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Investigating fluid-structure interaction and transient flow dynamics for enhanced pipeline fault detection

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ABSTRACT

Objective: The objective of this study is to investigate how fluid–structure interaction (FSI), along with unsteady friction, viscoelastic wall behavior, and potential column separation, affects transient pressure signals in pipelines and influences the accuracy of fault detection.

Method: To achieve this, a controlled experimental pipeline loop was employed, and simulations were performed using the Method-of-Characteristics (MOC). The study examined the effects of FSI through Poisson and junction coupling, valve maneuvers, and both elastic and viscoelastic pipe models.

Results: The results show that FSI systematically amplifies transient pressure fluctuations and can mimic the signatures of leaks or blockages. Sensor placement, valve-closure time, and axial support stiffness significantly influence the magnitude of FSI effects. Moreover, viscoelastic pipe models dissipate energy and attenuate oscillations, leading to better agreement with experimental measurements and enhanced system robustness.

Conclusions: The study highlights that accurate transient-based fault detection requires explicit modeling of FSI and careful consideration of measurement layout, actuation timing, and structural support in the design of fault-detection systems to ensure reliability.

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Introduction

This study focuses on improving the detection and management of pipeline faults through the analysis of fluid-structure interaction (FSI) and transient flow dynamics. The growing demand for water resources and the increasing complexity of pipeline networks make this an essential area of research. The objective of this work is to address the challenge of accurately identifying pipeline defects such as leakage, blockages, and structural weaknesses, which are critical for ensuring the reliability of water transmission systems (Chen et al., 2022; Islam, 2023).

The literature reveals substantial progress in understanding transient flows, particularly in their application to fault detection. For instance, (Tijsseling, 1996) provided a comprehensive review of water hammer effects, while (Wiggert, & Tijsseling, 2001) explored FSI mechanisms. (Colombo et al., 2009) examined transient-based leak detection methods, highlighting the potential of using transient signals for fault identification. However, there remains a gap in integrating these findings into robust, field-applicable diagnostic systems.

To address this gap, the methodology adopted in this study involves constructing a controlled experimental pipeline system, utilizing state-of-the-art measurement techniques, and validating the results through numerical simulations. Specifically, the method of characteristics (MOC) is employed to analyze transient events (Colombo et al., 2009; Joshi & Jaiman, 2018). By combining experimental and computational approaches, this research aims to bridge the gap between theoretical understanding and practical application.

The key results demonstrate the critical influence of FSI on pressure signal fluctuations during transient events. These fluctuations can mimic fault signals, underscoring the importance of accounting for FSI effects in fault detection systems. The findings highlight the need for improved support designs and advanced modeling techniques to enhance diagnostic accuracy and pipeline resilience.

Various numerical methods, including mathematical, graphical, and implicit methods, have been developed for transient flow analysis. Among these, the method of characteristics (MOC) is widely recognized for its accuracy in modeling unsteady flows (Joshi & Jaiman, 2018).

Factors Influencing Transient Flow Signals:Several factors significantly influence transient flow signals, each contributing uniquely to the complexity of fault detection in pipeline systems.

Fluid Column Separation (CS): Fluid column separation occurs when the pressure within a pipeline drops below the vapor pressure of the fluid, leading to cavity formation. This phenomenon can cause severe pressure fluctuations upon cavity collapse, which affects the integrity of the pipeline system. (Adamkowski & Lewandowski, 2009) developed a new method for predicting liquid column separation during hydraulic transients, enhancing the reliability of such predictions. Studies such as (Wiggert, & Tijsseling, 2001) have extensively analyzed the implications of this phenomenon.

Unsteady Friction (UF): Unsteady friction refers to transient, non-permanent frictional effects arising during changes in flow conditions. Unlike steady-state friction, these effects are time-dependent and can significantly dampen or amplify transient signals. (Zielke, 1968) introduced a convolution-based model to account for unsteady friction in transient pipe flow, providing a theoretical basis for understanding these effects.

Viscoelastic Properties of Pipe Walls (VE): The viscoelastic behavior of pipeline walls influences the propagation of pressure waves during transient events. This property causes energy dissipation and changes in wave speed, which are critical for accurately modeling transient flow (Meniconi et al., 2012). investigated the impact of pipe wall viscoelasticity on water hammer phenomena, highlighting the importance of considering material properties in transient analysis.

Leakage and Clogging: Pipeline faults such as leaks and clogs introduce localized pressure variations that interfere with transient signals. Identifying these faults requires distinguishing their effects from other damping mechanisms. (Colombo et al., 2009) conducted a selective

literature review of transient-based leak detection methods, discussing techniques for isolating fault-induced fluctuations.
These factors collectively influence the damping and fluctuations in transient flow signals, complicating the process of identifying and analyzing pipeline faults.
Pressure Head and Sensor Position:
Fig. 1 illustrates the transient pressure head (H) as a function of time (ms) for varying sensor positions along the pipeline. The position of the sensors is normalized using E1.

$$Ls=\frac{L\_sensor}{L\_pipeline}\times 100 \quad (1)$$

The results show that pressure signals exhibit distinct variations depending on the proximity of the sensors to the transient source (water hammer valve). Sensors closer to the valve capture sharper pressure changes and higher amplitudes, indicating the significant influence of sensor position on capturing transient phenomena.
The schematic demonstrates the experimental setup used to assess the influence of sensor positioning on pressure signal detection (Fig. 2). Sensors are strategically placed along the pipeline, with one near the water hammer valve (downstream) and another near the reservoir (upstream). This arrangement highlights the importance of sensor placement for accurately capturing pressure wave characteristics.

