were located with an accuracy between 4–15% of the total length of the pipeline, depending on the discretization of the system model.
56. Haghighi and Shamloo (2011) ITM Domain: Time Title: Transient generation in pipe networks for leak detection	Analysis approach: Hydraulic modeling Analysis technique: MOC Response Type: N/A Optimization Technique: SQP, GA Friction model: Steady State using Darcy Weisbach model Viscoelasticity: limited by considering upper and lower permissible bounds for pressure variations throughout the network. Noise: N/A	Network/Pipeline: Network Case Study: A water distribution network of 34 pipes (with unknown friction factors) and 22 junctions (with unknown leaks) Leak Unknowns: Number/Location/Intensity NO. measurement Points: Multiple Validation: Numerical	The focus of this work is that **excitation and its location in a pipe network** significantly influence the success of inverse-transient-analysis-based methods. **Methodology:** • The paper defines a mathematical programming model to produce rapid transient variations in the system subject to allowable high and low pressures. • The transient generation point in the network, the time interval and the magnitude of the excitation are decision variables. • Using MOC, a numerical model is developed to analyze transients and evaluate the objective function. • Based on genetic algorithms, an optimization solver is developed to solve the problem. • To demonstrate the efficiency of the method, a water distribution network is defined and analyzed. **Results:** • The results show that the proposed method makes a remarkable contribution to the success of applied inverse transient analysis.
57. Vítkovský John, Lee Pedro et al. (2011) SRM Domain: Frequency Title: Head- and Flow-Based Formulations for Frequency Domain Analysis of Fluid Transients in Arbitrary Pipe Networks	Analysis approach: Hydraulic modeling Analysis technique: MOC and three new formulations for arbitrary network analysis in frequency domain Response Type: Frequency Response Optimization Technique: SQP, GA Friction model: Steady State using Darcy Weisbach model, unsteady friction model by Vitkovskey et al 2006 Viscoelasticity: method presented in Vitkovskey et al 2006 Noise: N/A	Network/Pipeline: Network Case Study: Example of small pipe network (data from Liggett and Chen 1994) Leak Unknowns: N/A NO. measurement Points: N/A Validation: Numerical	This paper presents a number of formulations for the frequency-domain solution in pipe networks of arbitrary topology and size. The formulations focus on the **topology of arbitrary network**s and do not consider any complex network devices or boundary conditions other than head and flow boundaries. **Methodology:** • The frequency-domain equations are presented for node elements and pipe elements, which correspond to the continuity of flow at a node and the unsteady flow in a pipe, respectively. • A pipe-node-pipe and reservoir-pipe pair set of equations are derived. A matrix-based approach is used to display the solution to entire networks in a systematic and powerful way.

			• Three different formulations are derived based on the unknown variables of interest that are to be solved: head-formulation, flow-formulation, and head-flow-formulation. These hold significant analogies to different steady-state network solutions. **Results:** • The frequency-domain models are tested against MOC with good result. The computational efficiency of each formulation is discussed with the most efficient formulation being the head formulation.
58. Hu, Zhang et al. (2011) SRM Domain: Time-Frequency Title: Detection of small leakage from long transportation pipeline with complex noise	Analysis approach: Signal Processing Analysis technique: Wavelet Analysis Response Type: Frequency Response Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: Wavelet denoising	Network/Pipeline: Pipeline Case Study: in Daqin Oil Production Plant, and the pipeline named as "North I-II-Oil Transportation Terminal Stations" Leak Unknowns: Number/Location/Intensity NO. measurement Points: Multiple Validation: Field	Weak singularities in small leak signals are usually difficult to detect precisely under complicated noise background, which may cause false alarm or miss alarm. The advantage of applying the harmonic wavelet method is explored in this paper. **Methodology:** • Pipeline small leak sensitive characteristics are recognized and the negative pressure wave inflexions are extracted by harmonic wavelet analysis, expressed in terms of harmonic wavelet time-frequency mesh map, time-frequency contour map, and time-frequency profile plot. • A comparative study of both Daubechies wavelet and harmonic wavelet analysis when applied to pipeline small leak detection under complicated background noises, is also presented. **Key findings:** • Results of simulating test and field experiment show that it is possible to distinguish weak non-stationarities from complicated noises by harmonic wavelet analysis in pipeline small leak detection system. • The comparison clearly illustrates that harmonic wavelet-based pipeline small leakage detection method is significantly more accurate than other wavelets analysis such as Daubechies wavelet.
59. Meniconi, Brunone et al. (2011) SRM Domain: Time Title: Small Amplitude Sharp Pressure Waves to Diagnose Pipe Systems	Analysis approach: Hydraulic modeling, Signal Processing Analysis technique: MOC, Wavelet Analysis Response Type: N/A Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical/Lab	In this paper the possibility of using transient tests, generated by the **Portable Pressure Wave Maker** (PPWM) device, as a powerful tool in the management of pipe systems, is demonstrated. • **Tests carried out in different experimental set-ups** at the Water Engineering Laboratory of the University of Perugia, Italy show that small amplitude sharp pressure waves produced by the PPWM allow to locate and

	Noise: N/A		evaluate the entity of anomalies, such as leaks, illegal branches, partial blockages, and negligently partially closed in-line valves. • To improve the precision of localization of anomalies, arrival times of pressure waves are detected by means of wavelet analysis. **Key findings:** • Simple relations based on the water hammer theory are proposed to evaluate the entity of the anomalies.
60. Haghighi, Covas et al. (2012) ITM Domain: Time Title: Direct backward transient analysis for leak detection in pressurized pipelines: from theory to real application	Analysis approach: Hydraulic modeling Analysis technique: MOC Response Type: N/A Optimization Technique: SQP Friction model: Steady State using Darcy Weisbach model, Unsteady friction effects are considered by using Brunone's model (Brunone et al. 1991,1995) which has been modified by Vitkovskey et al. (2000a) Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: Real application--a branch from pipeline – Lintrathen East Trunk Main Network at SW (Dundee, UK) (Covas et al. 2004) Leak Unknowns: Number/Location/Intensity NO. measurement Points: Single Validation: Numerical/Field	A novel transient-based technique – the **direct backward transient analysis** (DBTA) – for leak location of single pressurized pipes is presented and tested using real-life data. **Methodology:** • A transient flow is generated in the pipe by closing the downstream end valve. • The transient pressure signal is then measured only at the valve location. • Using MOC and exploiting the measurements after full valve closure, the transient flow is backwardly analyzed by sweeping the pipe from the downstream to the upstream end. • Knowing the upstream end heads, additional equations are developed to make the problem of leak detection determined and possible to be solved directly. • A system of equations and unknown variables of leaks and flow specifications are then established and simultaneously solved together. Eventually, nodes with non-zero leak size are introduced as leaks. • The method is applied to a real transmission pipeline, and its abilities are investigated. **Results:** • The results show that the method is capable of dealing with real systems and is reliable, fast and easy to use.
61. Haghighi and Keramat (2012) N/A Domain: Time Title: A fuzzy approach for considering uncertainty in transient analysis of pipe networks	Analysis approach: Hydraulic modeling Analysis technique: MOC Response Type: N/A Optimization Technique: SA (simulated Annealing) Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A	Network/Pipeline: Network Case Study: A real Network: Baghmalek water distribution network, a city in southwest of Iran Leak Unknowns: N/A NO. measurement Points: System responses in all nodes were calculated	This study introduces a **fuzzy approach** for considering **uncertainty** in transient analysis of pipe networks. **Methodology:** • Uncertain parameters in the transient analysis of pipe networks lead to uncertain responses. • Exploiting the fuzzy set theory and a simple scheme of the simulated annealing method, a conceptual model is developed.

	Noise: N/A	Validation: N/A	**Key findings:** • Typical uncertainties are nodal demand, pipe friction coefficient and wave speed, which not only are imprecise in nature but also change significantly over time. • The results show that the **transient extreme pressures can be highly affected by the uncertainties**. • This model can help designers of pipe systems in finding out the extent to which uncertainties in the inputs can spread to the transient highest and lowest pressures.
62. Haghighi and Ramos (2012) ITM Domain: Time Title: Detection of Leakage Freshwater and Friction Factor Calibration in Drinking Networks Using Central Force Optimization	Analysis approach: Hydraulic modeling Analysis technique: MOC Response Type: N/A Optimization Technique: CFO Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Network Case Study: A small pipe network with 11 pipes and 7 nodes Leak Unknowns: Number/Location/Intensity NO. measurement Points: Multiple Validation: Numerical	The paper aims at applying the new method of Central Force optimization (CFO) to the problem of ITA. **Methodology:** • The concept and main structure of CFO are represented as well as of CFO. • A reference pipe-network is considered to be solved using the ITA equipped with CFO. • The results are discussed compared to the previous works. **Results:** • It is concluded that CFO is easy to implement, computationally efficient and has a remarkable performance in solving leak detection problem.
63. Duan, Ghidaoui et al. (2012) N/A Domain: Frequency Title: Relevance of Unsteady Friction to Pipe Size and Length in Pipe Fluid Transients	Analysis approach: Hydraulic modeling Analysis technique: 1D water-hammer equations. The continuity and momentum equations for 2D axisymmetric transient flow in pipelines are given as (Vardy and Hwang 1991; Silva-Araya and Chaudhry 1997; Pezzinga 1999; Zhao and Ghidaoui 2003) Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model, Unsteady friction effect by Zielke (1968) for laminar flow and Vardy and Brown (1995,1996) for turbulent flow in one dimensional model and the two-equation 2D κ-ε turbulence model	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: N/A NO. measurement Points: Single Validation: Numerical/Lab/Field	This paper investigates the importance of pipe system scale —specifically pipe length and diameter—on unsteady friction in pipe transients. **Methodology:** • A dimensionless analysis is conducted for the one-dimensional (1D) water-hammer model in this study and the analytical expression for the relative importance of unsteady friction damping to the total friction damping is obtained in the frequency domain. In addition, a two-dimensional (2D) water hammer model coupled with a 2D κ- ε turbulence model is applied to a reservoir-pipe-valve system. • A parametric study covering a number of pipe diameters, pipe lengths, and initial Reynolds numbers is conducted. • The investigation spans a range of water-hammer travel time and turbulent radial diffusion timescales. • In each case, the transient is generated by a sudden and complete valve closure.

	from Zhao and Ghidaoui (2006) for two-dimensional model Viscoelasticity: N/A Noise: N/A		**Results:** • The analytical solution for the importance of unsteady friction is verified by the numerical simulations and the results show that unsteady friction damping has less effect on the damping rate of the transient envelope as (1) the ratio of the wave travel timescale to the radial diffusion timescale increases and (2) the product of the initial friction factor and Reynolds number increases. • The implication of the findings is that the role of unsteady friction on the damping rate of the transient envelope diminishes with the scale ratio of pipe length and pipe diameter. • Additionally, laboratory experiments, which are usually limited to relatively small-scale ratios of pipe lengths and diameters, have lead researchers to overestimate the importance of unsteady friction on the damping of the transient envelope in real large pipe-scale systems.
64. Duan, Lee Pedro et al. (2012) SRM Domain: Frequency Title: System Response Function–Based Leak Detection in Viscoelastic Pipelines	Analysis approach: Hydraulic modeling Analysis technique: Transfer Matrix Method Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: linear Kelvin –Voigt (K-V) model Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location NO. measurement Points: Single Validation: Numerical	In this paper the possibility of leak detection in a viscoelastic pipe system is studied. **Methodology:** • The frequency response function method (FRFM) is used for leak detection, and the analytical expression for the FRFM originally developed for an elastic pipeline is extended to the viscoelastic situation in this study. • The extended FRFM is validated from numerical experiments with one-dimensional viscoelastic transient models. **Results:** • The analysis shows that the pipe-wall viscoelasticity effect has significant impact on the amplitude damping and phase shift of the pressure wave, but little influence on the leak-induced patterns of pressure head peaks in transient system frequency responses. • The results indicate that the extended FRFM is applicable to the viscoelastic situation. • The impact of viscoelastic parameters and incident wave bandwidth on the applicability of the extended FRFM is also investigated in this paper, and the results imply that transient input signals with rapid changes in time are preferable for leak location in viscoelastic pipelines.

65. Guo, Yang et al. (2012) SRM Domain: Frequency Title: Leak detection in pipelines by exclusively frequency domain method	Analysis approach: Hydraulic modeling Analysis technique: impedance method using Laplace transform Response Type: Frequency Response Optimization Technique: GA Friction model: Steady State using Darcy Weisbach model, Unsteady friction effect by instantaneous acceleration-based (IAB) model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical/Lab	This investigation presents and validates a development of exclusively inverse frequency domain method for leak detection in pipelines. **Methodology:** • The location and leakage determined by analyzing the difference of transient water head response between the simulated and measured data in frequency domain. • The transient signals are generated by portion sharp closure of a valve from the small constant opening and it needs only a few meters of water. • The discrete boundary conditions and observation data are both transformed in frequency domain by Laplace transform. • The pre calibration approach is presented to minimize the effect of data and model error and it splits the method into two parts. One uses data from a known state to fit the parameters of the model and the other uses data from the current state for the fitting of leak parameters using the now calibrated model. • Some important practical parameters such as wave speed, friction in steady and unsteady state and the adaptability of the method are discussed. **Results:** • The application of the method to an experimental pipeline confirms the analysis and illustrates successful detection of the single pipeline leak. • It was found that the nonlinearity errors associated with valve boundary condition could be prevented by consideration of the induced flow perturbation curve shape.
66. Kashima, Lee et al. (2012) N/A Domain: Frequency Title: Numerical errors in discharge measurements using the KDP method	Analysis approach: Hydraulic modeling Analysis technique: Transfer Matrix Method, MOC Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: The application of the KDP method to real systems, the signal-to-noise ratio of the measured pressure	Network/Pipeline: Pipeline Case Study: RPVR Leak Unknowns: N/A NO. measurement Points: Multiple Validation: Numerical	This study introduces the **kinetic differential pressure** (KDP) method for measuring unsteady discharge in pressurized fluid conduits. **Methodology:** • The method utilizes two pressure measurements to estimate the unsteady discharge at the sampling rate of the pressure sensors. • The technique is based on the linear approximation of the one-dimensional governing equations for transient flow. • The application of the method is affected by two sources of error: the numerical error due to linear approximation

	signal decreases if the transducers are measured close to the system reservoir boundary.		of the one-dimensional governing equation and the modeling error representing the inability of the one-dimensional model to replicate the real transient behavior. • The numerical error is quantified as a function of the measurement location, system and signal characteristics. **Results:** • The method exhibits minor numerical errors if the system resonance is avoided. • This research provides a first step in the verification of the KDP method by investigating the numerical error caused by the linear approximation.
67. Zecchin Aaron, Lambert Martin et al. (2012) SRM Domain: Time Title: Inverse Laplace Transform for Transient-State Fluid Line Network Simulation	Analysis approach: Hydraulic modeling Analysis technique: Combining the new Laplace-domain input/output (I/O) model derived from the network admittance matrix with the Fourier series expansion numerical inverse Laplace transform (NILT), MOC Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model, working from the basis of two-dimensional (2D) axisymmetric flow, Zielke (1968) and Vardy and Brown (2003, 2004, 2007) derived unsteady friction terms for laminar and turbulent flow, respectively. Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Network Case Study: The 11-pipe network is adapted from Pudar and Liggett (1992), the 35-pipe and 51-pipe networks from Vitkovskey (2001), and the 94-pipe network from Datta and Sridharan (1994). Interested readers are referred to Zecchin (2010) Leak Unknowns: N/A NO. measurement Points: Multiple Validation: Numerical	This paper presents a study combining the new Laplace-domain input/output (I/O) model derived from the network admittance matrix with the Fourier series expansion numerical inverse Laplace transform (NILT) to serve as a time-domain simulation model. **Methodology:** • A series of theorems are presented demonstrating the stability of the I/O model, which is important for the construction of the NILT method. • In the previous work by the first author, the Fourier series expansion algorithm was studied, where qualitative relationships between the parameters and numerical errors were analyzed, and reliable parameter heuristics were developed. These heuristics are used for a series of numerical examples dealing with networks of 11, 35, 51, and 94 pipes by using five different pipe models. • The examples are used as the basis from which the accuracy and numerical efficiency of the proposed NILT are compared to the standard MOC model for transient pipeline networks. **Results:** • Findings show that, for all case studies considered, the proposed NILT is numerically efficient for the pipe types involving convolution operations, and it is accurate for networks composed of both linear and nonlinear pipe types.
68. Ghazali, Beck et al. (2012) SRM Domain: Time-Frequency	Analysis approach: Signal Processing Analysis technique: HT, NHT, DQ, TEO, Cepstrum Analysis	Network/Pipeline: Pipeline Case Study: RPV	The current paper presents a comparative study of instantaneous frequency analysis techniques based on

Title: Comparative study of instantaneous frequency-based methods for leak detection in pipeline networks	Response Type: Frequency Response Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: For further analysis, white noise was added, then by removing some of the intrinsic mode functions (IMF), a pressure signal without noise was generate.	Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical/Field	pressure transients recorded within a live distribution network. **Methodology:** • The instantaneous frequency of the signals is analyzed using the Hilbert transform (HT), the Normalized Hilbert transform (NHT), Direct Quadrature (DQ), Teager Energy Operator (TEO) and Cepstrum. **Key findings:** • This work demonstrates the effectiveness of the instantaneous frequency analysis in detecting a leaks and other features within the network. • NHT and DQ allowed for the identification of the approximate location of leaks. The performance TEO is moderate, with Cepstrum being the worst performing method.
69. Srirangarajan, Allen et al. (2012) SRM Domain: Time-Frequency Title: Wavelet-based Burst Event Detection and Localization in Water Distribution Systems	Analysis approach: Signal Processing Analysis technique: Wavelet, Graph-based localization algorithm Response Type: N/A Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: Wavelet denoising	Network/Pipeline: network Case Study: leak-off experiments performed on the WaterWiSe@SG wireless sensor network test bed, deployed on the drinking water distribution system in Singapore Leak Unknowns: Location NO. measurement Points: Single Validation: Numerical/Lab	In this paper, Wavelet-based techniques for detecting and locating transient pipe burst events in water distribution systems are presented. **Methodology:** • The proposed method uses multiscale wavelet analysis of high-rate pressure data recorded to detect transient events. • A local search method is proposed to estimate accurately the arrival time of the pressure transient associated with a pipe burst event. • A propose a graph-based localization algorithm which uses the arrival times of the pressure transient at different measurement points within the water distribution system is also proposed to determine the actual location (or source) of the pipe burst. **Key findings:** • Both wavelet coefficients and Lipschitz exponents provide additional information about the nature of the signal feature detected and can be used for feature classification. • Based on experiments, a systematic analysis of the sources of localization error is presented.
70. Gong, Lambert Martin et al. (2013) SRM	Analysis approach: Hydraulic modeling	Network/Pipeline: Pipeline Case Study: RPV	This paper, reports a single-event leak detection technique for pipelines that uses only **the responses at the first three**

