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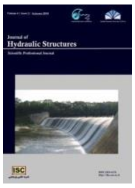

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# Experimental Analysis of Elastic Blockage in Viscoelastic Pipeline Systems

Saeed Rasouli[1]
Mehdi Ghomeshi[2]
Mahmood Shafai Bejestan[1]
Mostafa Rahmanshahi[3]
Alireza Keramat[3]

## Abstract

Blockages in water supply systems can arise from diverse causes, leading to pollution, energy loss, and reduced system performance. Detecting and addressing these blockages is crucial for managing pressurized systems like water supply and pipe networks. Analyzing pressure signals is a common method for detecting defects, with transient pressure signals being particularly effective compared to steady-state signals. This study focuses on experimentally investigating the impact of extended blockages on pressure signal characteristics in viscoelastic pipelines within the time and frequency domains. Elastic blockages of varying lengths and diameters were used in a laboratory experimental model of a viscoelastic pipeline. The findings reveal that blockages cause changes in the pressure signal shape, resonance frequencies, and phase in different domains. These changes are more pronounced with longer and higher percentage blockages. Increasing blockage length amplifies phase shifts and wave reflections, with pressure increase delayed by damping. Higher blockage percentages induce phase shifts and amplitude reflections during transient flow. Transient flow intensity affects only amplitude, not phase, with more pronounced reflections at high intensity. Blockage location influences the distribution of phase and amplitude frequencies. Geometric changes induce phase shifts and alter amplitude frequencies, while hydraulic characteristics solely impact amplitude.

**Keywords:** Transient Flow, Blockage, Viscoelastic Pipeline, Frequency Domain, Time Domain.

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[1] Faculty of Water and Environmental Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran.
[2] Faculty of Water and Environmental Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran. E-mail: m.ghomeshi@yahoo.com (**Corresponding Author**)
[3] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR.

## 1. Introduction

In the last two decades, there has been significant interest in using polymer pipes, such as polyethylene and PVC, in water supply systems and pipe networks [1]. These pipes have gained attention due to their excellent structural and hydraulic properties. Several studies have been conducted to investigate the behavior of polymeric pipes and the viscoelastic effects they exhibit when subjected to transient pressure oscillation [2–8].

Leakage and blockage are common issues encountered in piping systems, and they can lead to system failure, energy loss, and reduced efficiency. Various physical and chemical processes can cause these problems in pipelines and pipe networks. Transient flow has been employed to assess the effects of these defects. Many studies have explored transient flow and its application in determining the effects of defects in piping systems [8–14].

The most difficult fault to identify and handle is a partial obstruction, also known as a partial blockage, which does not show any external signs. Indirect indications of a partial blockage include decreased carrying capacity and increased pressure. However, these indications do not provide enough information to accurately locate or characterize the partial blockage through steady-state measurements. In water systems, partial blockages can occur due to the accumulation of sand, excessive calcium, and hydrates. Paraffin and asphaltene can obstruct the flow in pipelines that transport refined and crude oil. Additionally, in subsea pipelines, wax particles in the oil can crystallize and deposit on the inner surface due to low temperatures. These deposits, known as plaques and clots, act as partial blockages in the venous and arterial systems. In all cases, natural partial blockages start with minor irregularities on the inner walls of the pipes. If not detected early, they gradually protrude across the pipe's internal cross-sectional area, often taking on a radial and circumferential shape. A partial blockage can also be compared to an in-line valve carelessly set to a partially closed position [15,16].

Stephens et al. (2002) conducted field investigations using transient flows to identify blockages in a long pipeline within a piping system. They observed that the accuracy of blockage identification depended on the length of different segments in the pipe network. By artificially creating four blockages of two different sizes in a 575 mm long and 100 mm diameter pipeline, they found that the predicted blockage locations and size values closely matched the field measurements [17].

Adewumi et al. (2003) proposed a numerical method to determine the location and characteristics of extended blockages caused by hydrate deposition in gas pipelines. They demonstrated that transient pressures and the resulting pressure variations caused by blockage reflections could be used to identify the internal conditions of the system in the time domain [9]. Meniconi et al. (2012) examined the impact of changes in pipe cross-section on the behavior of transient waves with viscoelastic properties in a series pipeline system. Their findings indicated that pressure damping occurred over an extended period, while the effect of discontinuities was only significant during the initial phases of transient flow. They also compared the effects of partial blockages in two pipeline systems, one with elastic and the other with viscoelastic materials [18,19]. They determined the blockage characteristics using the Inverse Transient Analysis method and identified that the pipeline material, system boundary conditions, and blockage characteristics likely influenced prediction errors. Tuck et al. (2013) investigated the transient responses in a pipeline with and without extended blockages. They discovered that extended blockages altered the oscillation period depending on the length and severity of the blockage [11].