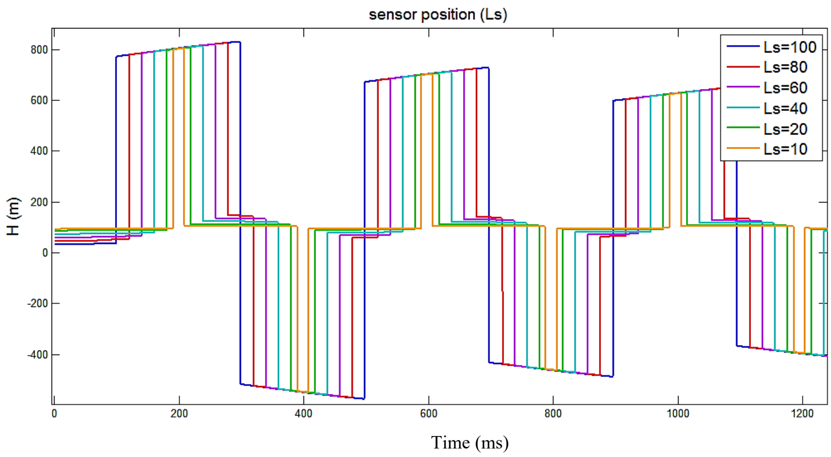

Figure 1. Effect of sensor position (Ls) on transient pressure head (H) over time

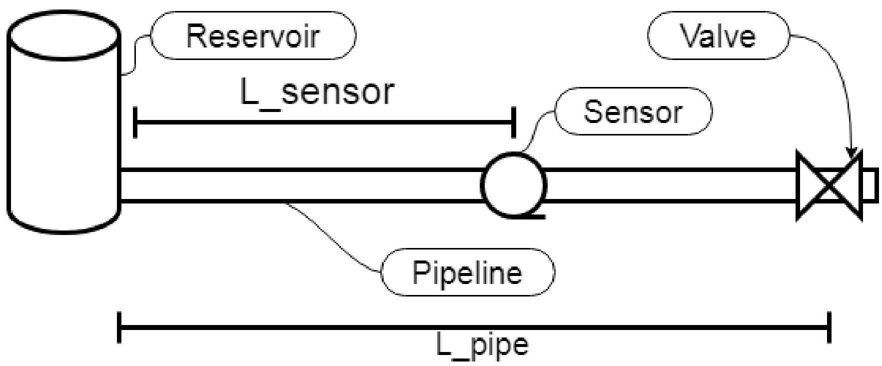

Figure 2. Schematic diagram of the experimental setup, including the reservoir, pipeline, valve, and sensor

The analysis confirms that the optimal position for pressure sensors is near the water hammer valve, where the system is most actively stimulated. Pressure waves diminish in intensity as they propagate further from the transient source, making downstream locations more suitable for capturing high-resolution pressure data. Additionally, the placement of a second sensor near the reservoir ensures accurate measurement of baseline pressure conditions, providing a reference for analyzing transient signals.

Fluid-Structure Interaction (FSI): Fluid-Structure Interaction (FSI) occurs when the fluid within a pipe interacts significantly with the structural dynamics of the pipe itself. This interaction becomes particularly critical during transient flow events, where sudden changes in flow conditions can amplify the effects. FSI often leads to axial vibrations and propagating stress waves within the pipe, which, if not adequately supported, can result in substantial displacements and potentially compromise the pipeline's integrity. Early studies, such as those by (Wiggert, & Tijsseling, 1996), laid the groundwork for understanding these dynamics in flexible piping systems.One key area of focus in FSI research is the behavior of pressure signals during transient events. These signals are most prominent in the first half-period of the transient flow, where their characteristics can provide insights into the interaction's mechanisms. Studies like (Tijsseling, 1996) emphasize the importance of analyzing this phase to accurately model and predict FSI effects.

Three primary coupling mechanisms characterize FSI:

Poisson Coupling: This mechanism arises from the pressure-induced axial stress within the pipeline. Poisson coupling influences how axial forces are distributed along the pipe's length, as discussed in early theoretical works by (Zielke, 1968).

Friction Coupling: Caused by the fluid friction along the pipe walls, this mechanism affects the transient flow's damping characteristics (Colombo et al., 2009). highlighted the role of friction coupling in modifying the amplitude of pressure waves.

Junction Coupling: This mechanism originates from discontinuities or fittings in the pipeline system, such as elbows or valves. Junction coupling's significance in transient flow behavior was explored in depth by (Adamkowski & Lewandowski, 2009), who investigated its impact on pressure wave reflections and refractions.