Domain: Frequency Title: Single-Event Leak Detection in Pipeline Using First Three Resonant Responses	Analysis technique: Transfer Matrix Method Response Type: Frequency Response Optimization Technique: N/A Friction model: the effects of unsteady friction are usually not significant on the first three resonances, and the new leak location algorithm is robust to measurement errors. Viscoelasticity: N/A Noise: N/A	Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical/Lab	**resonant frequencie**s to determine the location and size of a leak. • **The bandwidth of the excitation** only needs to be five times that of the fundamental frequency of the tested pipeline, which is much less than the requirement in conventional FRD-based techniques. • Sensitivity analysis and numerical simulations are performed to assess the robustness and applicable range of the proposed leak location technique.
71. Gong, Simpson et al. (2013) SRM Domain: Frequency Title: Determination of the linear frequency response of single pipelines using persistent transient excitation: a numerical investigation	Analysis approach: Hydraulic modeling Analysis technique: Linear Transfer Matrix Method Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical	This research conducts numerical analysis on how accurately determine the linear frequency response diagram (FRD) of single pipelines using persistent transient pressure signals. • Two types of persistent signals, the **maximum-length binary sequence** and the **inverse-repeat sequence** (IRS), are compared in terms of the accuracy in estimating the linear response of a pipeline at resonant frequencies. • The **IRS** is found to be more appropriate for identifying the linear portion of the FRD of a pipeline, since its antisymmetric property can suppress part of the nonlinear response.
72. Lee (2013) N/A Domain: Frequency Title: Energy analysis for the illustration of inaccuracies in the linear modeling of pipe fluid transients	Analysis approach: Hydraulic modeling Analysis technique: MOC-transfer matrix- energy relationships for the fundamental frequency component Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: N/A NO. measurement Points: Single Validation: Numerical	This paper proposes the use of the **energy phase diagram** to compare the accuracy of the **transmission line model** with that of MOC model. • The energy phase diagram is a powerful method for **summarizing the head and flow responses for all points in the system** and for all times into a single plot and is ideal for the comparison of responses from different numerical models. • This study identifies **errors from the transmission line model that were undetected previously** when the head responses at a single point were used to gauge model accuracy.
73. Lee, Duan et al. (2013) N/A Domain: Frequency Title: The effect of time–frequency discretization on the	Analysis approach: Hydraulic modeling Analysis technique: MOC, transfer matrix for transmission line Response Type: N/A Optimization Technique: N/A	Network/Pipeline: Pipeline Case Study: A single pipeline system bounded by a constant head upstream reservoir and a head loss device at the downstream boundary	This paper investigates the **errors induced by the discretization of the input signal** and provides guidelines for the appropriate selection of discretization size for the linear transmission line models.

accuracy of the transmission line modeling of fluid transients	Friction model: Steady State using Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Leak Unknowns: N/A NO. measurement Points: Single Validation: Numerical	• The accuracy of the model is quantified through comparison with a finely discretized MOC model. • The results show that the **transmission line models are sensitive to the time–frequency discretization size** and unlike the MOC, the appropriate size of the discretization changes depending on the transient event being modelled as well as the energy losses in the system.
74. Zecchin, White et al. (2013) N/A Domain: Frequency Title: Parameter identification of fluid line networks by frequency-domain maximum likelihood estimation	Analysis approach: Hydraulic modeling, Signal Processing Analysis technique: Laplace-domain admittance matrix, frequency-domain maximum likelihood estimation method. Response Type: N/A Optimization Technique: N/A Friction model: Steady State using Darcy Weisbach model, Unsteady friction using pipeline a resistance function model, namely the TUF model Viscoelasticity: N/A Noise: Easy noise reduction by removing non-excited frequencies, in Laplace domain	Network/Pipeline: Network Case Study: A 11-pipes network Leak Unknowns: N/A NO. measurement Points: Multiple Validation: Numerical	This paper presents a parameter identification method for fluid line networks based on transient-state measurements of the hydraulic variables of pressure and flow within the network. **Methodology:** • From a Laplace-domain admittance matrix representation of the system, a measurement model is derived that decouples the influence of unmeasured state variables from the measured state variables. • This decoupled measurement model is used as the basis of the development of a frequency-domain maximum likelihood estimation method. **Results:** • The proposed method is applied to different case studies with successful results.
75. Kim (2014) ITM Domain: Time-Frequency Title: Inverse Transient Analysis for a Branched Pipeline System with Leakage and Blockage Using Impedance Method	Analysis approach: Hydraulic modeling Analysis technique: Impedance Method Response Type: N/A Optimization Technique: GA Friction model: Steady State using Darcy Weisbach model, to consider the unsteady friction's impact, the impedance development process implemented both unsteady friction impact resulting from velocity profiles with two-dimensional distributions and unsteady friction resulting from acceleration Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: Branched RPR Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical	In this study, analytical expressions for pressure head and discharge in the frequency domain were presented for a branched pipeline system with both a leakage and a blockage. **Methodology:** • Based on impedance expressions defining this system, response functions were derived in the frequency domain and their corresponding time-domain responses were integrated into a meta-heuristic calibration scheme for inverse transient analysis. • The impacts of unsteady friction both from the impact resulting from velocity profiles with two-dimensional distributions and that resulting from instant acceleration were integrated into the development of the head and discharge expression in the frequency domain. • Response functions from the time domain responses are integrated into a meta-heuristic calibration scheme for inverse transient analysis.

			• Using an objective function to minimize the difference of squares between the measurement and optimized pressure head, the impulse response-based calibration is used to detect the locations and magnitudes of the abnormalities. **Results:** • The calibration results for different friction models indicated a difference in the strength and weakness of each friction consideration which could be explained by the distinct pressure attenuation characteristics in conjunction with the boundary condition.
76. Gong, Zecchin Aaron et al. (2014) SRM Domain: Frequency Title: Frequency Response Diagram for Pipeline Leak Detection: Comparing the Odd and Even Harmonics	Analysis approach: Hydraulic modeling Analysis technique: Impedance Method, Transfer Matrix Method Response Type: Frequency Response Optimization Technique: N/A Friction model: a case with Steady State Darcy Weisbach model, another case is frictionless Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical	This research analyses the relationship between the characteristics of the leak-induced patterns and the parameters of the pipeline system to compare the two approaches of using Odd and Even Harmonics in Frequency Response Diagram for Pipeline Leak Detection. **Methodology:** • A dimensionless analysis, based on hydraulic impedance, is adopted to simplify the equations. **Key findings:** • The amplitudes of leak-induced patterns at both the odd and even harmonics in the FRD are found to be dependent on a critical parameter: the dimensionless steady-state valve impedance, $Z*V$. The value of $Z*V$ is dependent on the steady-state valve opening. As a result, the initial valve opening can control amplitudes of the leak-induced patterns within the FRD for any specific pipeline system. • This research also derives the equations for calculating the dimensionless leak size based on the value of $Z*V$ and the amplitude of either leak-induced pattern. • Finally, the two existing FRD-based leak detection methods are compared, and the approach using the odd harmonics is found to be superior.
77. Kim Sang, Zecchin et al. (2014) ITM Domain: Frequency Title: Diagnosis of a Pipeline System for Transient Flow in Low Reynolds Number with Impedance Method	Analysis approach: Hydraulic modeling Analysis technique impedance-based method Response Type: N/A Optimization Technique: GA	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical/Lab	This study explores the comprehensive calibration potential of impedance-based methods implementing several unsteady friction models for a pipeline system with or without leakage. **Methodology:**

	Friction model: a case with Steady State Darcy Weisbach model, the frequency-dependent friction approach developed by Suo and Wylie (1989), derived on the basis of the radial distribution of velocity was used in this study Viscoelasticity: N/A Noise: The impact of noise and pressure oscillation that originated from the conventional pressure transducer and pump station, respectively, on the calibration performance of the proposed algorithm was found to be negligible.		• The corresponding response functions in the frequency domain approach have been derived by the impulse response method, and then incorporated into the genetic algorithm-based calibration method. • Unsteady models addressed either frequency-dependent friction or acceleration-based frictions. • To check the impact of pressure pulsation and noise, extended calibration tests were performed using oscillated and disturbed pressure data bounded by the frequency and amplitude of a pump system and the measurement error of a conventional pressure transducer. **Results:** • Parameter calibration exercises with experimental data have shown that the impedance-based approach provides a versatile and feasible optimization framework via the fitting of an objective function based on the predicted and measured pressure head variation. • The performance of the integrated optimization examples demonstrates the robustness of the impedance-based approach, both in the representation of a real-life system and the configuration of various system characteristics.
78. Amin, Hadi et al. (2014) SRM Domain: Time-Frequency Title: Leakage Detection in Pipeline Using Synchrosqueeze Wavelet Transform	Analysis approach: Signal Processing Analysis technique Synchrosqueeze Wavelet Transform Response Type: N/A Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: Noise is added to the Fourier oscillatory mode of the signal as a function of time (e(t))	Network/Pipeline: Pipeline Case Study: u-shaped and straight-shaped pipeline Leak Unknowns: Number/Location NO. measurement Points: Single Validation: Numerical/Lab	In this investigation, a method is developed based on pressure transient by using **single pressure transducer** and analyses on newly method of analyzing called **synchrosqueeze wavelet transform** (SWT) which is viable approach to detect and locate the leak in pipeline system. • The result show that newly developed techniques, SWT appears to improve the ability of the method to identify features in the signal.
79. Huang, Lin et al. (2015) ITM Domain: Time Title: An Optimization Approach to Leak Detection in Pipe Networks Using Simulated Annealing	Analysis approach: Hydraulic Modeling Analysis technique: MOC Response Type: N/A Optimization Technique: SA (simulated Annealing) Friction model: Steady-State Darcy Weisbach model in which f is approximately evaluated by Swamee-Jain equation Viscoelasticity: N/A	Network/Pipeline: Pipeline and Network Case Study: a RPV pipeline and a small synthetic pipe network with two loops Leak Unknowns: Number/Location/Intensity NO. measurement Points: Single Validation: Numerical	In this research, a numerical approach, named as leak detection simulated annealing (LDSA), is developed based on the combination of transient flow simulations and simulated annealing to detect leaks in a pipe network. **Methodology:** • In the LDSA framework, an analysis model for pipe networks is first used to determine the steady-state nodal head solution of the network. • For detecting the leaks, a valve closing suddenly at downstream side of the network is designed to create a

	Noise: Using standard error of the estimate (SEE) method, some results are consistent with the magnitude of noise added to the original observed data		transient event and then MOC is applied to simulate the transient flow in the network. • Results from an experiment on leak detection in a single pipeline presented in the literature are used to verify the capability of LDSA in identifying the leaks. **Results:** • The result shows that the leaks represented by orifices in two cases can be accurately detected. • For a very small value of discharge coefficient times effective area of orifice, it is found that the use of multiple observation points can increase the detection capability
80. Lee, Duan et al. (2014) ITM Domain: Time-Frequency Title: Numerical and Experimental Study on the Effect of Signal Bandwidth on Pipe Assessment Using Fluid Transients	Analysis approach: Hydraulic Modeling Analysis technique: MOC Response Type: N/A Optimization Technique: GA Friction model: Steady-State Darcy Weisbach model, unsteady-State using Vardy and Brown (2003) Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical/Lab	This paper presents **analytical, numerical and experimental results** to illustrate the effect of **signal bandwidth (frequency content)** of the induced transient signals has on the spatial resolution, accuracy and range of transient based fault detection. • The results demonstrate that **higher bandwidth signals provide more accurate fault detection at the expense of detection range.**
81. Duan (2017) SRM-ITM Domain: Frequency Title: Transient frequency response-based leak detection in water supply pipeline systems with branched and looped junctions	Analysis approach: Hydraulic Modeling Analysis technique: MOC, Transfer Matrix Response Type: Frequency Response Optimization Technique: GA Friction model: Only steady friction effect (Darcy Weisbach model) is considered in the analytical derivation and the unsteady friction effect will be included and validated in the numerical simulations Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPR with loop/branch junctions Leak Unknowns: Location/Intensity NO. measurement Points: Single Validation: Numerical	This paper aims to extend the transient frequency response TFR-based leak detection method to relatively more complex pipeline connection situations. **Methodology:** • The branched and looped pipe junctions are firstly investigated for their influences to the system TFR, so that their effects can be characterized and separated from the effect of other components and potential leakage defects in the system. • The leak-induced patterns of transient responses are derived analytically using the transfer matrix method for systems with different pipe junctions, which thereafter are used for the analysis of pipe leakage conditions in the system. • The developed method is validated through different numerical experiments in this study. **Results:** • The analytical results indicate that both the typical branched and looped pipe junctions may have great

			influences to the system TFRs but have little impacts on the leak-induced patterns. • The results demonstrate the applicability and accuracy of the developed method for leakage identification and detection in these multiple-pipeline systems. However, the results also imply that this method is more accurate to locate the pipe leakage than to size the leakage in these applications.
82. Duan and Lee (2016) SRM Domain: Frequency Title: Transient-Based Frequency Domain Method for Dead-End Side Branch Detection in Reservoir Pipeline-Valve Systems	Analysis approach: Hydraulic Modeling Analysis technique: Transfer Matrix Response Type: Frequency Response Optimization Technique: GA is used in an inverse problem of solving the analytical equations Friction model: The quasi-steady friction effect is represented by the Darcy-Weisbach formula, and the unsteady friction is calculated by Zielke 's model for laminar flows (Zielke 1968) and modeled by Vardy-Brown 's model for turbulent flows (Vardy and Brown 1995). Viscoelasticity: by means of procedures described in (Duan et al. 2012b) Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: N/A NO. measurement Points: Single Validation: Numerical	This paper investigates a transient-based frequency domain method for **detecting side branches** in pipe systems. **Methodology:** • The frequency response function for a pipe system with a single dead-end side branch is first derived by the transfer matrix method and the side branch was found to cause shifts in the system resonant frequencies. • The nature of the resonant frequency shifts is used to inversely determine the location and size of the side branch. • A two-step genetic algorithm-based optimization is proposed in this study to efficiently solve the derived analytical expression for the resonant frequency shifts. **Results:** • The results demonstrate the feasibility of this method for detecting side branches. • The accuracy for locating the side branch is higher than the accuracy in sizing the branches. • The sensitivity of the method to the magnitude and bandwidth of the transient wave signal is also discussed in the paper.
83. Ranginkaman, Haghighi et al. (2016) ITM Domain: Frequency Title: Inverse Frequency Response Analysis for Pipelines Leak Detection Using the Particle Swarm Optimization	Analysis approach: Hydraulic Modeling Analysis technique: Transfer Matrix method introduced in Visnovsky 2011 for arbitrary pipe networks Response Type: N/A Optimization Technique: PSO Friction model: Steady-State Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Number/Location/Intensity NO. measurement Points: Single Validation: Numerical	The paper introduces Inverse Frequency Response Analysis (IFRA) for leak detection of pipelines. **Methodology:** • To implement an IFRA for leak detection, a transient state is initiated in the pipe by fast closure of the downstream end valve. • Then, the pressure time history at the valve location is measured. Using the Fast Fourier Transform (FFT) the measured signal is transferred into the frequency domain. • Besides, using the transfer matrix method, a frequency response analysis model for the pipeline is developed as

			a function of the leak parameters including the number, location and size of leaks. • Then, a nonlinear inverse problem is defined to minimize the discrepancies between the observed and predicted responses at the valve location. • To find the pipeline leaks the method of Particle Swarm Optimization (PSO) is coupled to the transient analysis model while, the leak parameters are the optimization decision variables. **Results:** • This model predicts the frequency responses of the pipe in return for any random set of leak parameters. • The model is successfully applied to an example pipeline and in both terms of efficiency and reliability the results are satisfactory.
84. Ferrante, Capponi et al. (2016) SRM Domain: Time-Frequency Title: Numerical transient analysis of random leakage in time and frequency domain	Analysis approach: Hydraulic Modeling Analysis technique: MOC, IM, LM Response Type: N/A Optimization Technique: N/A Friction model: Frictionless Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: N/A NO. measurement Points: Single Validation: Numerical	Models of water pipeline systems should take into account the distribution in space and time of user demands and leakage. **In the usual approach such a distribution is simplified lumping the system outflows at a reduced number of nodes**. To investigate the effects of such a simplification. • In this paper through numerical models, both in the time and in the frequency domain, the uncertainty introduced by the random variation in leak size, location and number are explored. • In this study the number of leaks is also considered as a parameter. **Key findings:** • In the time domain, results show that the damping increases with the number of leaks. • The spreading of the simulated pressure signals increases with time whereas it decreases with the number of leaks. • In the frequency domain, the local minima and maxima values of the impedance are affected by the number of leaks for a given total outflow from the system.
85. Rubio Scola, Besançon et al. (2017) SRM Domain: Frequency Title: Blockage and Leak Detection and Location in	Analysis approach: Hydraulic Modeling Analysis technique: Transfer Matrix Method Response Type: Frequency Response Optimization Technique: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity NO. measurement Points: Multiple Validation: Numerical	This paper proposes a new approach based on the frequency response for fault identification in pipelines. The method focuses on extended blockage detection and location, and a case of simultaneous punctual blockage and leak identification. **Methodology:**

Pipelines Using Frequency Response Optimization	Friction model: Steady-State Darcy Weisbach model Viscoelasticity: N/A Noise: The additive noise on the measurement, as white, Gaussian, zero mean and with a certain maximal amplitude is considered. In the case of a single leak or blockage, the algorithm can be made more robust to additive measurement noise (assuming a white, Gaussian, and zero mean noise), by using several measurements, obtained for different excitation frequencies. Additionally, using a Fourier decomposition of the inputs and the outputs, one can recover the variables associated with the different frequencies. If the noise covariance is known, it can be used in the optimization for it to be optimal with respect to that specific noise (Simon 2006), in the form of weighting matrix W. Otherwise, W is taken as equal to the identity matrix.		• The proposed approach is based on a frequency modeling of pipeline dynamics including the effect of faults under study, by means of transfer matrix representation, and a related optimization. • Using measurements at both ends of the pipeline, together with an appropriate excitation, the parameters of the faults are directly identified from the frequency response. **Results:** • This methodology is shown to be efficient based on the simulation results, even in the presence of additive measurement noise.
86. Hanafi.M.Yusop, M.F.Ghazali et al. (2017) SRM Domain: Time-Frequency 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 Analysis technique: Wavelet, Cepstrum Analysis, PCA Response Type: N/A Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: Wavelet denoising	Network/Pipeline: Pipeline Case Study: A circular loop pipeline system Leak Unknowns: Location NO. measurement Points: Single Validation: Numerical/Lab	This study proposes **Cepstrum analysis** as a post-processing method to extract leak and pipe feature information from pressure transient signal by considering this method to analyze non-stationary data. The focus of this research is on the improvement of Cepstrum analysis to extract information about the leak, pipe feature, and its location. **Methodology:** • Pre-processing method as a filtering technique is implemented to analyze the real signal before the signal goes through Cepstrum analysis as post-processing method. • Discrete Wavelets Transform (DWT) and Principal Component Analysis (PCA) are proposed as Pre-Processing Methods. **Results:** • The results satisfactorily predicted the leak location as the comparison analysis using theoretical calculation and

			experimental results were just 0.4% to 3.8%. Therefore, PCA and DWT were recommended as data pre-processing methods to improve Cepstrum analysis result.
87. Motazedi and Beck (2017) SRM Domain: Time-Frequency Title: Leak detection using Cepstrum of cross-correlation of transient pressure wave signals	Analysis approach: Hydraulic Modeling, Signal Processing Analysis technique: Ansys Fluent 2D and 3D model, Cepstrum of cross-correlation of transient pressure wave signals Response Type: N/A Optimization Technique: N/A Friction model: Embedded model in Ansys Fluent Software Viscoelasticity: Embedded model in Ansys Fluent Software Noise: The Cepstrum method is not sensitive to the color of the spectrum and creates delta functions to echoes. However, the autocorrelation method only gives a delta function, where the spectrum is in white (either white noise or impulse).	Network/Pipeline: Pipeline and Network Case Study: A straight pipe and a T-Junction network Leak Unknowns: Location/Intensity NO. measurement Points: Multiple Validation: Numerical	This work proposes a leak detection method based on the **Cepstrum of the cross-correlation of the pressure signals** from two transducers. • Computational simulations of leaks with different properties, size, position and shape, in a straight pipe and a T-Junction network are studied. **Key findings:** • The proposed method was successful in estimating leakages and the pipeline features with a high precision. • For the results with a straight pipe, this method is considerably more accurate than using the cross-correlation leak detection method or the Cepstrum method alone. • The results obtained by Cepstrum and Cepstrum of cross-correlation for the T-Junction case were quite accurate, while Cepstrum alone showed a slightly better precision.
88. Rahmanshahi, Fathi-Moghadam et al. (2017) ITM Domain: Time Title: Leak Detection in Viscoelastic Pipeline using Inverse Transient Analysis	Analysis approach: Hydraulic Modeling Analysis technique: MOC Response Type: N/A Optimization Technique: GA Friction model: Steady-State Darcy Weisbach model Viscoelasticity: generalized Kelvin-Voigt model Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity NO. measurement Points: Multiple and Single Validation: Numerical/Lab	The current research investigated transient based techniques for leak detection in **Polyethylene water pipe systems**. • **Methodology:** • Firstly, an inverse transient analysis (ITA) tool was developed, and then for testing and validating this model, extensive experiments are carried out at Hydraulic Laboratory of Shahid Chamran University of Ahvaz to collect the necessary data. • A selected set of data corresponding to two leak locations with different sizes was used to assess the ITA method. **Results:** • Results indicated that the leak location can be accurately pinpointed using a sample size equal to one period of the collected pressure in ITA. • The error for estimation of the location for a significant leak was between 0.17% and 2.17% of the pipe length. Also, using two periods (2T) of the pressure signal, the uncertainties in leak quantity estimation were satisfactory, as less than 23% of the real leak quantity.