Duan et al. (2014) introduced an extended blockage in a pipeline and measured the resulting transient responses in the frequency domain. Their results demonstrated that the blockage affected resonant amplitudes and frequency locations, and a change in frequency location could be utilized to identify the location of the blockage [20].

Che et al. (2021) showed that a blockage in the pipe system affects the pressure heads. These changes may exceed the original transient design capacity and increase the risk of pipe system failure [21].

Based on previous research, a comprehensive study has not been conducted regarding the experimental investigation of the effect of extended elastic blockage on pressure signals in the time and frequency domain of viscoelastic pipelines. Most studies have either been numerical and conducted on elastic pipelines or have utilized multiple tests to determine blockage based on numerical methods. In this research, various experiments have been employed to investigate the effect of elastic blockage on pressure signals in viscoelastic pipelines. For this purpose, steel pipes with different diameters and lengths have been used to model the effect of varying blockage lengths and diameters on pressure signals. The blockage effect in this pipe system has been analyzed in both the time and frequency domains.

## 2. Material and methods

### 2.1. Experimental setup and data collection

For the experimental investigation of the effects of blockage on transient flow characteristics through a polyethylene pipeline constructed in the Faculty of Water and Environmental Engineering Hydraulic Laboratory at Shahid Chamran University of Ahvaz, the overall view of the experimental model is shown in Figure 1. The main pipeline consists of 158 m of 2-inch polyethylene pipe made of High-Density Polyethylene (HDPE100) with a nominal diameter (ND) of 63 mm, a wall thickness of 63 mm (SDR11), and a nominal pressure (NP) of 16 bar. A pressure vessel with a volume of 700 liters is placed as the upper boundary condition of the pipeline system at the system's beginning. To prevent the separation of the fluid column during the propagation of negative pressure waves, an air compressor is connected to the upper part of the reservoir to stabilize the reservoir pressure and provide a constant initial pressure for the pipeline system.

A ball valve is placed at the end of the pipeline to generate transient flow in the experiments. A globe valve located at the downstream end of the transient flow valve controls and adjusts the steady flow rate. The steady flow rate is also measured volumetrically at the end of the system. The flow is discharged into the drain pipe at the end of the path and then enters the laboratory reservoir through a channel. The pipes are anchored to the metal structure to prevent longitudinal and lateral movements of the system during the experiments. Pressure signals upstream of the transient flow valve (TR#1) and at the location of the pressurized reservoir (TR#2) are measured using the WIKA S-11 pressure transducer with a measurement range of zero to 16 bar and a sampling rate of 1 KHz.

To model blockages in the pipeline, pipes with smaller diameters ($D_b$) and lengths ($L_b$) are placed along the pipeline, as shown in Figure 2. The locations and specifications of the created blockages in the pipeline are presented in Table 1. Experiments were conducted on the model with and without blockages for different values of steady flow rates of 0.5 and 1 l/s under turbulent flow conditions.

The procedure for conducting the experiments in this study was as follows: first, the air compressor stabilized the pressure vessel, and the desired steady flow rate was adjusted at the end of the system. Then, by rapidly closing the ball valve at the end of the pipeline, transient flow was generated in the system, and pressure signals were measured using pressure transducers and a data acquisition system.

In this research, the pressure signal has been analyzed in both the time and frequency domains. The pressure signal in the time domain was obtained directly from the data logger. However, the Fast Fourier Transform was used to convert the time domain signal to the frequency domain.