The Fig. 3 illustrates the propagation of stress waves and pressure waves in a pipeline system during transient flow events. It shows the interaction of these waves when a valve is opened, demonstrating the effects of fluid-structure interaction (FSI) at various stages. Stress waves originate from the pipe walls due to structural dynamics, while pressure waves travel through the fluid, highlighting the coupled nature of the system. This visualization emphasizes how FSI influences transient flow behaviors, such as wave reflection and transmission, which are critical for analyzing pipeline stability and fault detection.

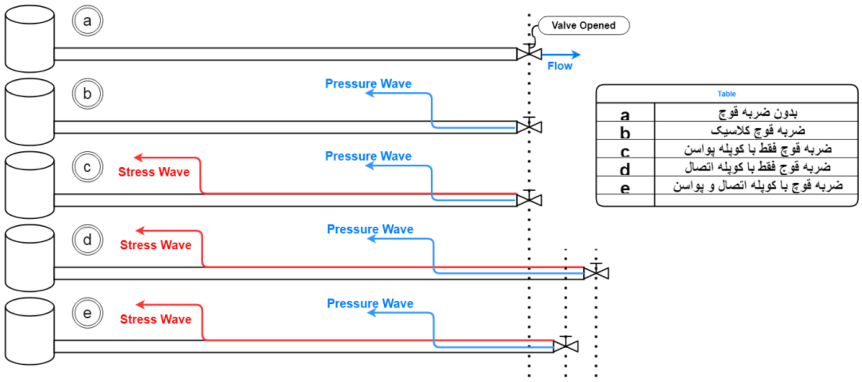

Figure 3. Wave propagation in a pipeline system during transient flow events, depicting stress waves (red) in the pipe walls and pressure waves (blue) in the fluid after valve operation:(a) Initial state: Valve is opened, and no flow or wave activity occurs. (b) Valve is opened, generating a pressure wave (blue) that propagates through the fluid. (c) Stress wave (red) in the pipe wall begins to interact with the pressure wave. (d) The stress and pressure waves reflect and propagate in the pipeline. (e) Multiple interactions between stress and pressure waves continue as transient flow stabilizes

Effect of Valve Closure Time: Fig.4 illustrates the effect of valve closure time (Tc) on transient pressure signals (H) in a pipeline system. As Tc decreases, represented by the blue curve (Tc=0.01), the pressure signal exhibits sharp and oscillatory peaks, indicating significant water hammer effects due to rapid valve closure. Conversely, as Tc increases (e.g., Tc=0.05, Tc=0.1, and Tc=0.15), the oscillations become smoother and less pronounced, reflecting a gradual dissipation of energy and reduced transient effects. (Colombo et al., 2009) studied the influence of valve closure time on pressure signals caused by water hammer and found that valve closure time plays a critical role in both fluid-structure interaction (FSI) and in detecting leaks and blockages in the system. As shown in the fig. 5, increasing the valve closure time reduces the intensity of the jumps caused by FSI. This trend highlights that longer valve closure times mitigate the intensity of pressure oscillations, leading to a more stable pressure response and reduced stress on the pipeline structure.

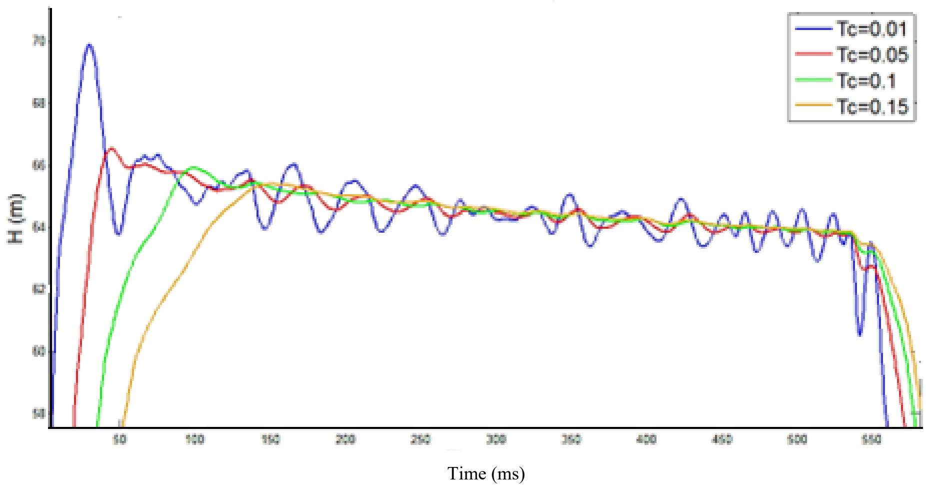

Figure 4. Effect of valve closure time (Tc) on transient pressure head (H) over time. Rapid closure (Tc=0.01) leads to higher oscillations, while slower closures (Tc=0.05–0.15) reduce oscillation intensity

Effect of Pipe Support Stiffness: The stiffness of pipe supports plays a crucial role in influencing pressure signals during transient flow. Research has shown that higher support stiffness can amplify pressure fluctuations, while inadequate stiffness may result in errors or larger pressure jumps (Wiggert & Tijsseling, 1985). demonstrated that higher support stiffness increases pressure compared to classic cases, highlighting the need for precise stiffness calibration in pipeline designs (Wiggert & Tijsseling, 2001). insufficient support stiffness leads to errors in transient analysis, making accurate stiffness evaluation critical for reliable modeling (Colombo et al., 2009). In another study, (Duan et al., 2010) found that lower support stiffness causes larger pressure jumps during transient events. Their findings underscore the importance of optimizing support design to mitigate such effects (Duan et al., 2010). Moreover, (Monteiro Andrade et al.,2023) investigated the impact of fixed and viscoelastic supports on fluid-structure interaction (FSI). Their results showed that support type and material significantly affect transient signal behavior, offering insights for improving pipeline resilience (Keramat et al., 2012;Meniconi et al., 2012).