			• The comparison between the observed data and the numerical results in different conditions indicated that the hydraulic model estimated the transient pressure accurately by just incorporating the pipe wall viscoelasticity into the model.
89. Hamat, Ghazali et al. (2017) SRM Domain: Time-Frequency Title: The Use of Transmission Line Modeling for Detection of Leakage in Pipeline	Analysis approach: Hydraulic Modeling, Signal Processing Analysis technique: TLM, Wavelet Analysis Response Type: N/A Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location NO. measurement Points: Multiple and Single Validation: Numerical	This paper implemented a Transmission Line Modeling to detect and locate leak in pipeline networks. **Methodology:** • The original data from the TLM modeling are analyzed using time-frequency representation (TFR). • A well-known and established signal processing method of TFR based wavelet transform is chosen for the data analysis. **Results:** • The results present two different cases; pipe network without leak and the second one with existing of leak. • From the study, features in the pipe networks such as inlet, valve, leak and outlet were successfully detected and located using TLM and wavelet analysis.
90. Kim (2017) SRM Domain: Frequency Title: Multiple Leakage Function for a Simple Pipeline System	Analysis approach: Hydraulic Modeling Analysis technique: Impedance method, MLF Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady-State Darcy Weisbach model, the impact of unsteady friction on turbulent flow conditions in considered with the difference in friction contribution between the temporal and convective accelerations using Brunone et al. 1991; Ramos et al. 2004 method. Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity/Intensity NO. measurement Points: Single Validation: Numerical	This study proposes a multiple leakage function (MLF) method, for an efficient multiple leakage representation of a reservoir pipeline valve system in the frequency domain. **Methodology:** • To address unsteady friction impact on a multiple leakage situation, the MLF is used with one-dimensional and two –dimensional unsteady friction models. • Model validation is achieved by comparing impedance frequency responses with those of existing approaches. • Strengths associated with the MLF were discussed in terms of model parsimony, computational accuracy, and leak detection capability. **Results:** • Feasibility of the MLF is confirmed for robustness in the leakage implementation sequence and for identification of any single leakage, which is useful in detecting multiple leakages in real systems.
91. Wang and Ghidaoui (2017) SRM Domain: Frequency	Analysis approach: Hydraulic Modeling, Signal Processing	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: Location/Intensity/Intensity	This research formulates and applies a transient-based leakage detection method using a **matched-field processing** (MFP) scheme.

Title: Pipeline leak detection using the matched-field processing method	Analysis technique: impedance transfer matrix method, Match field processing Response Type: Frequency Response Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A Noise: Both white and nonwhite noises are considered. It is assumed that the noise structure is known. On this basis, the measurement may be filtered such that the noise is whitened. through this approach, a systematic algorithm is introduced for signal denoising.	NO. measurement Points: Multiple Validation: Numerical	• Its robustness is demonstrated by showing that the MFP method is able to estimate the location and size of leak in the presence of (1) noise even for signal-to-noise ratio (SNR) as low as SNR =−3 dB, and (2) uncertainty in the fluid –pipe system wave speed. **Key findings:** • It is found to be efficient, robust, accurate, and provides a unique solution. • Its inherent efficiency stems from the fact that the MFP method decouples the search for the leak location and the leak size. • It is able to use all available frequencies, rather than just resonant frequencies, and does not need to identify resonant frequencies. As a result, the MFP method provides precise localization estimates even in noisy environments. • It is also shown that a unique identification is achieved by the MFP method provided that the pressure signal is measured at two locations along the pipe. • For the case of multiple leaks, MFP identifies each of the leaks provided that the distance between the leaks is of the same order or larger than the shortest probing half-wavelength.
92. Ranginkaman, Haghighi et al. (2017) SRM Domain: Frequency Title: Application of the Frequency Response Method for Transient Flow Analysis of Looped Pipe Networks	Analysis approach: Hydraulic Modeling Analysis technique: Transfer Matrix method introduced in vitkovskey 2011 for arbitrary pipe networks Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady-State Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Network Case Study: A network consists of 37 steel pipes, 27 main junctions and a reservoir with constant head that supplies the system by gravity Leak Unknowns: N/A NO. measurement Points: Multiple Validation: Numerical	This paper investigates the frequency response method (FRM) for analyzing water hammer phenomenon in looped pipe networks. **Methodology:** • The governing equations are linearized and transferred into the frequency domain. Then, the network's transient flow excitation in the time domain is transferred into the frequency domain using the fast Fourier transform (FFT). • For all frequency contents of the transferred excitation, the frequency responses of the network at main junctions are computed. • Using the principle of superposition in linear systems, the system's nodal transient pressures against the applied excitation are obtained. • By analyzing a real pipe network by both the FRM and the MOC, the advantages of transient flow analysis in the frequency domain compared with the time domain are addressed. **Key findings:**

			• The FRM needs neither discretization of the pipes nor interpolation of the responses in space, time, and frequency domains. Accordingly, the FRM is found computationally fast and reliable for pipe networks transient flow analysis.
93. Kim (2018) ITM Domain: Frequency Title: Development of Multiple Leakage Detection Method for a Reservoir Pipeline Valve System	Analysis approach: Hydraulic Modeling Analysis technique: multiple leakage function method Response Type: N/A Optimization Technique: GA Friction model: Steady-State Darcy Weisbach model, isolated multiple leakage function (IMLF) for unsteady friction impact Viscoelasticity: N/A Noise: Advanced schemes were developed to handle signal noise	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Location/Intensity/Intensity NO. measurement Points: Single Validation: Numerical	In this study, a leakage detection method is proposed to address unknown conditions on multiple leakage dimensions through introduction of revised leakage expressions based on a frequency domain approximation. **Methodology:** • A multiple leakage function is modified for an efficient representation of multiple abnormalities at a reservoir pipeline valve system. • An iterative metaheuristic scheme (IMS) is designed to handle an optimization scheme for multiple leakages using a pressure response for a discharge impulse introduced through value manipulation. • To address unsteady friction in hydraulic transients combined with multiple leakages, both one-dimensional and two-dimensional models are used to derive leakage expressions for turbulent and laminar flow conditions. • An isolated multiple leakage function (IMLF) was proposed to exclusively encapsulate the impact of leakages and unsteady fiction. • Considering uncertainties in the hydraulic transient propagation, data noise, and multiple local optima issues in large parameter calibrations, three advanced schemes are modularized to improve detectability of IMS. **Results:** • Several hypothetical examples were presented to show the potential of IMS, validity of three advanced schemes, and robustness in multiple leakage prediction compared to existing approaches.
94. Wang and Ghidaoui (2018) ITM Domain: Frequency Title: Identification of multiple leaks in pipeline: Linearized model, maximum likelihood, and super-resolution localization	Analysis approach: Hydraulic Modeling, Signal processing Analysis technique: impedance transfer matrix, MLE Response Type: N/A Optimization Technique: N/A Friction model: N/A Viscoelasticity: N/A	Network/Pipeline: Pipeline Case Study: RPR Leak Unknowns: Location/Intensity/Intensity NO. measurement Points: Multiple Validation: Numerical	This paper considers the problem of identifying multiple leaks in a water-filled pipeline based on inverse transient wave theory. **Key findings:** • The analytical solution to this problem involves nonlinear interaction terms between the various leaks. This paper shows analytically and numerically that these nonlinear terms are of the order of the leak sizes to the power two and; thus, negligible.

	Noise: multiple leaks are estimated by the ML approach in the presence of white noise as an additive term.		• As a result of this simplification, a maximum likelihood (ML) scheme that identifies leak locations and leak sizes separately is formulated and tested. • It is found that the ML estimation scheme is highly efficient and robust with respect to noise. In addition, the ML method is a super-resolution leak localization scheme because its resolvable leak distance is below the Nyquist-Shannon sampling theorem limit. • Moreover, the Cramér-Rao lower bound (CRLB) is derived and used to show the efficiency of the ML scheme estimates. The variance of the ML estimator approximates the CRLB proving that the ML scheme belongs to class of best unbiased estimator of leak localization methods.
95. Sabzkouhi and Haghighi (2018) N/A Domain: Frequency Title: Uncertainty Analysis of Transient Flow in Water Distribution Networks	Analysis approach: Hydraulic Modeling Analysis technique: Transfer Matrix method introduced in Vitkovskey 2011 for arbitrary pipe networks Response Type: N/A Optimization Technique: MOGA Friction model: Steady-State Darcy Weisbach model Viscoelasticity: N/A Noise: N/A	Network/Pipeline: Network Case Study: network consists of 37 steel pipes, 27 main junctions and a reservoir with constant head that supplies the system by gravity Leak Unknowns: N/A NO. measurement Points: Multiple Validation: Numerical	This paper introduces a fuzzy based uncertainty analysis approach for the uncertainty analysis of water distribution networks. **Methodology:** • A simulation model based on the fuzzy sets theory is introduced. • For this purpose, triangular fuzzy numbers are used to represent the input uncertainties. • Then, to obtain the extreme pressure heads in each location of the network and at each level of uncertainty, four independent optimization problems are solved. In these problems, the nodal maximum and minimum pressure heads are the objective functions and the simulation parameters are the decision variables. • Accordingly, for fuzzy analysis of a pipe network, a complicated **many-objective optimization problem** arises. • To solve the problem efficiently a many-objective genetic algorithm is coupled to the transient simulation model. To speed up the analysis, a transient simulation model in the frequency domain is used. **Results:** • The proposed model is applied to a pipe network and the results are discussed. The model is found computationally fast and promising for real applications.
96. Duan (2018) TRM Domain: Frequency	Analysis approach: Hydraulic Modeling and Signal Processing Analysis technique: Transient Frequency Response (TFR) Analysis	Network/Pipeline: Pipeline and Network	This study evaluates the **accuracy and sensitivity** of the TFR-based leak detection method for **branched and looped multi-pipeline systems**. The paper analyzes inherent

Title: Accuracy and Sensitivity Evaluation of TFR Method for Leak Detection in Multiple-Pipeline Water Supply Systems	Response Type: Frequency Response Optimization Technique: N/A Friction model: Steady-state Viscoelasticity: N/A Noise: Assumes some impact on data measurement but not explicitly modeled.	Case Study: Hypothetical systems with branched and looped configurations Leak Unknowns: Location, Size NO. Measurement Points: Multiple Validation: Numerical	assumptions, system parameters, and their effects on the method's applicability. Key findings include: • **Focus on Influencing Factors:** o System properties, such as pipeline layout and frictional characteristics, significantly affect the detection accuracy. o Analytical approximations and assumptions, especially in derivation, influence the reliability of TFR results. • **Leak Characteristics Analysis:** o Evaluates the sensitivity of the method to variations in leak size and location. o Provides insights into the range of applicability for small and large leaks. • **Pipeline System Complexity:** o The method is validated for both **simple branched systems** and **looped networks**, extending its practical applicability. • **Validation Methods:** o Conducts extensive **analytical and numerical simulations** to assess system behavior under varying conditions. • **Utility for Practical Applications:** o Confirms TFR as a **non-intrusive, efficient leak detection method** for complex pipeline systems. • Suggests a robust sensitivity range for real-world pipeline conditions, aiding practical implementations.
97. Lin and Yeh (2019) ITM Domain: Time Title: An Inverse Transient-Based Optimization Approach to Fault Examination in Water Distribution Networks	Analysis approach: Hydraulic Modeling Analysis technique: MOC Response Type: Impulse Response Optimization Technique: PEOS (Pipeline Examination Ordinal Symbiotic Organism Search) Friction model: Steady-state (considering pipe aging effects in the hydraulic model) Viscoelasticity: N/A Noise: Considered	Network/Pipeline: Pipeline and Network Case Study: Experimental system and hypothetical system Leak Unknowns: Location and size NO. Measurement Points: Multiple Validation: Numerical, experimental, and field	This study proposes the **Pipeline Examination Ordinal Symbiotic Organism Search (PEOS)**, an inverse transient-based heuristic optimization approach for detecting faults (leaks, blockages, and pipe deterioration) in pipeline systems and water distribution networks (WDNs). The method combines a modified steady hydraulic model with MOC to analyze transient behavior, employing PEOS to optimize fault detection by filtering solutions and reducing computation time. Key findings include:

			• **High Accuracy**: Experimental and numerical validations demonstrated precise fault detection, with predicted head distributions aligning closely with actual results. • **Superior Efficiency**: PEOS significantly outperformed traditional evolutionary algorithms in computational speed and accuracy, reducing average computation time to 50.6 minutes. • **Robustness**: Effective even with limited observations and measurement errors, with minimal impact from inappropriate transient operations. • **Scalability**: Successfully applied to both small-scale and large-scale WDNs, showcasing its adaptability to practical challenges. • Limitations include a focus on simplified systems, with future research needed to address real-world complexities like multiple simultaneous faults and diverse operational conditions. PEOS represents a promising technique for fault detection, offering improved accuracy, efficiency, and robustness over existing methods.

98. Keramat, Ghidaoui et al. (2019) ITM
Domain: Time
Title: Cramer-Rao Lower Bound for Performance Analysis of Leak Detection
	Analysis Approach: Hydraulic Modeling
	Analysis Technique: MOC for water-hammer equations and Fisher information analysis
	Response Type: Impulse Response
	Optimization Technique: Not optimization-focused; statistical bound estimation using CRLB
	Friction Model: Steady-state (linear model)
	Viscoelasticity: Not mentioned (assumed N/A)
	Noise: Random noise applied to measurements
		Network/Pipeline: Pipeline
		Case Study: Hypothetical system (evaluated through numerical analysis)
		Leak Unknowns: Location and size
		Number of Measurement Points: Single
		Validation: Numerical
			This study investigates the impact of uncertainties on leak detection by deriving the **Cramer-Rao Lower Bound (CRLB)** for leak variable estimation. Key contributions and findings include:
			• **Framework and Methodology:**
			  ○ The CRLB is applied to estimate the minimum variance in leak size and location using Fisher information derived from water-hammer equations.
			  ○ CRLB provides a theoretical lower bound for the accuracy of any unbiased estimator for leak detection.
			• **Factors Influencing Estimation Accuracy:**
			  ○ The variance of leak size estimates **increases** with:
			  ▪ Higher noise levels in measurements.
			  ▪ Longer valve closure times.
			  ○ The variance **decreases** with:
			  ▪ Longer measurement signal durations.

			▪ Reduced spacing between consecutive leak locations if distances exceed half the minimum wavelength of the probing signal. • **Implications for Leak Detection Design:** o The study highlights the importance of signal duration and proper test setup to minimize estimation errors. o CRLB aids in designing efficient transient tests by determining the maximum achievable accuracy for leak localization. • **Recommendations and Insights:** o Leak-size estimates become significantly inaccurate if the spatial resolution (mesh size) of the ITA is too coarse. • The findings provide guidance for the design of inverse problem formulations and test configurations to improve localization success rates and reduce uncertainty in practical leak detection scenarios.
99. Wang and Ghidaoui (2019) ITM Domain: Time Title: Identification of multiple leaks in pipeline II: Iterative beamforming and leak number estimation	Analysis Approach: Hydraulic Modeling Analysis Technique: Maximum Likelihood (ML) based iterative beamforming (IB) Response Type: Impulse Response Optimization Technique: Maximum Likelihood (ML), Iterative Beamforming (IB), Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC) Friction Model: Not explicitly mentioned; assumed N/A Viscoelasticity: Not mentioned; assumed N/A Noise: Robust to noise, validated through simulations	Network/Pipeline: Pipeline Case Study: Numerical system (hypothetical) Leak Unknowns: Location, size, and number NO. Measurement Points: Single Validation: Numerical	This paper presents an iterative beamforming (IB) method to solve the complex multi-leak detection problem in pipelines. The approach reduces computational complexity by decomposing the high-dimensional optimization problem into multiple one-dimensional problems. Key contributions and findings include: • **Methodology:** o IB estimates contributions from each leak to the pressure head measurement iteratively. o Introduces Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) for determining the optimal leak number, balancing model fit and complexity. • **Efficiency and Accuracy:** o The IB method simplifies computational demands and ensures super-resolution accuracy in detecting multiple leaks.

			○ Numerical simulations demonstrate the method's robustness and ability to handle up to five leaks with high accuracy. • **Key Advantages:** ○ The proposed method addresses challenges faced by conventional multi-leak detection techniques, including handling noise, reducing computational complexity, and improving resolution. ○ A multi-initialization strategy ensures global convergence of the algorithm. • **Challenges and Future Directions:** ○ While the IB method is validated through numerical simulations, real-world applications in field systems with more complex topologies require further investigation. • Exploring extensions to branched or looped networks and validating the framework with experimental data are logical next steps.
100. Keramat, Wang et al. (2019) ITM Domain: Time Title: Objective Functions for Transient-Based Pipeline Leakage Detection in a Noisy Environment: Least Square and Matched-Filter	Analysis Approach: Hydraulic Modeling Analysis Technique: ITA Response Type: Impulse Response Optimization Technique: Least-Square (LS) and Matched-Filter (MF) Friction Model: Steady-state Viscoelasticity: N/A Noise: Measurement noise explicitly analyzed; signal-to-noise ratio (SNR) considerations included	Network/Pipeline: Pipeline Case Study: Numerical simulations and experimental validation Leak Unknowns: Location and size NO. Measurement Points: Single Validation: Numerical and experimental validation	This paper investigates the effectiveness of two objective functions, Least-Square (LS) and Matched-Filter (MF), for transient-based leak detection under noisy conditions. The study focuses on improving the robustness and accuracy of leak localization by addressing the influence of noise on parameter estimation. **Key Findings:** • **Methodology:** ○ The LS objective function minimizes the L2 norm between modeled and measured pressure signals, commonly used for leak detection. ○ The MF objective function, designed to maximize the signal-to-noise ratio (SNR), is proposed as an alternative for environments with high noise levels (SNR ≤ 3 dB). • **Results:** ○ In high-noise scenarios (low SNR), MF consistently outperforms LS by reducing

			mean square error (MSE) in leak localization. ○ In low-noise scenarios (high SNR), both estimators provide similar results, converging to the same leak location and size estimates. ○ Numerical and experimental case studies support the robustness of the MF function in accurately localizing leaks under challenging noise conditions. • **Future Directions:** ○ Exploration of MF in larger and more complex pipeline systems with diverse noise sources. ○ Integration with adaptive filtering techniques to further enhance robustness. • Field studies to validate the practical applicability of the MF approach.
101. Bohorquez, Alexander et al. (2020) SRM Domain: Time Title: Leak Detection and Topology Identification in Pipelines Using Fluid Transients and Artificial Neural Networks	Analysis Approach: Hydraulic Modeling and AI-Enhanced Analysis Technique: Machine Learning (Artificial Neural Network - ANN), 1D Convolutional Network Response Type: Impulse Response Optimization Technique: N/A (as ANN is used for prediction, not optimization) Friction Model: Not explicitly mentioned; assumed N/A Viscoelasticity: Not mentioned; assumed N/A Noise: Robust to noise, ANN retrainable on real noisy data	Network/Pipeline: Pipeline Case Study: Numerical system (hypothetical) Leak Unknowns: Location, size NO. of Measurement Points: Single Validation: Numerical	This paper introduces a novel technique combining fluid transient pressure wave analysis and artificial neural networks (ANNs) for pipeline condition assessment, including topology identification and leak detection. The key aspects and findings are summarized as follows: • **Methodology:** ○ Transient pressure wave data, generated using MOC, are used to train ANNs for predicting junctions and leaks. ○ The ANNs learn directly from transient head traces without requiring prior hydraulic models during testing, making the approach data-driven. ○ Two ANN architectures (dense and 1D convolutional networks) are tested, with the 1D convolutional network showing superior performance. • **Accuracy and Results:** ○ Junction identification: ▪ 95% of cases predicted the junction location with an error < 2.32 m.