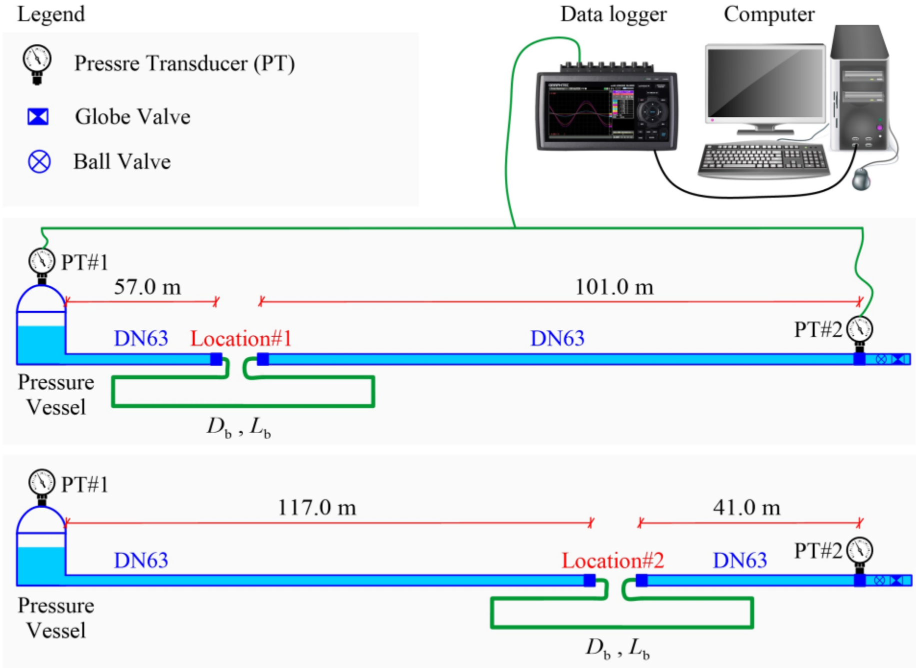


**Figure 1. Schematic of experimental facility and data collection system**

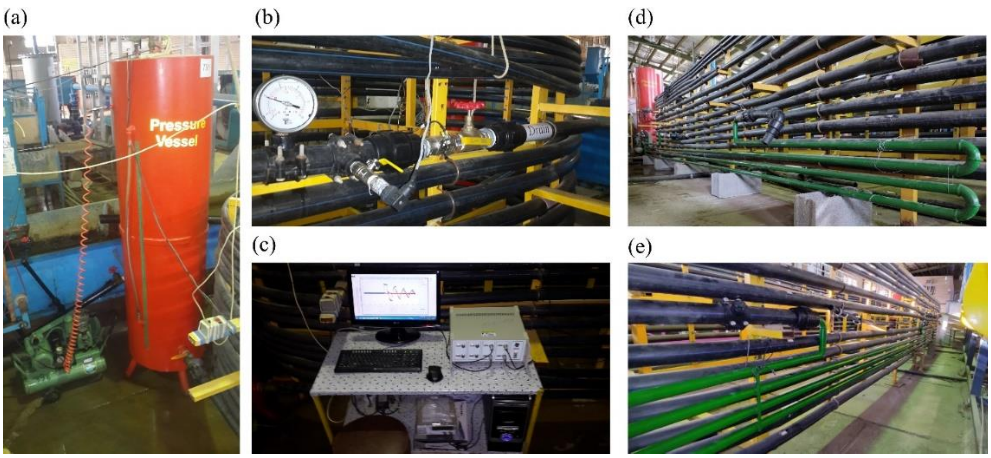


**Figure 2. Experimental views of (a) pressure vessel, (b) downstream valves, (c) data collection system, and (d,e) blockages at two locations**

**Table 1 Details of all experimental tests**

| Test No. | Pipe type | Location | $Q$ (l/s) | $D_b$(cm) | $L_b$ (m) | Blockage percentage (%) |
|---|---|---|---|---|---|---|
| Test#1 | VE | 2 | 1 | 5.05 | 22 | 0 |
| Test#2 | EL | 2 | 1 | 5.0 | 22 | 1 |
| Test#3 | EL | 2 | 1 | 2.71 | 22 | 46.33 |
| Test#4 | EL | 2 | 1 | 2.71 | 10 | 46.33 |
| Test#5 | EL | 2 | 1 | 2.71 | 5 | 46.33 |
| Test#6 | EL | 1 | 1 | 2.71 | 10 | 46.33 |
| Test#7 | EL | 1 | 1 | 3.89 | 10 | 23 |
| Test#8 | EL | 1 | 0.5 | 3.89 | 10 | 23 |

## 2.2. Fast Fourier Transform (FFT)

Fast Fourier Transform (FFT) is an efficient algorithm used to compute the discrete Fourier transform (DFT) of a sequence or signal. The DFT is a mathematical transformation that converts a time-domain signal into its frequency-domain representation, revealing the signal's frequencies and their corresponding amplitudes.

The FFT algorithm significantly reduces the computational complexity of the DFT from O(n^2) to O(n log n), making it practical for real-time applications and large data sets. It achieves this by leveraging the symmetry and periodic properties of the DFT.