These studies collectively emphasize the importance of proper support design in mitigating FSI-induced pressure fluctuations and ensuring pipeline system reliability. These findings emphasize the importance of proper support design to mitigate FSI-induced pressure fluctuations.

Method

The objective of this study is to address the research question: How can fluid-structure interaction (FSI) effects be accurately accounted for to improve pipeline fault detection? The relevance of this question lies in both theoretical advancements in transient flow analysis and practical applications in ensuring the reliability of water transmission systems.

Research Framework

The research framework combines experimental investigations with numerical simulations. A controlled experimental pipeline system was constructed, allowing for precise manipulation of flow conditions and structural dynamics. High-density polyethylene pipes were used for their viscoelastic properties, which are essential for studying FSI phenomena.

Experimental Setup

The experimental model was designed in the Hydraulic Laboratory at Shahid Chamran University of Ahvaz (Keramat et al., 2020). It includes a tank-pipe-valve system to simulate transient flow events. The detailed specifications of the pipeline system used in this study are summarized in Table 1. And Fig. 5 provides a comprehensive visual representation of the experimental setup used for investigating transient flow and fluid-structure interaction (FSI). The setup includes key components such as an air vessel, water supply pump, bypass and input water regulator valve, and transient and flow control valves.

Table 1. Pipeline specifications used in the experimental setup for studying fluid-structure interaction and transient flow behavior.

Specification	Pipe Material	Outer Diameter	Length	Wall Thickness	Young's Modulus	Poisson's Ratio
Values	High-density polyethylene	63 mm	158 m	6.5 mm	1.43 GPa	0.46

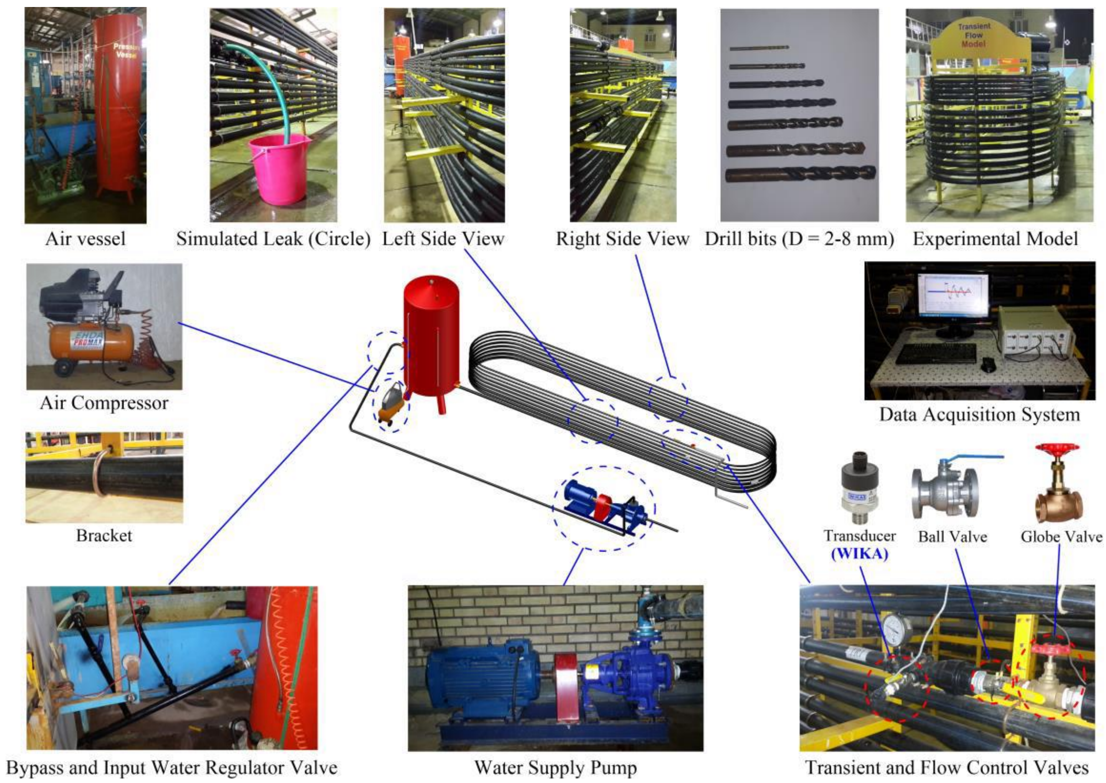

Figure 5. Overview of the experimental setup for transient flow and fluid-structure interaction (FSI) studies, including an air vessel, water pump, control valves, simulated leaks, and a data acquisition system (Rahmanshahi, 2016)

The system was installed in a semicircular frame to minimize secondary flows at sharp turns. Metal fasteners with plastic coatings were used to prevent lateral and longitudinal movements of the pipes. The schematic diagram illustrates the experimental setup used for studying transient flow behavior and fluid-structure interaction (FSI) in a pipeline system. The setup includes a pressure vessel with an adjustable water level, inlet flow control, and a pipeline equipped with pressure sensors for data collection. Key components such as a water hammer valve and flow control valve are also shown (Fig. 6), enabling precise manipulation of flow conditions to simulate transient events and analyze their effects on the system.