			▪ Perfect accuracy in predicting pipe diameters around junctions in 5,000 test cases. o Leak detection: ▪ 95% of cases located leaks with an error < 3.0 m. ▪ Leak size predicted with an average absolute error of 0.03 mm. • **Advantages:** o Fast and accurate, requiring only transient head trace data for testing. o No need for a hydraulic model or system knowledge during testing. o Highly amenable to retraining with real-world data, robust to noise. • **Challenges and Future Work:** o Application to more complex pipeline systems is required to address challenges from background noise, subtle anomalies, and deteriorating pipeline conditions. o Further validation with laboratory and field data is needed to benchmark against existing methods. • Expanding the approach to varied hydraulic system configurations and dimensions is suggested.
102. Wang, Waqar et al. (2020) SRM Domain: Frequency Title: Pipeline leak localization using matched-field processing incorporating prior information of modeling error	Analysis Approach: Hydraulic Modeling and Signal Processing Analysis Technique: Matched-Field Processing (MFP) Response Type: Impulse Response Optimization Technique: Maximum Signal-to-Noise Ratio Optimization Friction Model: Not explicitly mentioned; likely assumes standard steady-state models Viscoelasticity: K-V model Noise: Modeled as Gaussian random error combined with modeling error	Network/Pipeline: Pipeline Case Study: Experimental system Leak Unknowns: Location NO. Measurement Points: Single Validation: Experimental	This study extends the traditional matched-field processing (MFP) method for pipeline leak detection by incorporating modeling errors alongside random errors. Key aspects and findings of the study are summarized as follows: • **Methodology:** o A novel MFP technique with uncertainty information (MFP-UI) is developed, incorporating both random and modeling errors in leak detection. o Modeling errors are estimated from a prior transient test conducted when the pipeline is assumed to be defect-free, based on the observation that these errors remain consistent regardless of the presence of a leak.

			○ The technique maximizes the signal-to-noise ratio by combining baseline and current signals for leak localization. • **Applications:** ○ The method is tested experimentally in three scenarios with varying levels of modeling error complexity, demonstrating its robustness. • **Key Results:** ○ MFP-UI provides more accurate and reliable leak localization compared to traditional MFP methods. ○ The use of baseline transient data significantly enhances the accuracy of leakage detection by accounting for epistemic uncertainties. • **Advantages:** ○ Addresses both random and modeling errors, offering a more realistic and robust leak detection framework. ○ Validated through experimental setups, ensuring practical applicability. ○ The approach encourages routine transient tests to establish reliable baseline data. • **Challenges and Future Work:** ○ The methodology needs to be extended to more complex real-life pipe networks and tested under diverse field conditions. • Additional studies are required to validate the invariance of modeling errors in a wider range of pipeline systems.
103. Amini, Jing et al. (2020) SRM Domain: Time Title: A Two-Stage Deep-Learning Based Detection Method for Pipeline Leakage and Transient Conditions	Analysis Approach: AI-Enhanced Analysis Technique: Artificial Neural Networks (ANN) for classification of leakage and transient conditions Response Type: System response (pressure and flow difference as system responses to leakage and transient conditions) Optimization Technique: Hyperbolic-tangent estimator (for feature normalization)	Network/Pipeline: Pipeline Case Study: Industrial system (offline mode, industrial dataset) Leak Unknowns: Location and size (detected via feature vectors) NO. Measurement Points: Multiple points (pressure and flow difference) Validation: Experimental (offline mode)	This paper proposes a two-stage leak detection method using machine learning (ANN) to classify pipeline conditions (normal, leakage, and transient). Feature vectors derived from pressure and flow differences are used to train the model, which differentiates between abnormal conditions and detects leaks in the pipeline system. The second stage uses a simple logic approach to distinguish leakage from transient conditions and triggers alarms based on leak size tolerance. **Key Findings:**

	Friction Model: N/A (not explicitly modeled)
	Viscoelasticity: N/A (pipe material properties not considered)
	Noise: N/A (focus on feature extraction and classification)
			• **Two-Stage Detection:**
			  ○ **Stage 1 (ANN Classification):** Differentiates normal and abnormal conditions based on feature vectors derived from pressure and flow differences.
			  ○ **Stage 2 (Logic-Based Detection):** Distinguishes leakage from transient conditions using time-window analysis.
			  ○ **Leak-Size Tolerance:** Provides a method for triggering alarms based on predefined leak size tolerance, reducing false alarms.
			• **Performance:**
			  ○ The ANN model outperformed other machine learning models in terms of detection accuracy, achieving the highest **F1 score**.
			  ○ With increased leak-size tolerance, the method achieved **86.75% detection rate (DR)** without any false alarms.
			  ○ **Comparison to Existing Methods:** Demonstrated superior performance compared to the line balance and Kantorovich distance methods, with fewer false positives and higher accuracy.
			• **Efficiency and Robustness:**
			  ○ The method's efficiency was validated using an industrial dataset, showing its effectiveness in real-world applications.
			  ○ By focusing on leak signatures and using deep learning, the system significantly reduced false alarms while maintaining a high detection rate.
			• **Conclusion and Future Work:**
			  ○ The two-stage deep learning-based method proves to be more efficient and accurate compared to traditional methods.
			
			• Future work could explore real-time implementation and further fine-tuning for varying leak sizes and network configurations.

104. Liao, Yan et al. (2021) SRM Domain: Frequency Title: Deep learning identifies leak in water pipeline system using transient frequency response	Analysis Approach: Hydraulic Modeling and AI-Enhanced Analysis Technique: Matrix Form Transient Frequency Response (TFR) with Deep Learning; comparison with Method of Characteristics (MOC) for verification Response Type: Frequency Response Optimization Technique: Not applied; DL replaces traditional optimization methods like GA Friction Model: Unsteady-State (specific model not mentioned; uncertainties in friction coefficient considered) Viscoelasticity: N/A Noise: Not directly applied; robustness tested against hydraulic uncertainties like wave speed and friction	Network/Pipeline: Network Case Study: Hypothetical Leak Unknowns: Location and size NO. Measurement Points: Multiple Validation: Numerical	• **Objective**: The paper introduces a novel approach combining Transient Frequency Response (TFR) with Deep Learning (DL) for leak detection in water pipeline systems. This approach aims to overcome limitations in handling hydraulic uncertainties by leveraging a DL framework. • **Methodology**: • Developed extended TFR equations in matrix form for generating a training dataset, which allows for efficient DL model training. • Utilized a fully linear DenseNet (FL-DenseNet) architecture to identify leak locations by training on simulated Frequency Response Functions (FRFs) generated from a pre-calibrated hydraulic model. • Applied the trained FL-DenseNet model to measured FRFs for leak identification in a hypothetical pipeline system. • **Findings**: • **Efficiency of Extended TFR Equations**: Extended TFR equations in matrix form provided similar results to MOC but with enhanced computational efficiency, facilitating intensive data generation for DL training. • **Robustness Against Parameter Uncertainty**: FL-DenseNet demonstrated robustness to variations in parameters like wave speed and friction coefficient, though prediction accuracy decreased with higher uncertainty levels. • **Leak Size Sensitivity**: The framework was effective at detecting leaks as small as 1–1.5 L/s, though smaller leaks presented more subtle changes in the FRF, challenging detection. • **Performance Comparison**: The DL-based approach significantly outperformed traditional GA-based methods, especially when inaccuracies existed in the hydraulic model. • **Limitations**: • **Multiple Leak Scenarios**: The study only considers single-leak scenarios, though multiple leaks are common in real systems. • **Measurement Errors**: Measurement inaccuracies in transient signals are not considered, potentially impacting real-world application.

			• **Leak Location Precision**: While FL-DenseNet successfully identifies the general leak location, it does not pinpoint the exact location as precisely as optimization algorithms like GA. • **Future Directions**: • Improving DL techniques for fine-grained leak detection. • Extending the framework to handle multiple leaks and incorporate measurement errors in transient signals. •
105. Rezapour, Shafai Bejestan et al. (2021) ITM Domain: Time Title: Case study of leak detection based on Gaussian function in experimental viscoelastic water pipeline	Analysis approach: Hydraulic Modeling Analysis technique: MOC with viscoelastic effects and unsteady friction modeling Response Type: Impulse Response Optimization Technique: ITA Friction model: Unsteady-State (viscoelastic model accounting for pipe wall creep effects) Viscoelasticity: Linear Kelvin-Voigt (K-V) model Noise: Sensitivity to noise evaluated using experimental data	Network/Pipeline: Pipeline Case Study: Experimental system Leak Unknowns: Location and Size NO. Measurement Points: Single Validation: Numerical and Experimental	This study provides an enhanced ITA framework for transient-based leak detection in viscoelastic water pipelines. The methodology incorporates key features, including dynamic parameters, flow regimes, and spatial-step increments. Below are the summarized findings: • **Hydraulic Transient Solver (HTS):** o Developed to model dynamic effects of unsteady friction, viscoelasticity, and leaks. o Includes quasi-normal distribution for leakage characterization, reducing computational overhead and dimensionality. • **Leak Detection Performance:** o Successfully identified the location and size of leaks in polyethylene transmission pipelines. o Achieved accurate calibration for viscoelastic and creep effects, while unsteady friction effects were deemed negligible. • **Sample Size and Spatial Step Sensitivity:**

			○ Found that a sample size equivalent to half a period of the pressure signal is sufficient for location detection. ○ Leak size estimation requires only one full period of transient pressure data. ○ Optimal spatial-step-to-pipe-length ratio determined between 0.019 and 0.032. • **Multi-Leak Detection:** ○ Validated ITA's ability to detect multiple leaks simultaneously when multiple leak and creep functions are calibrated. • **Noise Tolerance:** • The approach demonstrated resilience to noise when applied to experimental data, affirming its robustness for real-world conditions.
106. Keramat and Duan (2021) SRM Domain: Frequency Title: Spectral based pipeline leak detection using a single spatial measurement leakage detection in reservoir pipeline valve systems	Analysis approach: Hydraulic Modeling and Signal Processing Analysis technique: Transfer Matrix Method Response Type: Frequency Response Optimization Technique: Matched Field Processing (MFP), Multidimensional Optimizations Friction model: Steady-State Viscoelasticity: N/A Noise: Accounted for by evaluating robustness to varying noise levels and using mean signal processing to reduce variance.	Network/Pipeline: Pipeline Case Study: Laboratory and Numerical systems Leak Unknowns: Location and Number NO. Measurement Points: Single (optional additional measurements for higher accuracy) Validation: Numerical and Experimental	This research enhances spectral-based leak detection methods by reformulating the Matched Field Processing (MFP) approach to enable single spatial measurement for leak localization. The study explores numerical and experimental verifications of the method, comparing its robustness and accuracy against conventional approaches. • **Innovative Methodology:** ○ Reformulates MFP to require only a single pressure spectrum measurement, reducing the dependency on multiple sensors. ○ Employs transfer matrix formulations to integrate data into the objective function for effective leak identification. • **Comparison with Conventional Methods:**

			○ Both old and new methods are robust for single-leak localization, but the new method suppresses side lobes more effectively, improving performance under high noise levels or multiple leaks. ○ Numerical and theoretical analyses demonstrate that the new merit function offers smoother behavior and reduced variance, ensuring greater stability. • **Performance Evaluation:** ○ Numerical simulations show superior robustness of the new method under extreme noise conditions. ○ Experimental verifications confirm its reliability, providing accurate leak localization even in laboratory setups with noisy signals. • **Multiple Leak Identification:** ○ The proposed method shows promise for extending to multi-leak scenarios using single-measurement models. • For higher accuracy, multiple transient tests at a single location or additional sensors can be employed, with the mean signal reducing measurement variance.
107. Pan, Duan et al. (2021) SRM Domain: Frequency Title: FRF-based transient wave analysis for the viscoelastic parameters identification and leak detection in water-filled plastic pipes	Analysis Approach: Hydraulic Modeling and Signal Processing Analysis Technique: Frequency Response Function (FRF) Response Type: Frequency Response Optimization Technique: N/A Friction Model: Unsteady state Viscoelasticity: Linear Kelvin-Voigt (K-V) model Noise: Not explicitly discussed but validated with laboratory experiments under varying conditions	Network/Pipeline: Pipeline Case Study: Laboratory experimental system with plastic pipes Leak Unknowns: Location and Size NO. Measurement Points: Single Validation: Numerical and Experimental	This research proposes an innovative **FRF-based transient wave analysis method (TWAM)** for leak detection in viscoelastic water-filled plastic pipes. Key findings and contributions include: • **Methodology and Innovation:** ○ Derives an analytical expression for FRF to characterize the interaction of

			transients with pipe-wall viscoelasticity and leaks. ○ Implements a two-step procedure for viscoelastic parameter identification and leak detection using FRF-based TWAM. • **Validation and Results:** ○ Validated through extensive laboratory experiments and numerical tests, confirming high accuracy and feasibility for practical applications. ○ Demonstrates improved accuracy in locating leaks compared to sizing leaks, consistent with findings in elastic pipes. • **Influence of Key Factors:** ○ Investigates the impact of initial flow conditions, leak information, and viscoelastic parameters on transient responses and leak detection accuracy. ○ Explores the validity range of input wave signal bandwidth, identifying preferable delayed time spans (DTS) for effective application. • **Performance and Practical Implications:** ○ Achieves overall accuracy of less than 10% error for leak detection across all tests, suitable for practical applications. ○ Highlights limitations, including the need for further validation in more complex systems and exploration of larger DTS ranges.

			• **Future Recommendations:** ○ Suggests additional studies to refine the validity and applicability of FRF-based TWAM for complex networks. • Recommends examining DTS characteristics further and extending research to multi-point measurement systems for enhanced accuracy.

108. Lin, Wang et al. (2021)
SRM
Domain: Time
Title: Multi-Sensor Fusion for Transient-Based Pipeline Leak Localization in the Dempster-Shafer Evidence Framework
	Analysis Approach: Signal Processing
	Analysis Technique: Multi-sensor fusion, Dempster-Shafer Evidence Framework
	Response Type: Impulse Response
	Optimization Technique: N/A (model-free)
	Friction Model: N/A
	Viscoelasticity: N/A
	Noise: Addresses noise explicitly using evidence fusion to improve detection in noisy environments
		Network/Pipeline: Pipeline
		Case Study: Laboratory experimental system
		Leak Unknowns: Location
		NO. Measurement Points: Multiple (multi-sensor approach)
		Validation: Numerical and experimental
			This study proposes a multi-sensor fusion method for transient-based pipeline leak localization, leveraging the Dempster-Shafer evidence framework to address the challenges of detecting leaks in noisy environments. Key contributions and findings include:
			• **Proposed Methodology:**
			  ○ Developed a model-free, multi-sensor fusion framework for leak localization using transient wave signals.
			  ○ Used Dempster-Shafer evidence theory to combine measurements from multiple sensors, enhancing the accuracy of leak detection and localization.
			• **Numerical and Experimental Validation:**
			  ○ Demonstrated the method's effectiveness through numerical simulations and laboratory experiments, showing significant improvements over traditional single-sensor methods.
			  ○ Successfully localized small leaks hidden under strong noise, which would be undetectable with conventional techniques.
			• **Advantages and Contributions:**
			  ○ Model-free nature makes the method robust to uncertainties in system modeling.
			  ○ Multi-sensor fusion significantly increases leak localization accuracy in noisy environments.
			• **Limitations and Future Work:**
			  ○ Method is validated only in a controlled laboratory setup; real urban water supply

			systems with more complex noise and uncertainty remain to be tested. • Future studies could focus on scaling the method for larger, more complex networks and real-world applications.
109. Waqar, Louati et al. (2021) SRM Domain: Time Title: Model-Free Matched Field Processing for Condition Assessment of Pressurized Pipe	Analysis Approach: Signal Processing Analysis Technique: Matched-Field Processing (Data-to-Data) Response Type: Impulse Response Optimization Technique: N/A (model-free approach) Friction Model: N/A Viscoelasticity: N/A Noise: Accounts for real-world uncertainties but specifics not explicitly addressed	Network/Pipeline: Pipeline and Network Case Study: Laboratory, field-scale pipeline, and real-field distribution system Leak Unknowns: Location NO. Measurement Points: Single or multiple, depending on test setup Validation: Experimental (laboratory and field tests)	This study proposes a **model-free Matched-Field Processing (MFP-DD)** method for defect localization in pressurized freshwater pipe systems, relying solely on measured data rather than hydraulic models. Key contributions and findings include: • **Proposed Methodology:** o Introduces a novel MFP-DD technique that correlates reference transient responses with recent transient signals to localize defects. o Eliminates the dependency on transient models, requiring only repeatable transient tests and topological information of the system. • **Validation and Testing:** o Successfully validated through laboratory experiments, field-scale tests on transmission-like pipelines, and real-world distribution systems in Hong Kong. o Demonstrated its robustness by identifying a simulated leak and, unexpectedly, detecting an unknown modification made by water authority officers during blind testing. • **Advantages and Contributions:** o Robust to incomplete system information, making it suitable for real-world applications where data may be lacking or unreliable. o Offers a straightforward and practical approach for condition assessment and leak localization. • **Limitations and Future Directions:** o The method relies on the availability of a baseline reference transient response,

			which may not always be feasible in older systems. • Future work could focus on integrating noise mitigation techniques and scaling the approach for more complex networks with multiple leaks.
110. Wang (2021) ITM Domain: Frequency Title: Uniformly optimal multi-sensor design in pipe networks for transient-based leakage localization	Analysis Approach: Hydraulic Modeling Analysis Technique: Quasi-Monte-Carlo Simulation Response Type: Impulse Response Optimization Technique: CRLB-based Optimization Friction Model: Steady state Viscoelasticity: N/A Noise: Modeled as Gaussian-distributed random error	Network/Pipeline: Pipeline and Network Case Study: Hypothetical system Leak Unknowns: Location NO. Measurement Points: Multiple Validation: Numerical	This study focuses on developing a robust methodology for optimal sensor placement in pipe networks to enhance transient-based leakage localization. The methodology leverages the Fisher information matrix and Cramér–Rao lower bound (CRLB) to optimize sensor placement, ensuring accurate and reliable leak detection. The key aspects of the work are summarized below: • **Methodology:** o The CRLB is used to quantify the lower limit of leak localization error, guiding the optimal placement of sensors. o A probabilistic framework is introduced to model leak randomness across the pipe network, ensuring that all potential leak scenarios are considered. o The proposed method employs quasi-Monte-Carlo simulations to compute the expectation of the CRLB for various sensor configurations, optimizing their distribution to minimize the CRLB. • **Applications:** o The methodology is demonstrated through examples ranging from a single-pipe system to a complex pipe network, highlighting its scalability and effectiveness. • **Key Results:** o The sensor placement strategy ensures uniformly optimal performance across all potential leak scenarios. o The proposed framework efficiently addresses uncertainties in leak locations and minimizes the expected leak localization error. • **Advantages:**

			○ Provides a systematic approach to sensor placement that is robust across diverse pipe network configurations. ○ Utilizes probabilistic modeling to handle randomness in leak locations effectively. ○ Scalable methodology applicable to both simple and complex pipe systems. • **Challenges and Future Work:** ○ Real-world uncertainties, such as parameter mismatches and measurement errors, need to be better quantified and modeled. • Future research should incorporate stochastic characteristics of system parameters and generalize the sensor placement methodology for real-life pipe networks.
111. Choura, Capponi et al. (2021) ITM Domain: Time Title: A Nelder–Mead algorithm-based inverse transient analysis for leak detection and sizing in a single pipe	Analysis Approach: Hydraulic Modeling Analysis Technique: ITA Response Type: Impulse Response Optimization Technique: Nelder–Mead algorithm Friction Model: Unsteady-State Friction (specific decay coefficient calibrated) Viscoelasticity: Generalized Kelvin–Voigt (KV) model (five elements) Noise: N/A (not explicitly discussed, but experimental data are used, so noise could be inherent in measurements)	Network/Pipeline: Single pipeline Case Study: Experimental system (HDPE pipe at the University of Perugia, Italy) Leak Unknowns: Location and size NO. Measurement Points: Six measurement sections Validation: Experimental validation	This paper presents an **ITA-based methodology** for leak detection and sizing in HDPE pipes. The method uses the Nelder–Mead algorithm to minimize the objective function, aligning numerical simulations with experimental pressure data. The pipe's viscoelastic behavior and unsteady-state friction are calibrated before leak detection. **Key Findings:** • **Methodology:** ○ A five-element generalized Kelvin–Voigt model characterizes pipe-wall viscoelasticity. ○ Unsteady-state friction coefficients and viscoelastic parameters are calibrated using pressure signals from six measurement points. ○ Leak location and size are determined using the calibrated model and experimental pressure data from a leaky pipe. • **Results:** ○ **Leak Location:** Achieved with high accuracy, with relative errors smaller than 5%.

			○ **Leak Size:** Performance was less accurate, highlighting challenges in pressure signal interpretation for leak sizing. ○ The accuracy of the method depends on the initial guesses, sample period length, and characteristics of the measurement sections. • **Challenges and Insights:** ○ The ambiguity of pressure signal features and material properties may affect leak sizing accuracy. ○ Leak location estimation is robust due to reliance on pressure wave travel time, which is easier to detect accurately. • **Future Work:** ○ Further numerical and experimental tests to improve leak sizing accuracy. • Investigation of pressure signal features and material properties' role in ITA performance.
112. Wang (2022) ITM Domain: Frequency Title: Fast computation of inverse transient analysis for pipeline condition assessment via surrogate modeling with sparse sampling strategy	Analysis Approach: Hydraulic Modeling Analysis Technique: Impedance Matrix Response Type: Frequency Response Optimization Technique: Sequential Leak Detection Algorithm (Single and Dual Path Algorithms) Friction Model: Not explicitly mentioned; assumed steady-state friction for numerical modeling Viscoelasticity: Not incorporated or mentioned Noise: Not explicitly mentioned but highlighted as a future consideration for real-world applicability	Network/Pipeline: Network Case Study: Hypothetical system Leak Unknowns: Location and number NO. Measurement Points: Single Validation: Numerical	This study proposes a robust framework for detecting multiple leaks in pipe network systems, leveraging transient pressure wave analysis. The highlights and findings of the study are summarized below: • **Methodology:** ○ A **mathematical formulation** for modeling multiple leaks in pipe networks is proposed, improving model parsimony and complexity. ○ A **leakage decomposition scheme** isolates individual leak signals from transient pressure responses, enabling robust leak identification and analysis of interactions between leaks. ○ A **sequential leak detection algorithm**: ▪ **Single Path Algorithm**: Based on time-domain reflectometry, it identifies leaks along a single pathway. ▪ **Dual Path Algorithm**: Considers multiple pressure

			pathways to handle interactions and interference between leaks. • **Applications:** o Demonstrated on a heterogeneous hypothetical pipe network system with multiple leaks. o Highlights the applicability for systems with nonlinear interactions between leaks and complex network structures. • **Key Results:** o The proposed methods efficiently identify multiple leaks while addressing challenges of signal interference. o Quantitative analysis of leak interactions enhances robustness in detection. o The decomposition and sequential algorithms are validated to provide accurate leakage information for multiple leaks. • **Advantages:** o Provides flexibility for multiple leak representation in complex network systems. o Reduces model complexity while maintaining high accuracy in leak detection. o Combines single and dual path algorithms for comprehensive analysis. • **Challenges and Future Work:** o Incorporating more general pipeline structures, including air valves and surge protection devices. o Addressing uncertainties such as unknown pipeline components or air bubbles. Introducing more flexible and less disruptive transient wave generation methods to comply with pipeline management constraints.
113. Pan, Duan et al. (2022) SRM Domain: Time	Analysis approach: Hydraulic Modeling Analysis technique: MOC	Network/Pipeline: Network (Tree-shaped structure)	This paper extends the forward-backward transient analysis method to tree-shaped pipe networks for leak and burst

Title: Efficient Pipe Burst Detection in Tree-Shape Water Distribution Networks Using Forward-Backward Transient Analysis	Response Type: Impulse Response Optimization Technique: N/A (This method avoids optimization and directly calculates defect locations.) Friction model: Steady-state Viscoelasticity: N/A Noise: N/A	Case Study: Experimental system and hypothetical system Leak Unknowns: Location NO. Measurement Points: Single Validation: Numerical and experimental	detection. The method leverages differences in transient wave arrival times between intact and defective pipes to localize faults. Below is a concise summary: • **Principle:** Utilizes mass conservation and energy relationships at junctions to propagate forward and backward transient analysis through a network. • **Framework:** Develops a systematic approach for burst detection without relying on optimization procedures. • **Efficiency:** Directly calculates defect locations, bypassing traditional least-squares-based optimization methods. • **Validation:** Experimental and numerical tests confirm the method's robustness and practicality. • **Advantages:** o Effective for both online monitoring and offline identification. o Reduces reliance on measured flow rate data. o Demonstrates robustness over classical wave reflection methods by integrating all collected transient data systematically. • **Application:** Shows potential for practical implementation in tree-structured water distribution systems. • **Future Scope:** Discusses combining the proposed method with other approaches for enhanced applicability.
114. Keramat, Duan et al. (2022) ITM Domain: Frequency Title: Gradient-based optimization for spectral-based multiple-leak identification	Analysis approach: Hydraulic Modeling and Signal Processing Analysis technique: Frequency Response Response Type: Frequency Response Optimization Technique: Gradient-Based Optimization with Closed-Form Gradient Computations (Steepest Descent Method) Friction model: Steady-State Viscoelasticity: Linear Kelvin-Voigt (K-V) model Noise: N/A	Network/Pipeline: Pipeline Case Study: Experimental system Leak Unknowns: Location and Number NO. Measurement Points: Single Validation: Numerical and Experimental	This paper develops an efficient gradient-based optimization framework for multiple-leak detection in the frequency domain using transient data. The method emphasizes **accuracy, efficiency, and versatility**, leveraging closed-form gradient formulations and a steepest descent optimization approach. Key findings include: • **Gradient Formulation:** o Novel closed-form expressions are derived for evaluating gradient vectors, significantly reducing computational overhead.

			○ The steepest descent method with multiple initializations iteratively converges toward global extrema with enhanced accuracy. • **Handling Local Extrema:** ○ The study highlights the challenge of numerous local extrema in multi-dimensional optimization for multiple leaks, particularly as the number of leaks increases. ○ A multiple initialization algorithm based on leak-sensitive locations ensures capturing all local extrema to approximate the global maximum. • **Efficiency and Robustness:** ○ The method drastically reduces the need for exhaustive domain enumeration and calls to forward models. ○ For single and two-leak cases, the method consistently identified the global maximum with fewer iterations. ○ For three-leak cases, the presence of multiple local extrema near the global maximum necessitated additional harmonic waves for precise localization. • **Experimental Validation:** ○ Application to a laboratory system demonstrated performance beyond the super-resolution limit for two leaks using a single measurement station. ○ The accuracy in single-leak cases was notably higher than in multi-leak scenarios, highlighting areas for

			improvement in transient modeling and parameter calibration.
			
			• **Future Research Directions:**
			  o Exploring the minimum number of monitoring stations required for specific accuracy levels.
			  o Optimizing sensor placement and their numbers for improved localization precision.
			
			• Extending the methodology to integrate metaheuristic algorithms for escaping local extrema and achieving global optimization.

115. Kim (2022)
SRM
Domain: Time
Title: Time-domain impedance method for transient analysis and leakage detection in reservoir pipeline valve systems
	Analysis approach: Hydraulic Modeling
	Analysis technique: Time-domain Impedance Function (TIF)
	Response Type: Impulse Response
	Optimization Technique: Particle Swarm Optimization (PSO)
	Friction model: Steady-State (exponential-based formulation for laminar and turbulent flows)
	Viscoelasticity: Linear Kelvin-Voigt (K-V) model
	Noise: Not explicitly discussed
		Network/Pipeline: Pipeline
		Case Study: Numerical and Experimental systems
		Leak Unknowns: Location
		NO. Measurement Points: Single
		Validation: Numerical and Experimental
			This study introduces an alternative approach to transient analysis and leakage detection in reservoir pipeline valve (RPV) systems using the time-domain impedance function (TIF). The methodology integrates mathematical modeling, transient response analysis, and optimization for robust leak detection.
			
			• **Mathematical Development:**
			  o Derived exponential-function-based impedance formulations for flow regimes and leak conditions in RPV systems.
			  o TIF introduced for transient response simulation under various valve maneuvers and flowrates.
			
			• **Leak Detection Scheme:**
			  o The leakage-identified impedance function (LIIF) enhances detection accuracy by isolating transient impacts without requiring an intact benchmark.

			○ Can predict leak location using pressure head measurements with or without an intact benchmark. • **Integration of PSO:** ○ Particle Swarm Optimization (PSO) integrated into the inverse TIF algorithm for robust leak detection across a wide range of surge amplitudes. • **Advantages of the Method:** ○ Simulates transient responses without the need for full mathematical modeling. ○ Mitigates excessive pressure problems common in transient-based methods. ○ Demonstrates potential for both water hammer simulation and leakage detection. • **Validation Results:** ○ Numerical and experimental validations show successful application of the method in simple pipeline systems. • Demonstrates robustness in predicting leak locations under varying flow and system conditions.
116. Pan, Capponi et al. (2022) ITM Domain: Frequency Title: Efficient leak detection in single and branched polymeric pipeline systems by transient wave analysis	Analysis Approach: Hydraulic Modeling Analysis Technique: Transfer Matrix Method (TMM) Response Type: Frequency Response Optimization Technique: Global Optimized Nonlinear Curve Fitting Friction Model: Unsteady-State Viscoelasticity: Linear Kelvin–Voigt (K–V) model Noise: Not explicitly mentioned; assumed negligible in experiments	Network/Pipeline: Pipeline Case Study: Experimental system and numerical simulations Leak Unknowns: Location, size, and system viscoelastic parameters NO. Measurement Points: Single Validation: Numerical and Experimental	This study introduces a **frequency domain inverse transient analysis (FDITA)** framework for the simultaneous identification of viscoelastic parameters and leaks in viscoelastic pipelines. The developed method extends transient-based leak detection to both single and branched polymeric pipe systems. Key findings are summarized as follows: • **Innovative Approach:**

			○ The FDITA method integrates transient frequency responses to identify viscoelastic properties and leaks in a one-step procedure. ○ Analytical solutions derived using the Transfer Matrix Method enable efficient representation of transient responses in viscoelastic pipelines with leaks. • **Validation and Applicability:** ○ The method was validated through extensive experimental tests in laboratory settings and numerical simulations, demonstrating high accuracy and efficiency. ○ A sensitivity analysis showed the impact of wave reflections, leak size, and viscoelasticity on detection accuracy. • **Mechanism Insights:** ○ The interaction between transient waves, leaks, and viscoelasticity was analyzed, revealing that clear wave reflection patterns are critical for accurate leak localization. ○ The methodology is particularly suitable for systems where leaks induce significant wave reflections, such as rigid polymeric pipelines. • **Limitations:** ○ Simultaneous identification of viscoelasticity and leak parameters may suffer from accuracy issues when one factor dominates the system response.

			○ The study was limited to relatively simple systems with single-point measurements, highlighting the need for validation in more complex network scenarios. • **Future Directions:** ○ The proposed method should be extended to more complex pipeline systems, including looped or branched networks. • Incorporating multi-point measurements could enhance the precision of simultaneous parameter and leak identification.
117. Che, Wang et al. (2022) ITM Domain: Frequency Title: Leak Localization in Looped Pipe Networks Based on a Factorized Transient Wave Model: 2. Regularization of Ill-Conditioned Problems	Analysis Approach: Hydraulic Modeling Analysis Technique: Matched Field Processing (MFP) Response Type: Frequency Response Optimization Technique: Regularization of ill-conditioned problems through theoretical upper bounds of noise-induced errors (non-conventional optimization) Friction Model: Steady-State (assumed in hydraulic modeling) Viscoelasticity: N/A Noise: Handled by discarding wave information at ill-conditioned frequencies	Network/Pipeline: Network (looped networks with dynamic boundaries) Case Study: Hypothetical system (numerical simulations) Leak Unknowns: Location NO. Measurement Points: Multiple Validation: Numerical	This study addresses the challenges of applying transient-based methods to looped pipe networks with ill-conditioned inverse problems and noisy environments. Key findings are summarized as follows: • **Innovative Framework:** ○ The study provides an alternative to Tikhonov regularization by deriving theoretical upper bounds for noise-induced errors to identify ill-conditioned frequencies. ○ An efficient algorithm is developed to discard wave information at ill-conditioned frequencies, enhancing robustness in noisy environments. • **Numerical Validation:** ○ Numerical experiments confirm the ability to localize a single leak anywhere in a looped network with high accuracy. ○ The proposed method remains effective even in the presence of significant noise,

			addressing practical challenges in real-world applications.
			
			• **Limitations:**
			  ○ The method performs best in relatively small, controllable looped networks, as higher complexities result in more ill-conditioned frequencies.
			  ○ The approach currently considers only single-leak scenarios; extending it to multiple leaks remains an important research direction.
			
			• **Future Directions:**
			  ○ The framework could be enhanced by dividing large networks into sub-looped networks using isolating valves or dynamic boundaries for better applicability.
			
			• Further research should focus on improving the accuracy of inverse computations and generalizing the approach to scenarios involving multiple leaks.

118. Wang (2022) ITM Domain: Time Title: Pipeline leakage alarm via bootstrap-based hypothesis testing	Analysis Approach: Hydraulic Modeling and Statistical Signal Processing Analysis Technique: Hypothesis Testing and Bootstrap Method Response Type: N/A (Focus on statistical analysis rather than response characteristics) Optimization Technique: N/A Friction Model: Steady-state friction model assumed Viscoelasticity: N/A Noise: Handled using a combination of baseline signal and bootstrap method to account for aleatoric and epistemic uncertainties	Network/Pipeline: Pipeline Case Study: Experimental system Leak Unknowns: Location and Size NO. Measurement Points: Single Validation: Experimental	This study introduces a novel hypothesis testing framework to address the limitations of traditional transient-based methods for pipeline leak detection. Key aspects and findings are summarized as follows: • **Methodology and Innovation:** ○ Proposes a statistical hypothesis testing framework to determine the probability of the existence of a leak, accounting for uncertainties in transient measurements.

			○ Employs the bootstrap method to handle aleatoric uncertainties from limited transient data. ○ Epistemic uncertainties are modeled using a baseline signal obtained from the same pipeline under no-leak conditions. • **Key Features:** ○ Constructs the distribution of leakage features under the null hypothesis (no-leak case) to compare against real-time transient data. ○ Provides a probabilistic measure of leak existence, distinguishing between real leaks and noise-induced fictitious leaks. • **Experimental Validation:** ○ Validated on a single-pipe laboratory test rig, demonstrating the capability to accurately distinguish between no-leak and small-leak cases. ○ Achieves reliable results with minimal real-time measurements and one pre-leak baseline signal. • **Advantages and Limitations:** ○ Advantages: ▪ Accurately distinguishes real leaks from fictitious ones caused by noise or uncertainties. ▪ Requires only a limited number of real-time measurements.

			○ Limitations: ▪ Validated only on a simple pipeline system; its generalization to urban water supply systems with complex structures and uncontrolled uncertainties remains untested. • **Future Directions:** ○ Expand the method to more complex systems, such as branched or looped networks. • Investigate the impact of uncontrolled uncertainties and optimize the hypothesis testing framework for real-world applications.
119. Zhang, Duan et al. (2022) TRM Domain: Frequency Title: On the leak-induced transient wave reflection and dominance analysis in water pipelines	Analysis Approach: Hydraulic Modeling and Signal Processing Analysis Technique: Transient Wave Reflection Method (TWRM), MOC-based numerical analysis, Dimensional Analysis Response Type: Reflection Coefficient (Frequency Response) Optimization Technique: Nonlinear Multiple Regression Friction Model: Unsteady Viscoelasticity: N/A Noise: Not explicitly mentioned	Network/Pipeline: Pipeline Case Study: Laboratory experiments and numerical validations Leak Unknowns: Location, Size NO. Measurement Points: Single Validation: Numerical (MOC-based simulations) and Laboratory Experimental	This study investigates the leak-induced transient wave reflections in rigid pipelines and provides an analytical framework for deriving reflection coefficients. Key contributions and findings include: • **Analytical Derivation and Validation:** ○ Developed an analytical formula for the leak-induced reflection wave at the measurement point, accounting for damping effects during wave propagation. ○ Validated the derived formula through MOC-based numerical simulations and experimental data from laboratory tests. • **Dimensional and Dominance Analysis:** ○ Performed dimensional analysis to identify critical factors influencing the reflection coefficient. ○ Conducted a dominance analysis using 280,000 scenarios to rank the relative importance of dimensionless parameters: ▪ Leak factor (40%) ▪ Transient intensity (23%) ▪ System and flow conditions (20%)

			▪ Measurement distance from leak (17%) • **Practical Implications:** o Highlighted the importance of accurately modeling wave propagation and damping effects for effective leak detection. o Provided insights into the performance of TRMs under different uncertainties and conditions, aiding systematic decision-making for leakage management. • **Limitations and Future Work:** o Encourages further laboratory experiments for validation of findings, particularly in viscoelastic pipelines where damping effects are significant. • Suggests exploring the influence of creep coefficients on leak-induced reflection waves for improved accuracy in viscoelastic systems.
120. Wang (2022) ITM Domain: Time Title: Fast computation of inverse transient analysis for pipeline condition assessment via surrogate modeling with sparse sampling strategy	Analysis Approach: Hydraulic Modeling and AI-Enhanced Analysis Technique: Surrogate Modeling using Kriging Response Type: Impulse Response Optimization Technique: Sparse Sampling Strategy, Single Implementation for Convex Problems Friction Model: Not explicitly stated; assumed steady state for numerical modeling Viscoelasticity: K-V model, Incorporated as an unknown parameter in estimation Noise: Not explicitly mentioned in this study	Network/Pipeline: Pipeline Case Study: Numerical and experimental systems Leak Unknowns: Location and size NO. Measurement Points: Single Validation: Numerical and experimental	This study proposes an innovative surrogate-based ITA approach to overcome the computational challenges of traditional ITA in pipeline condition assessment. The main aspects and findings are summarized below: • **Methodology:** o Surrogate modeling replaces full-wave numerical simulations during optimization. o A sparse sampling strategy is introduced to efficiently handle high-dimensional parameters with sparse features. o Kriging is used to develop an analytical function for the transient wave response. • **Applications:** o The approach is applied to two examples: ▪ **Pipe Wall Viscoelastic Parameter (VEP) Estimation:** Accurate parameter identification with reduced computation. ▪ **Leak Identification:** Efficiently detects and sizes

			leaks using fewer parameter samples. • **Key Results:** o Surrogate modeling requires fewer than 100 full-wave numerical simulations to construct an accurate model. o Computational cost is significantly reduced while maintaining accuracy comparable to traditional ITA. o The convex nature of the optimization problems ensures convergence with a single initialization, although non-convex problems might require multi-initialization strategies. • **Advantages:** o Fast and efficient compared to traditional ITA. o Handles complex high-dimensional parameter spaces effectively. o Demonstrates robust performance in both numerical and experimental validations. • **Challenges and Future Work:** o Optimization of the sampling strategy for VEP estimation could further enhance efficiency. o Incorporating prior knowledge about parameter correlation could improve sampling accuracy. • Future work could explore applications in non-convex problems and extend the method to larger, more complex pipeline systems.
121. Che, Wang et al. (2022) SRM Domain: Frequency Title: Leak Localization in Looped Pipe Networks Based on a Factorized Transient Wave Model: Theoretical Framework	Analysis Approach: Hydraulic Modeling Analysis Technique: Matched-Field Processing (MFP) Response Type: Impulse Response Optimization Technique: Not explicitly applied; focuses on efficient 1D search through factorized wave propagation model. Friction Model: steady state. Viscoelasticity: Not considered.	Network/Pipeline: Network (looped) Case Study: Hypothetical system Leak Unknowns: Location and size NO. Measurement Points: Boundary nodes only Validation: Numerical	This study presents a novel theoretical framework for leak localization in looped pipe networks using transient wave propagation models and matched-field processing (MFP). The following summarizes its methodology, findings, and implications: • **Methodology:** o An analytical transient wave propagation model is developed, addressing the inherent multipath challenges in looped networks.