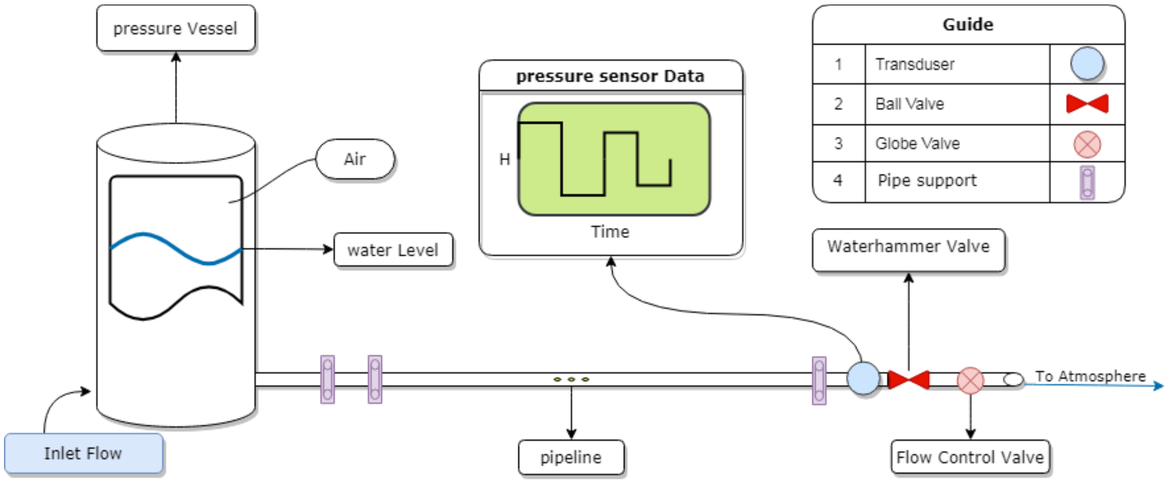

Figure 6. Schematic of the experimental setup used to study transient flow and fluid-structure interaction (FSI) in pipelines, highlighting the pressure vessel, control valves, and pressure sensors

Effect of Structural Vibrations and Noise on Pressure Sensor

Fluid-structure interaction (FSI) causes vibrations in the pipeline, while system noise introduces uncertainty in pressure signal reflections and jumps, reducing the accuracy of identifying weak parameters such as magnitude, length, and location of faults (Duan, 2015). To evaluate the influence of structural vibrations on pressure sensors near the transient flow source, specifically at the valve location, an additional sensor was employed. As shown in the schematic diagram, this second sensor was exclusively attached to the pipeline structure and had no direct contact with the fluid inside the pipe. Additionally, a reference pressure sensor, which was not attached to any part of the system, was used to monitor environmental noise.

After generating the transient flow, the signals from all three sensors were compared. Since pipeline vibrations enter a critical state at high flow rates, the experiment was repeated three times at a flow rate of 2.4 L/s. The results, shown in Fig. 8, reveal that at higher frequencies, oscillations appeared in the sensors. Repeating the experiments confirmed that these oscillations were due to environmental noise, which was mitigated using a low-pass filter in MATLAB to process the data recorded by the data logger.

The experimental results demonstrated that the pressure jumps observed during the first half-period of the transient signal were not influenced by sensor vibrations. Furthermore, the repeatability of the tests indicated that these oscillations were not random but were driven by underlying mechanisms affecting the signal. This finding highlights the importance of accurate noise filtering and structural vibration analysis in transient flow studies.