	Noise: Small uncertainties and noise incorporated in numerical simulations.		○ A factorized wave propagation model is formulated by applying conservation laws within a tree-shaped control volume of the looped network. ○ The MFP technique is applied for efficient and accurate 1D searches for leak localization along all pipes in the looped network. • **Key Findings:** ○ The proposed framework enables unique identification of leaks in looped pipe networks by overcoming the complexities of multipath wave propagation. ○ Numerical experiments confirm the accuracy and efficiency of the method in a five-loop network with 13 pipes. ○ The computational complexity of the MFP-based leak localization method is demonstrated to be low. • **Challenges and Limitations:** ○ Severe damping and dispersion of transient signals in large and complex networks, due to physical uncertainties like air entrainment, fluid-structure interaction, and unknown system properties, hinder practical application. ○ The inverse problem of hydraulic property estimation at boundary nodes may become unstable in noisy environments, distorting target signals and reducing accuracy. • **Future Directions:** ○ Application of the proposed method in controllable sub-networks to mitigate system complexity and uncertainties. • Further investigation into the stability of hydraulic property estimation in noisy environments, expected to be presented in the next work.
122. Wang, Ghidaoui et al. (2022) ITM Domain: Frequency	Analysis Approach: Hydraulic Modeling and Signal Processing Analysis Technique: ITA Response Type: Impulse Response	Network/Pipeline: Single pipeline Case Study: Experimental system Leak Unknowns: Location NO. Measurement Points: Single measurement	This paper introduces a framework to derive **confidence intervals** for pipeline leakage localization using transient-based methods. It generalizes traditional point localization

Title: Confidence interval localization of pipeline leakage via the bootstrap method	Optimization Technique: Bootstrap Method for confidence intervals (including standard interval, percentile, and BCa methods)
	Friction Model: N/A (not explicitly stated in the text)
	Viscoelasticity: N/A (not explicitly stated)
	Noise: Aleatoric uncertainties explicitly modeled using empirical distributions of transients
		Validation: Experimental validation using a single-pipe system	techniques by integrating stochastic elements and bootstrap methods to address uncertainties in measurements.
			
			Key Findings:
			
			• **Methodology:**
			  ○ A **semi-parametric transient model** is employed to address aleatoric uncertainties.
			  ○ The **bootstrap method** is used to generate multiple predictions of leak location, constructing confidence intervals through standard interval, percentile, and BCa methods.
			  ○ The framework relies on limited transient test data to estimate the empirical distribution of transient wave measurements.
			• **Results:**
			  ○ **Leak Localization:** Point localization errors were tolerable with only seven transient tests.
			  ○ **Confidence Intervals:** Accurately predicted the actual leak location with satisfactory coverage probabilities, aligning with ground-truth results.
			  ○ The method provides **additional decision-making information** for pipeline maintenance by quantifying imprecision and uncertainty.
			• **Challenges and Insights:**
			  ○ Experimental validation was conducted in a controlled single-pipe setup, and further work is required to generalize the approach to complex pipe networks.
			  ○ Determining the **presence of a leak** was identified as a future development area.
			• **Future Work:**
			  ○ Apply the methodology to real-world pipe networks with complex topologies.
			
			• Enhance the framework to detect and confirm the **existence of leaks**.

123. Bohorquez, Lambert et al. (2022) SRM Domain: Time Title: Stochastic Resonance Enhancement for Leak Detection in Pipelines Using Fluid Transients and Convolutional Neural Networks	Analysis approach: Hydraulic Modeling and AI-Enhanced Analysis technique: MOC for data generation, deployment of stochastic resonance and convolutional neural networks (CNNs) for detection Response Type: N/A Optimization Technique: N/A Friction model: Not mentioned in the paper Viscoelasticity: N/A Noise: This methodology finds the optimal artificial noise intensity to be introduced into the training dataset for a set of CNNs.	Network/Pipeline: pipeline Case Study: RPV Leak Unknowns: location and size NO. Measurement Points: single Validation: Numerical and experimental	In this paper, the enhanced detection of leaks in pressurized pipelines via the deployment of stochastic resonance is demonstrated. The methodology is presented for the active inspection of pipelines using convolutional neural networks (CNNs). **Methodology:** • The methodology divided into two stages of model development and model application. • The model development stage includes the design and training of CNNs capable of identifying leaks in transient pressure head traces with different noise intensities. • The model application stage describes the preprocessing and analysis steps for any pressure transient measurements obtained from a transient event caused by the closure of a valve in a pipeline. • It finds the optimal artificial noise intensity to be introduced into the training dataset for a set of CNNs. The methodology has been applied to a real pipeline **Results:** • The results demonstrate that the use of CNNs trained with numerical samples with the addition of noise isa promising technique for leak detection in pipelines under more realistic conditions. • Also, the addition of noise to the transient pressure head training samples significantly enhances the CNN predictions for the leak location highlighting the existence of an optimum noise intensity to obtain both accurate and reliable results.
124. Ayati, Haghighi et al. (2022) SRM Domain: Time/Frequency Title: Machine learning approach to transient-based leak detection of pressurized pipelines: Classification vs Regression	Analysis Approach: Hydraulic Modeling and AI-Enhanced Analysis Technique: MOC for transient modeling Response Type: Impulse Response (pressure reflections from leaks and transient waveforms)	Network/Pipeline: Pipeline Case Study: Experimental system (reservoir-pipe-valve setup) Leak Unknowns: Leak location (single leak) NO. Measurement Points: Single Validation: Numerical and experimental validation	This study introduces an **ITM framework** using machine learning (Support Vector Machines, SVM) to analyze transient wave responses for leak detection in pipelines. It explores both classification and regression approaches under experimental conditions, focusing on detecting and localizing leaks.

	Optimization Technique: Support Vector Machines (SVM) for classification and regression (data-driven optimization of transient response patterns) Friction Model: N/A (not explicitly modeled in this study) Viscoelasticity: N/A (pipe material properties not considered) Noise: Signals denoised before processing to ensure robustness		**Key Findings:** • **Framework Methodology:** o A transient model based on MOC was used to simulate datasets. o SVM classifiers and regressors were employed to detect leaks and predict their locations, respectively. • **Performance Highlights:** o **Classification (Preferred Approach):** Demonstrated higher accuracy, stability, and robustness compared to regression, especially in noisy environments. o **Regression:** Performed satisfactorily but required refinement for practical use in complex systems. o The framework avoided the multimodal and ill-posed optimization issues commonly faced by traditional ITM methods. • **Advantages Over Traditional ITM:** o Faster leak detection since SVM enables real-time processing post-training. o Direct pattern recognition avoids time-consuming optimization during field applications. • **Robustness and Reliability:** o Stable under high levels of uncertainty in initial flow conditions and pipe roughness. o The methodology focused on early transient signals, minimizing the effects of wave damping. • **Limitations and Future Directions:** o Assumed only single leaks, no pipe blockages, and no deterioration. o Did not consider multiple anomalies or uncalibrated systems. • Future research should extend the method to multiple leaks and validate it in real-world settings.
125. Ayati, Haghighi et al. (2022) SRM	Analysis Approach: Hydraulic modeling combined with machine	Network/Pipeline: Water distribution network (WDN) and	This study presents a hybrid leak detection model combining machine learning and hydraulic transient modeling. The

Domain: Time/Frequency Title: Machine Learning–Assisted Model for Leak Detection in Water Distribution Networks Using Hydraulic Transient Flows	learning for leak detection (AI-Enhanced) Analysis Technique: Transient hydraulic modeling (time-domain analysis) Fast Fourier Transform (FFT) for frequency domain transformation Neighborhood Component Analysis (NCA) for feature selection Classification algorithms for leak detection Response Type: Frequency response (data transformed to frequency domain using FFT) Optimization Technique: NCA for feature selection, comparison of classifiers for model selection Friction Model: N/A (uncertainties in pipe friction factors are considered, but no specific model stated) Viscoelasticity: N/A (focus on transient hydraulic responses and machine learning) Noise: Uncertainty in pipe friction factors and nodal demands (treated as uncertainty in system parameters)	experimental reservoir-pipe-valve (RPV) system Case Study: Experimental system (RPV system) and real-world system (WDN) Leak Unknowns: Location (and potentially size) NO. Measurement Points: Multiple measurement sites, optimized using graph-based methods Validation: Experimental and numerical (two case studies)	process starts with a transient hydraulic simulation in the time domain, followed by transforming the data to the frequency domain using FFT. Feature selection is performed using NCA, and the best classifier is chosen to identify leaks from the data. The method is applied to two case studies: an experimental reservoir-pipe-valve system and a complex water distribution network. **Key Findings:** • **Hybrid Approach:** o Combines hydraulic modeling and machine learning to accurately detect leaks in water distribution systems. o Hydraulic responses from measurement sites are used to generate data sets for analysis. o Feature selection and classifier optimization improve the model's accuracy. • **Measurement Site Selection:** o A graph-based method is employed to determine the optimum locations for sampling the hydraulic responses, ensuring effective data collection. • **Leak Detection Accuracy:** o The model detects leaks with high accuracy, even in the presence of significant uncertainties in system parameters (e.g., friction factors and nodal demands). o The model remains stable and reliable when subjected to high levels of uncertainty in these parameters. • **Performance under Different Excitations:** o The model performs well with both fast and slow transient excitations, demonstrating its robustness across different types of transient responses. • **Real-World Applicability:** o The method was validated in both an experimental system (RPV) and a real-world water distribution network,

			confirming its potential for practical applications in leak detection. • **Conclusion and Future Work:** o The hybrid model shows promising results for leak detection in complex pipe networks, with high accuracy and robustness against uncertainties. • Future work may include further validation with additional case studies and the refinement of machine learning algorithms to enhance performance in more complex systems.
126. Ayati and Haghighi (2023) SRM Domain: Time/Frequency Title: Multiobjective Wrapper Sampling Design for Leak Detection of Pipe Networks Based on Machine Learning and Transient Methods	Analysis Approach: Hydraulic modeling (transient simulation) combined with machine learning (for classification and feature selection) (AI-Enhanced) Analysis Technique: Fast Fourier Transform (FFT) for frequency domain transformation Filter and Wrapper feature selection methods for dimensionality reduction Linear Discriminant Analysis (LDA) for classification Non-dominated Sorting Genetic Algorithm II (NSGA-II) for Multiobjective optimization Response Type: Frequency response (using FFT to analyze the hydraulic responses in the frequency domain) Optimization Technique: Multiobjective optimization (NSGA-II) to balance leak detection error and sampling site count Friction Model: N/A (no specific friction model mentioned, but transient hydraulic simulations likely consider some form of frictional losses) Viscoelasticity: N/A (focused on transient response and machine learning-based classification)	Network/Pipeline: Pipe networks Case Study: Experimental (with simulated networks and optimization) Leak Unknowns: Location and possibly size NO. Measurement Points: Optimized measurement sites selected via sampling design Validation: Numerical (via simulation and multiobjective optimization)	This paper introduces a new sampling design method for hybrid Machine Learning and Transient-Based (ML/TB) leak detection in pipe networks. The method combines hydraulic transient simulations, feature selection techniques, and multiobjective optimization to detect leaks efficiently while minimizing the number of sampling points. Hydraulic responses are measured at candidate sites and then analyzed in the frequency domain using Fast Fourier Transform (FFT). The processed data are used to train a classifier based on Linear Discriminant Analysis (LDA), and multiobjective optimization via Non-dominated Sorting Genetic Algorithm (NSGA-II) is employed to balance leak detection accuracy and the number of sampling sites. **Key Findings:** • **Sampling Design and Optimization:** o A multiobjective optimization approach (NSGA-II) is used to balance the trade-off between minimizing leak detection error and reducing the number of sampling nodes. o The method uses FFT to transform the hydraulic responses into the frequency domain, optimizing the analysis of transient responses for leak detection. • **Feature Selection:** o Filter and Wrapper methods are applied to select the most relevant features from the transformed frequency domain data,

	Noise: High-frequency responses are filtered out to reduce the impact of noise in the frequency domain		reducing dimensionality and improving classification performance. • **Leak Detection Accuracy:** o The proposed method outperforms existing sampling design techniques, achieving higher accuracy in leak detection while requiring fewer sampling sites. This is achieved by selecting optimal measurement locations using the optimization process. • **Comparison with Existing Methods:** o Four existing sampling design methods were compared, and the proposed approach demonstrated superior performance in terms of accuracy and efficiency. • **Real-World Applicability:** o The method was applied to two example pipe networks, showing promising results that could translate into real-world applications where minimizing measurement points is critical for cost-effectiveness. • **Future Work:** • Further refinement of the model and additional case studies could help extend the applicability to more complex pipe network structures, taking into account other potential factors affecting leak detection.
127. Asghari, Kazemi et al. (2023) ITM Domain: Frequency Title: Machine learning modeling for spectral transient-based leak detection	Analysis approach: AI-Enhanced Analysis technique: Machine Learning Framework (MLF) Response Type: Frequency Response Optimization Technique: N/A (the study replaces optimization with machine learning classification) Friction model: N/A Viscoelasticity: N/A Noise: Noise tested up to 10% of the signal	Network/Pipeline: Pipeline Case Study: hypothetical Leak Unknowns: Location and size NO. Measurement Points: Single Validation: Numerical	• **Purpose**: The study addresses limitations in TBLD, typically solved with Metaheuristic Optimization Algorithms (MOAs), by introducing a machine learning model as a solution for identifying leak locations and sizes more effectively. • **Methodology**: • The study trained an ensemble of CatBoost models on over 3.8 million records, achieving leak classification and leak size prediction. • The ML models bypass the time-consuming optimization process, focusing on direct classification and regression. • **Performance**:

			• The CatBoost model achieved 97% accuracy in detecting leak locations with an F1-score of 0.86, significantly outperforming conventional methods. • The approach also reduced computational time by up to four orders of magnitude compared to optimization algorithms, such as Genetic Algorithms (GA). • **Robustness to Noise**: • The ML model-maintained accuracy with noise levels up to 10% of the measured signals, indicating strong reliability in real-world conditions. • **Limitations**: • The ML approach exhibited reduced sensitivity to detecting very small leaks, suggesting room for improvement in cases involving minimal leak sizes. • **Future Potential**: • Although tested on a single-pipe system, the framework is adaptable to network-level TBLD, with potential applicability in large water distribution networks. • The study invites further research to enhance sensitivity, apply hyperparameter tuning, and explore other ML models for even greater accuracy. • **Conclusion**: • The ML-based TBLD method demonstrates promising accuracy and computational efficiency, marking a shift from traditional optimization toward data-driven leak detection models. This shift could benefit complex, large-scale pipeline systems, and further development is encouraged to validate and expand the approach in practical applications.
128. Keramat, Ahmadianfar et al. (2023) ITM Domain: Frequency Title: Spectral transient-based multiple leakage identification in water pipelines: An efficient hybrid gradient-metaheuristic optimization	Analysis approach: Hydraulic Modeling and Signal Processing Analysis technique: Standing Wave Difference Method (SWDM) Response Type: Frequency Response Optimization Technique: Hybrid Gradient-Metaheuristic Optimization (MGBO) Friction model: Steady-state, Darcy-Weisbach Viscoelasticity: N/A	Network/Pipeline: Pipeline Case Study: Hypothetical system Leak Unknowns: Location and Number NO. Measurement Points: Multiple Validation: Numerical	This paper presents an efficient **hybrid gradient-metaheuristic optimization (MGBO)** approach to tackle the **multi-dimensional, non-convex optimization** problem in transient-based leak detection. The methodology addresses challenges in localizing single and multiple leaks using standing wave properties and optimization techniques. Key points include:

	Noise: Robust to low-bandwidth and noisy signals		• **Development of the MGBO Algorithm:**
			  ○ Combines gradient search mechanisms (GSR) for global exploration with a **Local Escaping Operator (LEO)** to avoid local optima.
			  ○ Reduces computational overhead by limiting the initialization population size to less than 0.3% of classical methods.
			• **Single Leak Cases:**
			  ○ Comparable performance to classical gradient-based algorithms, with fewer initialization nodes required.
			  ○ Faster convergence due to the GSR mechanism.
			• **Multiple Leak Cases:**
			  ○ Demonstrates robustness and efficiency for two and three leak cases, even under low bandwidth and noisy conditions.
			  ○ Tailored metaheuristic algorithms accelerate convergence to the global extremum.
			• **Numerical Validation:**
			  ○ Achieves an RMSE of less than 15% in over 96% of three-leak localization cases.
			  ○ Demonstrates convergence within a few iterations in most cases.
			• **Future Applications:**
			  ○ The methodology can be extended to solve more complex leak detection

			problems, including **uncertainty quantification** and **Bayesian model updating.** • Improved feasibility for field test practices due to efficiency gains in optimization execution.
129. Zhang, Duan et al. (2023) TRM Domain: Frequency Title: Transient Wave-Leak Interaction Analysis for Improved Leak Detection in Viscoelastic Pipelines	Analysis Approach: Hydraulic Modeling and Signal Processing Analysis Technique: Transient Wave Reflection Method (TWRM), Analytical Reflection Coefficient Response Type: Frequency Response and Impulse Response Optimization Technique: Custom optimization algorithm based on reflection coefficients Friction Model: Both steady-state (SF) and unsteady-state (UF) friction models considered Viscoelasticity: Explicitly incorporates viscoelastic effects in pipelines Noise: Not explicitly mentioned	Network/Pipeline: Pipeline Case Study: Numerical and Laboratory Experimental system Leak Unknowns: Location and Ratio NO. Measurement Points: Single Validation: Numerical and Experimental	This research investigates transient wave behavior and its interaction with leaks and viscoelasticity in pipelines, focusing on deriving and validating an analytical reflection coefficient for improved leak detection. Key findings and contributions include: • **Analytical Model Development:** o Derived a reflection coefficient formula to analyze leak-induced wave reflections and phase differences in viscoelastic pipelines, incorporating quasi-steady and unsteady friction. o Provided insights into the effects of measurement distance and leak ratio on transient wave behavior. • **Key Observations:** o Leak ratio significantly affects wave amplitude but has minimal influence on phase differences for practical leak ratios (<50%). o Steady friction (SF) attenuates waves without causing phase shifts, while unsteady friction (UF) affects both amplitude and phase, depending on measurement points and wave frequency. • **Validation and Applicability:** o Extensive numerical and laboratory experiments confirmed the model's effectiveness, achieving error rates under 10% for practical leak scenarios. o Demonstrated the model's capability to handle various leak locations, sizes, and transient oscillation types. • **Practical Implications:** o Highlights the need to account for viscoelasticity and frictional interactions

			in transient wave propagation models for leak detection in pipelines. • Provides a robust framework for accurately detecting leaks in viscoelastic pipelines, particularly under realistic conditions where leakage is less than 50%.
130. Xu, Waqar et al. (2024) TRM Domain: Frequency Title: High-resolution pipeline leak localization using the side-lobes of the defect detection functional of matched-field processing	Analysis Approach: Signal Processing Analysis Technique: Matched-Field Processing (MFP) Response Type: Frequency Response Optimization Technique: N/A Friction Model: Steady state Viscoelasticity: N/A Noise: Addresses white, colored, and impulse-type noise robustly	Network/Pipeline: Pipeline Case Study: Numerical and Experimental system Leak Unknowns: Location NO. Measurement Points: Single Validation: Numerical and Experimental	This research proposes a **modified broadband Matched-Field Processing (MB-MFP)** technique for high-resolution leak detection in pipelines. Key findings and contributions include: • **Methodological Advancements:** o Converts side-lobes from a nuisance into an asset by analyzing their trajectories, which converge toward the actual leak location as frequency increases. o Introduces two modified broadband MFP methods (MB-MFP1 and MB-MFP2) with improved side-lobe suppression and higher resolution for leak localization. • **Robustness Against Noise:** o Demonstrates effectiveness against white, colored, and impulse-type noise, enhancing the accuracy of leak localization under noisy conditions. • **Experimental and Numerical Validation:** o Validates the accuracy and robustness of the proposed methods using both numerical simulations and experimental data. • **Resolution and Accuracy:** o Achieves high-resolution leak localization by leveraging broadband

			frequency information, significantly reducing ambiguity caused by high-level side-lobes. • **Future Directions:** o Extending the method to handle complex pipeline network topologies, such as branched and looped systems. • Investigating the capability of the technique for simultaneous detection of multiple leaks.
131. Zhang, Keramat et al. (2024) SRM Domain: Time Title: Formulation and analysis of transient flows in fluid pipelines with distributed leakage	Analysis Approach: Hydraulic Modeling Analysis Technique: Fourier Series Analysis Response Type: Time-Domain Pressure Signals Optimization Technique: N/A (Focus on analytical modeling and validation) Friction Model: Steady-state mentioned but includes distributed leakage effects; further friction modeling recommended for future work. Viscoelasticity: Not considered but highlighted for future extensions. Noise: Not explicitly included but minor damping effects of distributed leakage are discussed.	Network/Pipeline: Pipeline (single pipeline) Case Study: Numerical and experimental systems Leak Unknowns: Size and distribution NO. Measurement Points: Multiple points for validation Validation: Numerical and experimental	This study focuses on the transient response of pipelines with distributed leakage, such as longitudinal cracks, using Fourier series-based analytical modeling. Below are the main points: • **Methodology:** o Analytical solutions based on Fourier series are developed to model transient flow in pipelines with longitudinal crack-shaped leakages. o The results are numerically validated against MOC for different leakage scenarios, demonstrating good agreement. • **Key Findings:** o Distributed leaks cause a smoothing effect on pressure peaks with minor differences in magnitude compared to discrete orifice leaks. o Increasing the distributed flow size does not significantly alter the resonant frequencies of the pipeline system. o The derived Fourier series solution provides a reliable and computationally efficient benchmark for transient behavior modeling. • **Challenges and Future Directions:** o Current research simplifies the complex effects of friction, entrapped air, fluid–structure interactions, and viscoelasticity,

			which need to be included for real-life applications. • Further experimental validation is required to solidify the findings and ensure applicability to practical systems.
132. Liao, Shuming et al. (2024) ITM Domain: Frequency Title: Reducing linearization errors in the frequency domain analysis of fluid transients due to pipeline burst	Analysis Approach: Hydraulic Modeling Analysis Technique: FDA and ITA Response Type: Frequency Response Optimization Technique: Not explicitly stated; focuses on surrogate modeling and sparse sampling for efficiency Friction Model: Linearized friction term, with higher-order modifications for accuracy Viscoelasticity: N/A Noise: Not explicitly analyzed but considers modeling error through adjustments to FDA	Network/Pipeline: Network Case Study: Numerical simulations on a real-life water distribution system Leak Unknowns: Location and size NO. Measurement Points: Multiple measurement points Validation: Numerical validation using MOC	This study proposes an enhanced Frequency Domain Analysis (FDA) approach for transient simulations in pressurized pipes, addressing challenges posed by linearization errors in burst scenarios. It incorporates computationally efficient surrogate models and explores sparse sampling strategies to enhance pipeline condition assessments. **Key Findings:** • **Methodology:** o FDA is modified to address linearization errors in friction terms and valve equations using the Heaviside property. o Surrogate modeling with sparse sampling strategies replaces traditional full-wave numerical simulations, significantly reducing computational demands. o Validation is performed against MOC-based results in scenarios with varying burst discharges. • **Results:** o The modified FDA provides accuracy comparable to MOC, even in highly nonlinear scenarios with burst discharges of 20% of system demand. o Computational efficiency is preserved, making FDA feasible for near-real-time applications. o Modifications to friction terms and valve equations enable accurate steady-state and transient predictions. • **Future Directions:** o Expanding the methodology to complex networks with diverse burst scenarios and boundary conditions.

			○ Combining FDA with machine learning for real-time inverse analysis. • Field-based validations to confirm broader applicability.
133. Rad, Azizi Nadian et al. (2024) SRM Domain: Frequency Title: Investigation of Pressure Signal and Leak Detection in Pipes by Using Wavelet Transform in Transient Flow	Analysis approach: Signal processing Analysis technique: Wavelet Analysis Response Type: N/A Optimization Technique: N/A Friction model: Not mentioned in the paper Viscoelasticity: Not mentioned in the paper Noise: Wavelet noise reduction	Network/Pipeline: pipeline Case Study: RPV Leak Unknowns: single leak location NO. measurement Points: single Validation: Numerical and Experimental	In this study, the behavior of the signal and the effectiveness of wavelet transform are investigated by conducting laboratory experiments and using deferent wavelet transforms. • Results showed the effectiveness of wavelet transform in transient based leak detection in terms of noise reduction, and efficient transient signal analysis.
134. Li and Zhang (2024) SRM Domain: Frequency Title: Pipeline leakage localization method based on transient signal detection and data fusion from multi-sensor	Analysis approach: Signal processing Analysis technique: MUSIC-like algorithm and multi-sensor leakage data fusion. Frequency domain analysis Response Type: Frequency Response Spectrum Optimization Technique: N/A Friction model: Darcy–Weisbach Viscoelasticity: N/A Noise: Gaussian white noise with zero mean is added to all pressure sensors	Network/Pipeline: Pipeline Case Study: RPVR Leak Unknowns: Location, Multiple leaks NO. Measurement Points: Four Validation: Numerical	This paper applies a method for localizing pipeline leakages, integrating transient signal detection with multi-sensor data fusion. **Methodology:** • To address the challenges in detecting small leaks amidst strong noise and uncertainty, the method employs the Dempster–Shafer evidence framework for data fusion and an algorithm to analyze transient pressure waves. • Comparing it with three spectrum-based methods, the performance of the fusion method is discussed in the single-leakage and multi-leakage cases. **Key Findings:** • In the single-leakage case, even with high levels of noise, the fusion algorithm delivers precise localization estimates. • The fusion method excels over the other three methods in the multi-leakage case. • The approach enhances the accuracy of leak localization in water pipelines. • Simulations demonstrate the method's effectiveness in noisy environments

135. Capponi, Menapace et al. (2024) SRM Domain: Time Title: Hybrid Transient-Machine Learning Methodology for Leak Detection in Water Transmission Mains	Analysis approach: Hydraulic Modeling Analysis technique: Neural network model consists of an FFNN architecture Response Type: N/A Optimization Technique: N/A Friction model: not mentioned in the paper Viscoelasticity: not mentioned in the paper Noise: Three synthetic datasets with different levels of noise applied	Network/Pipeline: Pipeline Case Study: RPV Leak Unknowns: Single leak, size, location NO. Measurement Points: Single Validation: Numerical and Experimental	This study proposes a hybrid approach integrating transient test-based techniques with machine learning for automatic leak detection in water transmission mains. • Transient numerical simulations calibrated using experimental tests are used to develop a data-driven method based on neural networks to identify leak locations and characteristics. • The accuracy of leak localization is demonstrated using three different degrees of noise in terms of mean absolute error.

136. Waqar, Memon et al. (2025) SRM
Domain: Frequency
Title: Pipeline leak detection using hydraulic transients and domain-guided machine learning
	Analysis Approach: Hydraulic Modeling and AI-Enhanced
	Analysis Technique: Neural Network (Feedforward NN) trained on transient hydraulic data (using MOC)
	Response Type: Impulse Response
	Optimization Technique: Iterative refinement of neural network architecture (not explicitly heuristic-based optimization)
	Friction Model: Unsteady friction
	Viscoelasticity: Kelvin-Voigt model
	Noise: Gaussian noise applied to pressure head signals
		Network/Pipeline: Pipeline and Network (series and tree-type configurations)
		Case Study: Numerical simulations and experimental system
		Leak Unknowns: Location, size, and number (up to four leaks)
		NO. Measurement Points: Single or multiple, depending on configuration
		Validation: Numerical and experimental
			This study presents a **domain-guided machine learning framework** for detecting multiple leaks in pipelines using transient hydraulic datasets. Key contributions and findings include:
			
			• **Framework and Methodology:**
			  ○ Introduces a novel machine learning (ML) framework using a "leak function" with pulse-like signatures as target variables, making it adaptable to multiple leak scenarios without requiring retraining.
			  ○ Uses a five-layer feedforward neural network (ANN) trained on numerical and experimental data, refined iteratively to handle operational uncertainties like valve closure time and pre-transient conditions.
			• **Validation and Testing:**
			  ○ Validated using both numerical simulations and experimental data from a laboratory-scale viscoelastic pipe system.
			  ○ Demonstrated accuracy in detecting up to four leaks with minor errors in sizing, attributed to modeling limitations.
			• **Performance and Adaptability:**
			  ○ Extended the framework to series and tree-type network configurations, showing moderate accuracy in more complex systems.

			○ Observed challenges in scaling the ANN model for complex systems, requiring careful tuning of the network's architecture and hyperparameters. • **Limitations and Future Directions:** ○ ANN predictions deviate as system complexity increases; potential solutions include expanding the network's architecture and optimizing hyperparameters. Future work will involve testing on real-field data and exploring hybrid ML models for better scalability and accuracy.
137. Liu, Wang et al. (2025) SRM Domain: Frequency Title: Frequency-informed transformer for real-time water pipeline leak detection	Analysis approach: Signal Processing Analysis technique: Frequency-Informed Transformer model together with applying the self-attention mechanism to capture and emphasize frequency patterns within vibration data Response Type: Frequency Response Optimization Technique: N/A Friction model: Not mentioned in the paper Viscoelasticity: Experimental model with PVC pipes. Not mentioned in the paper Noise: To minimize potential noise, classification token is not fed into the MLP component. Instead, it undergoes a linear projection while the MLP component processes the remaining tokens.	Network/Pipeline: Network Case Study: looped and branched networks Leak Unknowns: Leak existence and leak type NO. Measurement Points: six Validation: experimental	This paper introduces a Frequency-Informed Transformer model, which integrates the Fast Fourier Transform and self-attention mechanisms to enhance water pipe leak detection accuracy. **Results:** • Experimental results show that through the integration of FFT for frequency domain conversion and a self-attention mechanism for adaptive frequency band selection, the model exhibits superior accuracy and efficiency. • The model achieves high accuracy in leak detection and leak-type classification and operates efficiently with short sample lengths, allowing for rapid response in real-time scenarios. • By significantly simplifying key features and frequency band selection and improving accuracy and response time, the proposed method offers a potential solution for real-time water leak detection, enabling timely interventions and more effective pipeline safety management
138. Asada, Hagiwara et al. (2025) ITM Domain: Time Title: Field verification of single leak detection method based on transient pressures using optimization	Analysis approach: Hydraulic Modeling Analysis technique: MOC Response Type: Time domain pressure response	Network/Pipeline: Branched pipe line Case Study: Ogura irrigation pipeline system in Sado, Niigata, Japan	This study, for the first time, tested the effectiveness of ITA, on detecting a single-point leak in a real field pipeline (the Ogura irrigation pipeline system in Sado, Niigata, Japan).

technique in in-situ irrigation pipeline system including branch junctions and diameter changes	Optimization Technique: comprehensive learning particle swarm optimization Friction model: Friction factors were calculated theoretically using the Blasius equation Viscoelasticity: N/A Noise: random noise, such as measurement noise, traffic noise, turbulence, and air bubbles in the water are considered	Leak Unknowns: Single leak size and location NO. Measurement Points: Four Validation: Field	**Methodology:** • a new leak detection method based on transient pressures and utilizing the CLPSO algorithm was developed and validated for a single-point leak in the field long distance irrigation pipeline system with branch junctions and changes in diameter. • The transient model used for this leak detection method was calibrated 10 times to account for result variability due to the randomness of the CLPSO, considering parameters such as wave speeds along the pipeline, valve closure completion time, valve opening degrees during valve closure, and flow rate in the Minagawa branch pipeline. **Results:** • In cases of the leak near the downstream end of the main pipeline, smaller steady flow rate resulted in smaller variability and higher accuracy in the estimated leak location. • Conversely, for the leak in the branch pipeline, larger steady flow rate was better for the estimated leak position. This suggests that the optimal steady flow rate for accurate leak detection varies depending on the leak location. • By accumulating baseline pressure variation data under known flow conditions for calibration purposes, and monitoring pressure variations during routine functional diagnostics, the method becomes feasible and facilitates easier leak detection.

References

Al-Khomairi, A. (2008). "Leak detection in long pipelines using the least squares method." Journal of Hydraulic Research **46**(3): 392-401.

Al-Shidhani, I., et al. (2003). Leak monitoring in pipeline networks using wavelet analysis. Key Engineering Materials, Trans Tech Publ.

Amin, M. M., et al. (2014). "Leakage Detection in Pipeline Using Synchrosqueeze Wavelet Transform." Applied Mechanics and Materials **465-466**: 467-471.

Amini, I., et al. (2020). A Two-Stage Deep-Learning Based Detection Method for Pipeline Leakage and Transient Conditions. 2020 IEEE Electric Power and Energy Conference (EPEC).

Asada, Y., et al. (2025). "Field verification of single leak detection method based on transient pressures using optimization technique in in-situ irrigation pipeline system including branch junctions and diameter changes." Paddy and Water Environment **23**(2): 243-262.

Asghari, V., et al. (2023). "Machine learning modeling for spectral transient-based leak detection." Automation in Construction **146**: 104686.

Ayati , A. H. and A. Haghighi (2023). "Multiobjective Wrapper Sampling Design for Leak Detection of Pipe Networks Based on Machine Learning and Transient Methods." Journal of Water Resources Planning and Management **149**(2): 04022076.

Ayati, A. H., et al. (2022). "Machine Learning–Assisted Model for Leak Detection in Water Distribution Networks Using Hydraulic Transient Flows." Journal of Water Resources Planning and Management **148**(2): 04021104.

Ayati, A. H., et al. (2022). "Machine learning approach to transient-based leak detection of pressurized pipelines: Classification vs Regression." Journal of Civil Structural Health Monitoring.

Bartecki, K. (2009). "Frequency-and time-domain analysis of a simple pipeline system." IFAC Proceedings Volumes **42**(13): 366-371.

Beck, S. B., et al. (2005). "Pipeline Network Features and Leak Detection by Cross-Correlation Analysis of Reflected Waves." Journal of Hydraulic Engineering **131**(8): 715-723.

Beck, S. B. M., et al. (2006). Wavelet and Cepstrum Analyses of Leaks in Pipe Networks. Progress in Industrial Mathematics at ECMI 2004, Berlin, Heidelberg, Springer Berlin Heidelberg.

Bohorquez, J., et al. (2020). "Leak Detection and Topology Identification in Pipelines Using Fluid Transients and Artificial Neural Networks." Journal of Water Resources Planning and Management **146**(6): 04020040.

Bohorquez, J., et al. (2022). "Stochastic Resonance Enhancement for Leak Detection in Pipelines Using Fluid Transients and Convolutional Neural Networks." Journal of Water Resources Planning and Management **148**(3): 04022001.

Brunone, B. (1999). "Transient test-based technique for leak detection in outfall pipes." Journal of Water Resources Planning and Management **125**(5): 302–306.

Brunone, B. and M. Ferrante (2001). "Detecting leaks in pressurised pipes by means of transients." Journal of Hydraulic Research **39**(5): 539-547.

Brunone, B. and M. Ferrante (2004). "Pressure waves as a tool for leak detection in closed conduits." Urban Water Journal **1**(2): 145-155.

Capponi, C., et al. (2024) Hybrid Transient-Machine Learning Methodology for Leak Detection in Water Transmission Mains. Engineering Proceedings **69**, DOI: 10.3390/engproc2024069142

> This contribution proposes a hybrid approach integrating transient test-based techniques with machine learning for automatic leak detection in water transmission mains. Transient numerical simulations calibrated using experimental tests are used to develop a data-driven method based on neural networks to identify leak locations and characteristics. The accuracy of leak localization is demonstrated using three different degrees of noise in terms of mean absolute error, ranging between 0.54 m and 2.1 m. This proposed hybrid approach shows prospects for in-field applications.

Che, T.-C., et al. (2022). "Leak Localization in Looped Pipe Networks Based on a Factorized Transient Wave Model: Theoretical Framework." Water Resources Research **58**(4): e2021WR031364.

Che, T.-C., et al. (2022). "Leak Localization in Looped Pipe Networks Based on a Factorized Transient Wave Model: 2. Regularization of Ill-Conditioned Problems." Water Resources Research **58**(11): e2022WR033293.

Choura, O., et al. (2021). "A Nelder–Mead algorithm-based inverse transient analysis for leak detection and sizing in a single pipe." Water Supply **21**(4): 1580-1593.

Covas, D. and H. Ramos (2001). Hydraulic transients used for leakage detection in water distribution systems. 4th Intl. Conf, Water pipline system. York UK**:** 227-241.

Covas, D. and H. Ramos (2010). "Case Studies of Leak Detection and Location in Water Pipe Systems by Inverse Transient Analysis." Journal of Water Resources Planning and Management **136**(2): 248–257.

Covas, D., et al. (2005). "Standing wave difference method for leak detection in pipeline systems." Journal of Hydraulic Engineering **131**(12): 1106-1116.

Duan, H.-F. (2017). "Transient frequency response based leak detection in water supply pipeline systems with branched and looped junctions." Journal of Hydroinformatics.

Duan, H.-F. (2018). "Accuracy and Sensitivity Evaluation of TFR Method for Leak Detection in Multiple-Pipeline Water Supply Systems." Water Resources Management **32**(6): 2147-2164.

Duan, H.-F., et al. (2010). "Unsteady friction and visco-elasticity in pipe fluid transients." Journal of Hydraulic Research **48**(3): 354-362.

Duan, H.-F., et al. (2012). "System Response Function–Based Leak Detection in Viscoelastic Pipelines." Journal of Hydraulic Engineering **138**(2): 143-153.

Duan, H.-F., et al. (2010). "Essential system response information for transient-based leak detection methods." Journal of Hydraulic Research **48**(5): 650-657.

Duan, H.-F., et al. (2011). "Leak detection in complex series pipelines by using the system frequency response method." Journal of Hydraulic Research **49**(2): 213-221.

Duan, H. F., et al. (2012). "Relevance of Unsteady Friction to Pipe Size and Length in Pipe Fluid Transients." Journal of Hydraulic Engineering **138**(2): 154-166.

Duan, H. F. and P. J. Lee (2016). "Transient-Based Frequency Domain Method for Dead-End Side Branch Detection in Reservoir Pipeline-Valve Systems." Journal of Hydraulic Engineering **142**(2): 04015042.

Ferrante, M. and B. Brunone (2003). "Pipe system diagnosis and leak detection by unsteady-state tests. 1. Harmonic analysis." Advances in Water Resources **26**(1): 95-105.

Ferrante, M. and B. Brunone (2003). "Pipe system diagnosis and leak detection by unsteady-state tests. 2. Wavelet analysis." Advances in Water Resources **26**(1): 107-116.

Ferrante, M., et al. (2007). "Wavelets for the Analysis of Transient Pressure Signals for Leak Detection." Journal of Hydraulic Engineering **133**(11): 1274-1282.

Ferrante, M., et al. (2009). "Leak-edge detection." Journal of Hydraulic Research **47**(2): 233-241.

Ferrante, M., et al. (2009). "Leak detection in branched pipe systems coupling wavelet analysis and a Lagrangian model." Journal of Water Supply: Research and Technology - Aqua **58**(2): 95.

Ferrante, M., et al. (2016). "Numerical transient analysis of random leakage in time and frequency domains." Civil Engineering and Environmental Systems **33**(1): 70-84.

Ghazali, M., et al. (2012). "Comparative study of instantaneous frequency based methods for leak detection in pipeline networks." Mechanical Systems and Signal Processing **29**: 187-200.

Ghazali, M. F., et al. (2010). "Instantaneous phase and frequency for the detection of leaks and features in a pipeline system." Structural Health Monitoring **10**(4): 351-360.

Gong, J., et al. (2013). "Single-Event Leak Detection in Pipeline Using First Three Resonant Responses." Journal of Hydraulic Engineering **139**(6): 645-655.

Gong, J., et al. (2013). "Determination of the linear frequency response of single pipelines using persistent transient excitation: a numerical investigation." Journal of Hydraulic Research **51**(6): 728-734.

Gong, J., et al. (2014). "Frequency Response Diagram for Pipeline Leak Detection: Comparing the Odd and Even Harmonics." Journal of Water Resources Planning and Management **140**(1): 65-74.

Guo, X., et al. (2012). "Leak detection in pipelines by exclusively frequency domain method." Science China Technological Sciences **55**(3): 743-752.

Haghighi, A., et al. (2012). "Direct backward transient analysis for leak detection in pressurized pipelines: from theory to real application." Journal of Water Supply: Research and Technology - Aqua **61**(3): 189-200.

Haghighi, A. and A. Keramat (2012). "A fuzzy approach for considering uncertainty in transient analysis of pipe networks." Journal of Hydroinformatics **14**(4): 1024-1035.

Haghighi, A. and H. M. Ramos (2012). "Detection of Leakage Freshwater and Friction Factor Calibration in Drinking Networks Using Central Force Optimization." Water Resources Management **26**(8): 2347-2363.

Haghighi, A. and H. Shamloo (2011). "Transient generation in pipe networks for leak detection." Proceedings of the Institution of Civil Engineers - Water Management **164**(6): 311-318.

Hamat, A. M., et al. (2017). "The Use of Transmission Line Modelling for Detection of Leakage in Pipeline." Journal of Mechanical Engineering **4**(4): 74-83.

Hanafi.M.Yusop, et al. (2017). "Improvement of Cepstrum Analysis for the Purpose to Detect Leak, Feature and Its Location in Water Distribution System based on Pressure Transient Analysis." Journal of Mechanical Engineering **4**(4): 103-122.

Hu, J., et al. (2011). "Detection of small leakage from long transportation pipeline with complex noise." Journal of Loss Prevention in the Process Industries **24**(4): 449-457.

Huang, Y.-C., et al. (2015). "An Optimization Approach to Leak Detection in Pipe Networks Using Simulated Annealing." Water Resources Management **29**(11): 4185-4201.

Jönsson, L. and M. Larson (1992). Leak detection through hydraulic transient analysis. In Pipeline Systems Springer**:** 273–286.

Jung, B. S. and B. W. Karney (2008). "Systematic exploration of pipeline network calibration using transients." Journal of Hydraulic Research **46**(sup1): 129-137.

Kapelan, Z. S., et al. (2003). "A hybrid inverse transient model for leakage detection and roughness calibration in pipe networks." Journal of Hydraulic Research **41**(5): 481-492.

Kashima, A., et al. (2012). "Numerical errors in discharge measurements using the KDP method." Journal of Hydraulic Research **50**(1): 98-104.

Keramat, A., et al. (2023). "Spectral transient-based multiple leakage identification in water pipelines: An efficient hybrid gradient-metaheuristic optimization." Expert Systems with Applications **224**: 120021.

Keramat, A. and H.-F. Duan (2021). "Spectral based pipeline leak detection using a single spatial measurement." Mechanical Systems and Signal Processing **161**: 107940.

Keramat, A., et al. (2022). "Gradient-based optimization for spectral-based multiple-leak identification." Mechanical Systems and Signal Processing **171**: 108840.

Keramat, A., et al. (2019). "Cramer-Rao Lower Bound for Performance Analysis of Leak Detection." Journal of Hydraulic Engineering **145**(6): 04019018.

Keramat, A., et al. (2019). "Objective Functions for Transient-Based Pipeline Leakage Detection in a Noisy Environment: Least Square and Matched-Filter." Journal of Water Resources Planning and Management **145**(10): 04019042.

Kim, S. (2014). "Inverse Transient Analysis for a Branched Pipeline System with Leakage and Blockage Using Impedance Method." Procedia Engineering **89**: 1350-1357.

Kim, S. (2022). "Time-domain impedance method for transient analysis and leakage detection in reservoir pipeline valve systems." Mechanical Systems and Signal Processing **167**: 108527.

Kim Sang, H., et al. (2014). "Diagnosis of a Pipeline System for Transient Flow in Low Reynolds Number with Impedance Method." Journal of Hydraulic Engineering **140**(12): 04014063.

Kim, S. H. (2005). "Extensive development of leak detection algorithm by impulse response method." Journal of Hydraulic Engineering **131**(3): 201-208.

Kim, S. H. (2017). "Multiple Leakage Function for a Simple Pipeline System." Water Resources Management **31**(9): 2659-2673.

Kim, S. H. (2018). "Development of Multiple Leakage Detection Method for a Reservoir Pipeline Valve System." Water Resources Management **32**(6): 2099-2112.

Lee Pedro, J. and P. Vitkovsky John (2010). "Quantifying Linearization Error When Modeling Fluid Pipeline Transients Using the Frequency Response Method." Journal of Hydraulic Engineering **136**(10): 831-836.

Lee Pedro, J., et al. (2008). "Valve Design for Extracting Response Functions from Hydraulic Systems Using Pseudorandom Binary Signals." Journal of Hydraulic Engineering **134**(6): 858-864.

Lee, P. J. (2013). "Energy analysis for the illustration of inaccuracies in the linear modelling of pipe fluid transients." Journal of Hydraulic Research **51**(2): 133-144.

Lee, P. J., et al. (2014). "Numerical and Experimental Study on the Effect of Signal Bandwidth on Pipe Assessment Using Fluid Transients." Journal of Hydraulic Engineering **141**(2): 04014074.

Lee, P. J., et al. (2013). "The effect of time–frequency discretization on the accuracy of the transmission line modelling of fluid transients." Journal of Hydraulic Research **51**(3): 273-283.

Lee, P. J., et al. (2006). "Experimental verification of the frequency response method for pipeline leak detection." Journal of Hydraulic Research **44**(5): 693-707.

Lee, P. J., et al. (2007). "Leak location in single pipelines using transient reflections." Australasian Journal of Water Resources **11**(1): 53-65.

Lee, P. J., et al. (2007). "Leak location in pipelines using the impulse response function." Journal of Hydraulic Research **45**(5): 643-652.

Lee, P. J., et al. (2002). Leak detection in pipelines using an inverse resonance method. 2002 Conference on Water Resources Planning & Management.

Lee, P. J., et al. (2005). "Frequency Domain Analysis for Detecting Pipeline Leaks." Journal of Hydraulic Engineering **131**(7): 596-604.

Lee, P. J., et al. (2005). "Leak location using the pattern of the frequency response diagram in pipelines: a numerical study." Journal of Sound and Vibration **284**(3): 1051-1073.

Li, J. and Z. Zhang (2024). "Pipeline leakage localization method based on transient signal detection and data fusion from multi-sensor." Journal of Hydroinformatics **26**(9): 2235-2250.

Liao, Z., et al. (2024). "Reducing linearization errors in the frequency domain analysis of fluid transients due to pipeline burst." Engineering Applications of Computational Fluid Mechanics **18**(1): 2397005.

Liao, Z., et al. (2021). "Deep learning identifies leak in water pipeline system using transient frequency response." Process Safety and Environmental Protection **155**: 355-365.

Liggett, A. and L. C. Chen (1994). "Inverse Transient Analysis in Pipe Networks." Journal of Hydraulic Engineering **120**(8): 934-955.

Lin, C.-C. and H.-D. Yeh (2019). "An Inverse Transient-Based Optimization Approach to Fault Examination in Water Distribution Networks." Water **11**(6): 1154.

Lin, J., et al. (2021). "Multi-Sensor Fusion for Transient-Based Pipeline Leak Localization in the Dempster-Shafer Evidence Framework." Water Resources Research **57**(9): e2021WR029926.

Liou, C. P. (1998). "Pipeline Leak Detection by Impulse Response Extraction." Journal of Fluids Engineering **120**(4): 833-838.

Liu, F., et al. (2025). "Frequency-informed transformer for real-time water pipeline leak detection." Autonomous Intelligent Systems **5**(1): 11.

Meniconi, S., et al. (2011). "Small Amplitude Sharp Pressure Waves to Diagnose Pipe Systems." Water Resources Management **25**(1): 79-96.

Motazedi, N. and S. Beck (2017). "Leak detection using cepstrum of cross-correlation of transient pressure wave signals." Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science: 0954406217722805.

Mpesha, W., et al. (2001). "Leak Detection in Pipes by Frequency Response Method." Journal of Hydraulic Engineering **127**(2): 134-147.

Mpesha, W., et al. (2002). "Leak detection in pipes by frequency response method using a step excitation." Journal of Hydraulic Research **40**(1): 55-62.

Nash, G. A. and B. W. Karney (1999). "Efficient inverse transient analysis in series pipe systems." Journal of Hydraulic Engineering **125**(7): 761–764.

Nixon, W., et al. (2006). "Range of Validity of the Transient Damping Leakage Detection Method." Journal of Hydraulic Engineering **132**(9): 944-957.

Nixon, W. and S. Ghidaoui (2007). "Numerical Sensitivity Study of Unsteady Friction in Simple Systems with External Flows." Journal of Hydraulic Engineering **133**(7): 736-749.

Pan, B., et al. (2022). "Efficient leak detection in single and branched polymeric pipeline systems by transient wave analysis." Mechanical Systems and Signal Processing **162**: 108084.

Pan, B., et al. (2022). "Efficient Pipe Burst Detection in Tree-Shape Water Distribution Networks Using Forward-Backward Transient Analysis." Water Resources Research **58**(11): e2022WR033465.

Pan, B., et al. (2021). "FRF-based transient wave analysis for the viscoelastic parameters identification and leak detection in water-filled plastic pipes." Mechanical Systems and Signal Processing **146**: 107056.

Rad, N. V., et al. (2024) Investigation of Pressure Signal and Leak Detection in Pipes by Using Wavelet Transform in Transient Flow. Engineering Proceedings **69**, DOI: 10.3390/engproc2024069076

Rahmanshahi, M., et al. (2017). "Leak Detection in Viscoelastic Pipeline using Inverse Transient Analysis."

Ranginkaman, M. H., et al. (2017). "Application of the Frequency Response Method for Transient Flow Analysis of Looped Pipe Networks." International Journal of Civil Engineering **15**(4): 677-687.

Ranginkaman, M. H., et al. (2016). "INVERSE FREQUENCY RESPONSE ANALYSIS FOR PIPELINES LEAK DETECTION USING THE PARTICLE SWARM OPTIMIZATION." IUST **6**(1): 1-12.

Rezapour, I., et al. (2021). "Case study of leak detection based on Gaussian function in experimental viscoelastic water pipeline." Water Supply **21**(7): 3860-3874.

Rubio Scola, I., et al. (2017). "Blockage and Leak Detection and Location in Pipelines Using Frequency Response Optimization." Journal of Hydraulic Engineering **143**(1): 04016074.

Sabzkouhi, A. M. and A. Haghighi (2018). "Uncertainty Analysis of Transient Flow in Water Distribution Networks." Water Resources Management.

Salvatore, B., et al. (1998). "Leak detection in liquefied gas pipelines by artificial neural networks." AIChE Journal **44**(12): 2675-2688.

Sattar, A. M. and M. H. Chaudhry (2008). "Leak detection in pipelines by frequency response method." Journal of Hydraulic Research **46**(sup1): 138-151.

Shamloo, H. and A. Haghighi (2009). "Leak detection in pipelines by inverse backward transient analysis." Journal of Hydraulic Research **47**(3): 311-318.

Shamloo, H. and A. Haghighi (2010). "Optimum leak detection and calibration of pipe networks by inverse transient analysis." Journal of Hydraulic Research **48**(3): 371-376.

Sintef-Ife, O. (1990). Model Numerics and Users Guide, Internal Publication.

Soares, A. K., et al. (2011). "Leak detection by inverse transient analysis in an experimental PVC pipe system." Journal of Hydroinformatics **13**(2): 153.

Srirangarajan, S., et al. (2012). "Wavelet-based Burst Event Detection and Localization in Water Distribution Systems." Journal of Signal Processing Systems **72**(1): 1-16.

Stephens, M. L., et al. (2004). Field Tests for Leakage, Air Pocket, and Discrete Blockage Detection Using Inverse Transient Analysis in Water Distribution Pipes. 6th Annual Symposium on Water Distribution Systems Analysis. Salt Lake City, Utah, USA, American Society of Civil Engineers.

Taghvaei, M., et al. (2007). "Leak detection in pipeline networks using low-profile piezoceramic transducers." Structural Control and Health Monitoring **14**(8): 1063-1082.

Taghvaei, M., et al. (2006). "Leak detection in pipelines using cepstrum analysis." Measurement Science and Technology **17**(2): 367.

Torres, L., et al. (2009). Multi-leak estimator for pipelines based on an orthogonal collocation model. Decision and Control, 2009 held jointly with the 2009 28th Chinese Control Conference. CDC/CCC 2009. Proceedings of the 48th IEEE Conference on, IEEE.

Vitkovsky, J., et al. (2003). Leak blockage detection in pipelines via an impulse response method. Pumps, Electromechanical Devices and Systems Applied to Urban Water Management. E. Cabrera and E. C. Jr. Lisse, The Netherelands, A.A. Balkema Publishers. **1:** 423–430.

Vitkovsky John, P., et al. (2007). "Experimental Observation and Analysis of Inverse Transients for Pipeline Leak Detection." Journal of Water Resources Planning and Management **133**(6): 519-530.

Vítkovský John, P., et al. (2011). "Head- and Flow-Based Formulations for Frequency Domain Analysis of Fluid Transients in Arbitrary Pipe Networks." Journal of Hydraulic Engineering **137**(5): 556-568.

Vitkovsky, J. P., et al. (2003). "Optimal Measurement Site Locations for Inverse Transient Analysis in Pipe Networks." Journal of Water Resources Planning and Management **129**(6): 480-492.

Vitkovsky, J. P., et al. (2002). Minimization algorithms and experimental inverse transient leak detection. Conference on Water Resources Planning and Management (2002 : Roanoke, Virginia, USA).

Vitkovsky, P., et al. (2000). "Leak Detection and Calibration Using Transients and Genetic Algorithms." Journal of Water Resources Planning and Management **126**(4): 262-265.

Wang, X.-J., et al. (2002). "Leak Detection in Pipelines using the Damping of Fluid Transients." Journal of Hydraulic Engineering **128**(7): 697-711.

Wang, X. (2021). "Uniformly optimal multi-sensor design in pipe networks for transient-based leakage localization." Mechanical Systems and Signal Processing **149**: 107216.

Wang, X. (2022). "Fast computation of inverse transient analysis for pipeline condition assessment via surrogate modeling with sparse sampling strategy." Mechanical Systems and Signal Processing **162**: 107995.

Wang, X. (2022). "Pipeline leakage alarm via bootstrap-based hypothesis testing." Mechanical Systems and Signal Processing **179**: 109334.

Wang, X. and M. Ghidaoui (2017). Pipeline leak detection using the matched-field processing method.

Wang, X. and M. S. Ghidaoui (2018). "Identification of multiple leaks in pipeline: Linearized model, maximum likelihood, and super-resolution localization." Mechanical Systems and Signal Processing **107**: 529-548.

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

Wang, X., et al. (2022). "Confidence interval localization of pipeline leakage via the bootstrap method." Mechanical Systems and Signal Processing **167**: 108580.

Wang, X., et al. (2020). "Pipeline leak localization using matched-field processing incorporating prior information of modeling error." Mechanical Systems and Signal Processing **143**: 106849.

Waqar, M., et al. (2021). "Model-Free Matched Field Processing for Condition Assessment of Pressurized Pipes." Journal of Water Resources Planning and Management **147**(10): 04021066.

Waqar, M., et al. (2025). "Pipeline leak detection using hydraulic transients and domain-guided machine learning." Mechanical Systems and Signal Processing **224**: 111967.

Xu, C., et al. (2024). "High-resolution pipeline leak localization using the side-lobes of the defect detection functional of matched-field processing." Mechanical Systems and Signal Processing **217**: 111529.

Zecchin Aaron, C., et al. (2012). "Inverse Laplace Transform for Transient-State Fluid Line Network Simulation." Journal of Engineering Mechanics **138**(1): 101-115.

Zecchin Aaron, C., et al. (2009). "Transient Modeling of Arbitrary Pipe Networks by a Laplace-Domain Admittance Matrix." Journal of Engineering Mechanics **135**(6): 538-547.

Zecchin, A. C., et al. (2013). "Parameter identification of fluid line networks by frequency-domain maximum likelihood estimation." Mechanical Systems and Signal Processing **37**(1): 370-387.

Zhang, Y., et al. (2022). "On the leak-induced transient wave reflection and dominance analysis in water pipelines." Mechanical Systems and Signal Processing **167**: 108512.

Zhang, Y., et al. (2023). "Transient wave-leak interaction analysis for improved leak detection in viscoelastic pipelines." Measurement **208**: 112442.

Zhang, Y., et al. (2024). "Formulation and analysis of transient flows in fluid pipelines with distributed leakage." Mechanical Systems and Signal Processing **212**: 111294.