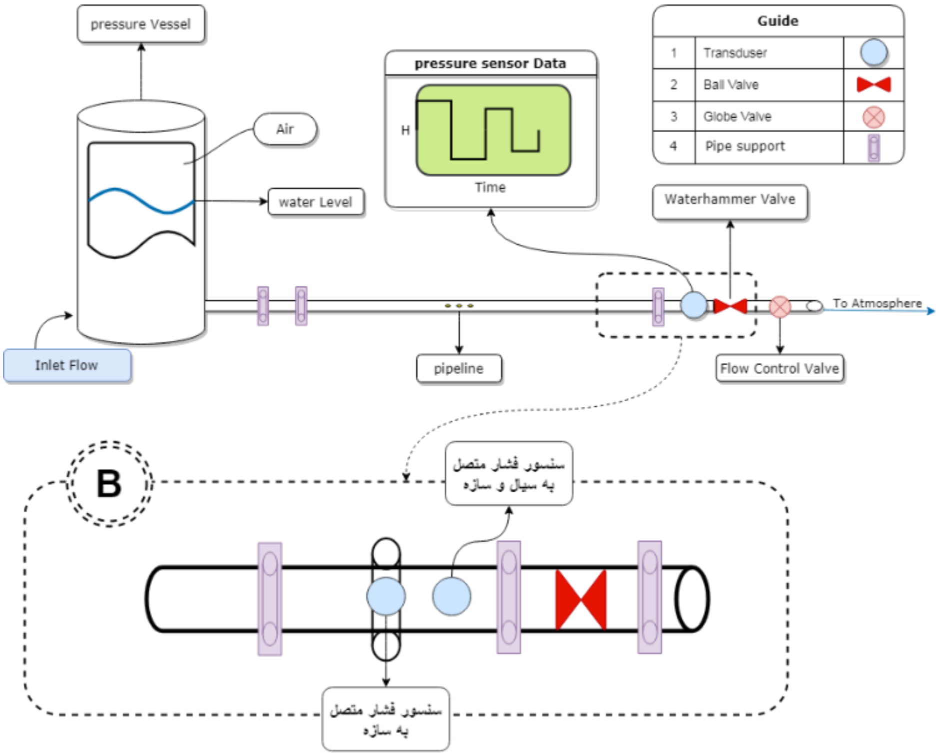

Figure 7. Schematic of the experimental setup, including the pressure vessel, inlet flow, water level, pipeline, waterhammer valve, flow control valve, and pressure sensors attached to the fluid and structure for transient flow analysis

Data Collection and Analysis

To ensure accuracy, noise removal from collected signals was achieved using a low-pass frequency filter. Experiments were repeated three times under each condition to validate repeatability. The transient signals were analyzed to observe the effects of FSI, including damping and pressure fluctuations.

Numerical Simulation

The Method of Characteristics (MOC) was employed for numerical analysis of transient flow events. This method, recognized for its accuracy, was used to model the interaction between fluid dynamics and structural responses. By integrating experimental results with computational simulations, the study aims to provide a comprehensive understanding of FSI in pipelines.
The chosen methods align with the research objectives, providing both theoretical insights and practical solutions for improving pipeline fault detection systems.

Governing Equations

The pressure wave occurs due to the phenomenon of ram impact in pressurized channels caused by a sudden change in speed downstream. For practical applications of transient flow in pressurized pipes, the mass and momentum conservation equations are commonly used (Covas et al., 2005). To derive the governing equations for transient flow with fluid-structure interaction (Poisson coupling) under viscoelastic pressure, the following assumptions are made: the pipe is straight, with a thin, homogeneous, and isotropic wall. The material of the pipe behaves linearly, and the fluid is single-phase and non-viscous. Friction effects are neglected, as the focus is on the first half-period of the pressure head where damping effects are insignificant.

The viscoelastic behavior of the pipe wall is described using the comprehensive Kelvin-Voigt model with a constant Poisson's ratio. These equations, representing one-dimensional flow in a horizontal pipe and ignoring transfer acceleration terms, are based on prior studies (Lavooij & Tijsseling, 1991; Keramat et al., 2012):

Fluid Momentum Equation:

$$\frac{\partial Q}{\partial t}+gA_f\frac{\partial \tilde{H}}{\partial z}=0 \qquad (2)$$

Fluid Continuity Equation:

$$\frac{1}{A_f}\frac{\partial Q}{\partial z}+\frac{g}{c_f^2}\frac{\partial \tilde{H}}{\partial t}-2\vartheta\frac{\partial \dot{u}_z}{\partial z}=(\vartheta^2-1)\rho_f g\frac{D}{e}\frac{\partial I_{\tilde{H}}}{\partial t} \qquad (3)$$

Axial Vibration of the Tube Wall:

$$\frac{\partial^2 u_z}{\partial t^2}-c_t^2\frac{\partial^2 u_z}{\partial z^2}-g\frac{\rho_f}{\rho_t}\frac{\vartheta D}{2e}\frac{\partial H}{\partial z}=E_0 g\frac{\rho_f}{\rho_t}\frac{\vartheta D}{2e}\frac{\partial I_{\tilde{H}}}{\partial z}-E_0 I_{\ddot{u}_z} \qquad (4)$$

In the governing equations for transient flow and fluid-structure interaction (FSI), the variables are
defined as follows:
Q: Volumetric flow rate (m^3/s).
H: Total head and perturbation head, respectively (m).
A_f: Cross-sectional area of the fluid (m^2).
C_f: Wave speed of the fluid (m/s).
g: Gravitational acceleration (m/s^2).
ϑ: Poisson ratio of the pipe material.
U_z: Axial displacement of the pipe wall (m).
ρ_f and ρ_t: Densities of the fluid and the pipe material (kg/m3), respectively.
D: Pipe diameter (m).
e: Wall thickness of the pipe (m).
E_0: Young's modulus of the pipe material (Pa).
C: Wave speed in the pipe wall (m/s).

Finite element analysis is applied to the pipe wall motion, while the method of characteristics is employed for the fluid. This approach demonstrates how fluid-structure interaction influences water hammer parameters in elastic and viscoelastic pipes, differing from classical theory.

Results

Experimental results indicate that FSI significantly impacts pressure signal fluctuations during the first half-period of transient flow. These fluctuations closely resemble those caused by pipeline faults such as leakage and clogging. Properly accounting for FSI effects is crucial for accurate fault detection. If FSI is neglected, ensuring adequate stiffness of valve supports can mitigate pressure jumps and improve detection accuracy. The transient pressure head (H) as a function of time (ms) for an elastic pipeline material is presented in Fig. 8. The blue line represents the case with no Poisson coupling, showing a significantly lower pressure response. In contrast, the orange and purple lines correspond to cases with only Poisson coupling and both Poisson and junction coupling, respectively. The results demonstrate that Poisson coupling substantially increases pressure oscillations, while the addition of junction coupling further amplifies and stabilizes the response. This highlights the significant influence of coupling mechanisms on transient flow dynamics in elastic materials.

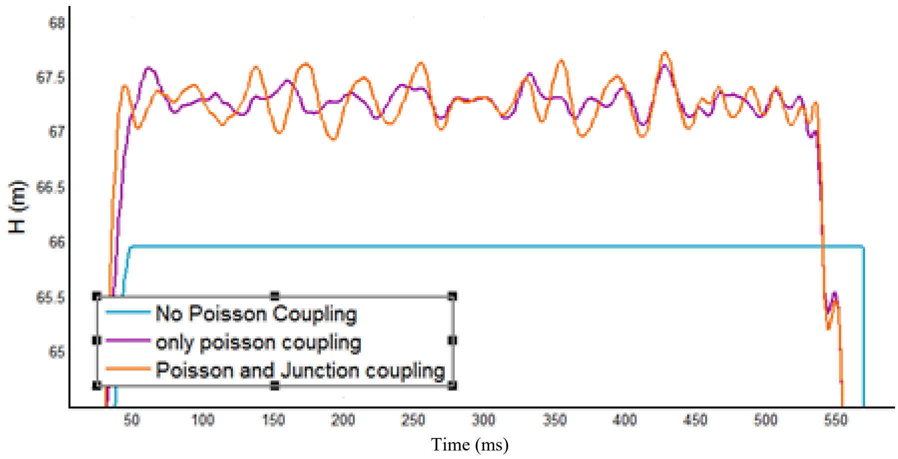

Figure 8. Comparison of transient pressure head (H) under elastic conditions for different coupling mechanisms: no Poisson coupling, only Poisson coupling, and Poisson with junction coupling.

Fig. 9 shows the transient pressure head (H) over time for a viscoelastic pipeline material. Compared to the elastic case, the pressure response is notably dampened. The blue line, representing no Poisson coupling, exhibits a significantly reduced pressure head. Meanwhile, the orange and purple lines, corresponding to only Poisson coupling and both Poisson and junction coupling, demonstrate the effect of viscoelasticity in mitigating pressure oscillations. These findings emphasize the energy-dissipating properties of viscoelastic materials, which reduce the intensity of pressure waves.

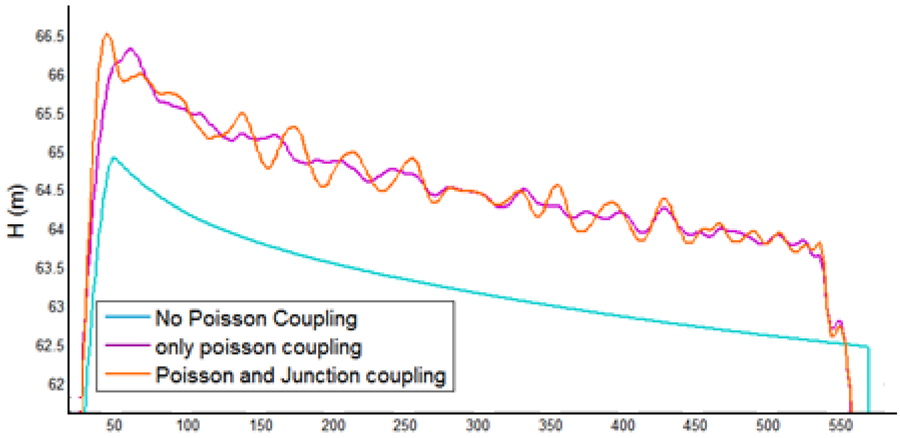

Figure 2. Comparison of transient pressure head (H) under viscoelastic conditions for different coupling mechanisms: no Poisson coupling, only Poisson coupling, and Poisson with junction coupling.

The comparison between elastic and viscoelastic cases underscores the critical role of material properties in influencing transient flow behavior. Elastic materials exhibit higher pressure oscillations, making them more prone to structural stress and potential failure under transient conditions. In contrast, viscoelastic materials effectively dampen pressure waves, reducing the risk of high-intensity oscillations. Furthermore, the inclusion of Poisson and junction coupling mechanisms enhances the understanding of dynamic interactions, demonstrating their importance in accurately modeling pipeline systems.

These findings validate the experimental setup and underscore the necessity of considering material properties and coupling mechanisms in the design and analysis of pipeline systems.

Fig. 10 compares the pressure head (H) over time for two scenarios: water hammer with fluid-structure interaction (FSI) and classic water hammer without FSI. The blue line represents the water hammer with FSI, showing significant oscillations and higher amplitude pressure peaks due to the dynamic interaction between the fluid and the pipeline structure. In contrast, the red dashed line represents the classic water hammer, which follows a predictable pressure decay with no additional oscillations. The chart highlights the influence of FSI in amplifying and sustaining pressure oscillations over time, which is critical for understanding the complexities of transient flow in pipeline systems. This comparison underscores the necessity of considering FSI effects in the design and analysis of hydraulic systems to predict and mitigate potential risks effectively.

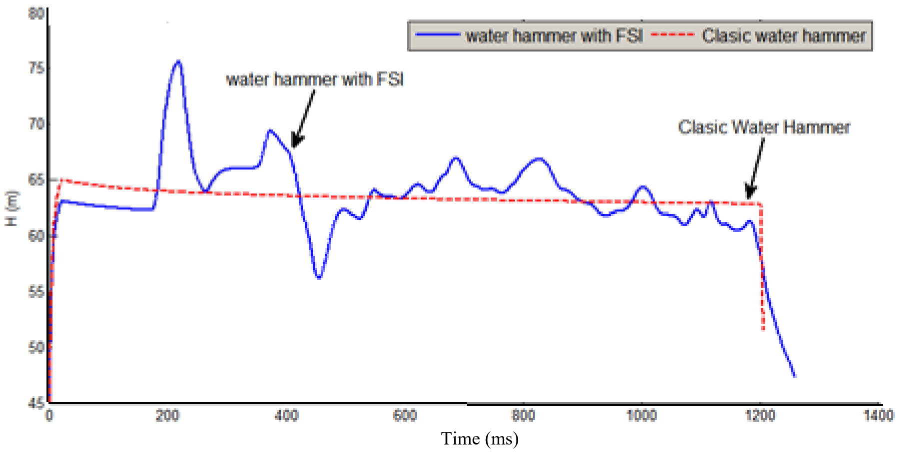

Figure 3. Comparison of water hammer effects with and without fluid-structure interaction (FSI). The blue line shows water hammer with FSI, exhibiting amplified oscillations, while the red dashed line represents the classic water hammer with a predictable pressure decay.

Experimental results indicate that FSI significantly impacts pressure signal fluctuations during the first half-period of transient flow. These fluctuations closely resemble those caused by pipeline faults such as leakage and clogging. Properly accounting for FSI effects is crucial for accurate fault detection. If FSI is neglected, ensuring adequate stiffness of valve supports can mitigate pressure jumps and improve detection accuracy.

Conclusions

This study delineates the coupled fluid–structure mechanisms that govern early-time transients used for pipeline fault detection. We show that fluid–structure interaction (FSI)—arising from Poisson coupling of circumferential strain to pressure and junction/axial coupling of the pipe to its supports—can amplify or phase-shift pressure responses to valve maneuvers, producing signatures that mask or mimic true faults (e.g., small leaks, incipient blockages). The magnitude of these FSI-induced fluctuations is not a fixed property of the fluid alone; it depends materially on structural boundary conditions. In particular, the stiffness and layout of valve and pipe supports regulate axial wall motion and therefore the local head jump during the first half-period. As a result, nominally identical hydraulic events can yield measurably different transients across installations with different support designs.

These findings have two immediate implications for reliable diagnostics. First, models and detection algorithms should explicitly account for FSI. In practice, that means using transient solvers (e.g., Method of Characteristics) with (i) wave-speed correction for circumferential compliance, (ii) junction/axial coupling to supports, (iii) viscoelastic wall rheology (e.g., Kelvin–Voigt or standard-linear-solid) to capture decay envelopes, and (iv) an appropriate treatment of unsteady friction where relevant. Second, where full FSI modeling is impractical, systems can be engineered to suppress the confounding effects: tune the effective support stiffness in the vicinity of actuated valves, select valve-closure laws that limit high-frequency content, and place sensors at positions that balance sensitivity with robustness to support-induced amplification.

For practitioners, we recommend the following workflow: (1) document and, where possible, estimate effective support stiffness and spacing near the actuation point; (2) calibrate wall viscoelastic parameters from ring-down tests to match measured decay; (3) report quantitative effect sizes for key design choices—sensor location, valve-closure time (Tc), and support stiffness (k)—using peak-to-peak head, time-to-first-extremum, and signal-to-noise ratio; and (4) perform a brief sensitivity/uncertainty analysis to establish how much apparent "fault signal" can be attributed to FSI under site-specific conditions. Taken together, these steps reduce false positives and improve the transferability of detection thresholds across assets.

Future work should integrate advanced modeling and field validation: coupled fluid–structure solvers with identifiable, minimal parameter sets; Bayesian calibration to propagate uncertainty in support stiffness and wall rheology to detection decisions; physics-informed learning to fuse pressure and structural vibration measurements; and multi-site trials to quantify how material (HDPE vs. steel), diameter, and support typologies scale FSI effects. Such developments will enable fault-detection methodologies that remain accurate across the full envelope of hydraulic actuation and structural variability encountered in modern distribution systems.

Author Contributions

All authors contributed equally to the conceptualization of the article and writing of the original and subsequent drafts.

Data Availability Statement

Data available on request from the authors.

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Ethical Considerations

The authors avoided data fabrication, falsification, plagiarism, and misconduct.

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Conflict of Interest

The authors declare no conflict of interest.

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