The process of calculating the FFT involves the following steps:

1. Preprocessing: If the length of the input sequence is not a power of 2, it is typically zero-padded or truncated to the nearest power of 2.
2. Divide and conquer: The input sequence is divided into two halves, with one containing the even-indexed elements and the other containing the odd-indexed elements.
3. Recursive computation: The FFT algorithm recursively computes the DFT of the even-indexed and odd-indexed subsequences.
4. Combine: The results of the DFT computations are combined using twiddle factors. Twiddle factors are complex exponential values that account for the frequency shifts and phase shifts.
5. Repeat: Steps 2-4 are repeated on the divided subsequences until the base case of a sequence length of one is reached.
6. Output: The final output is the DFT of the original sequence, represented as complex numbers or amplitudes and phases.

The FFT algorithm finds applications in various fields, including signal processing, image processing, audio analysis, data compression, and scientific computing. Its efficiency and speed make it an indispensable tool for analyzing and manipulating signals in both research and practical applications.

## 3. Results and discussions

In this section, an analysis has been conducted on the impact of different geometric parameters of blockage and the intensity of the transient on the characteristics of the signal in both the time and frequency domains.

### 3.1. Comparison of elastic and viscoelastic pipes

In this subsection, the analysis of the results from two tests, labeled Test#1 and Test#2, is presented. In Test#1, the entire pipe was constructed using viscoelastic material. In Test#2, only the middle 22 m of the pipe was made of elastic steel, with a diameter approximately similar to that of the polyethylene pipe, resulting in a blockage of only 1%.

Figure 3a compares the signals from these two tests in the time domain, while Figure 3b magnifies the results of the first half cycle. The findings indicate that the presence of the elastic pipe causes a phase shift in the pressure signal, which increases gradually from the beginning of the transient. Additionally, oscillations, particularly in the first half cycle, are observed due to the pressure reflection from the elastic pipe back towards the valve. These oscillations gradually diminish over time due to attenuation. The presence of these oscillations results in an increase in pressure during the first half cycle, attributed to the higher velocity of the pressure wave in the elastic pipe. The interval between the peaks of these oscillations represents the time it takes for the outgoing and returning waves between the valve and the elastic pipe, which can be utilized to accurately determine the distance from the valve.

Figure 4a presents the comparison of the signals from these two tests in the frequency domain. Furthermore, Figure 4b displays the amplitudes of the signals at resonance frequencies. Similar to the time domain signal, Figure 4a demonstrates a phase shift in the signal and changes in resonance frequencies due to the variation in pipe material. Apart from the resonance frequencies, there is a noticeable alteration in the amplitude of the signal at resonance frequencies as well. Based on these two figures, it can be observed that the variations in signal amplitude in the frequency domain for the simple pipe exhibit a decreasing trend. Conversely, for the series pipe that includes an elastic pipe, the variations in signal amplitude at resonance frequencies are oscillatory and do not follow a specific pattern.

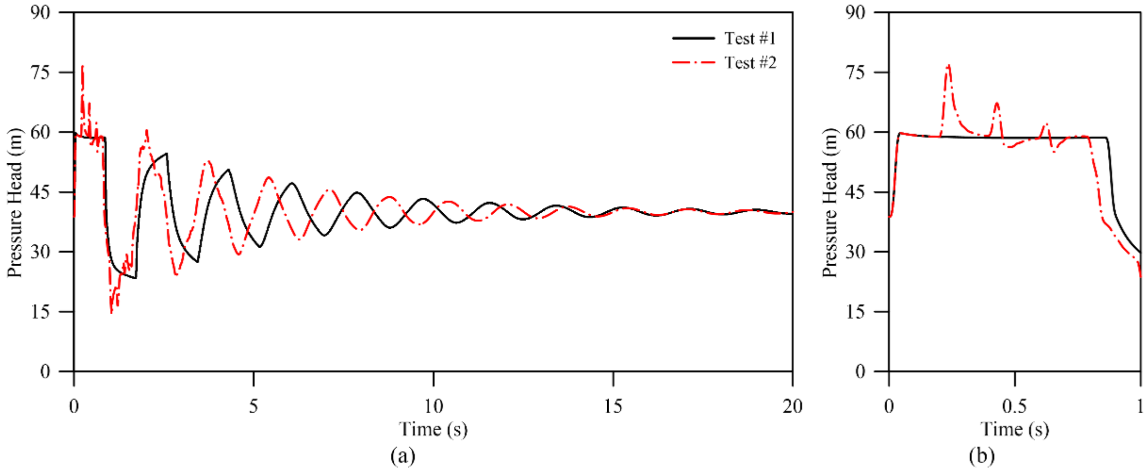


**Figure 3. Comparing the viscoelastic and elastic-viscoelastic series pipes pressure signal in the time domain**

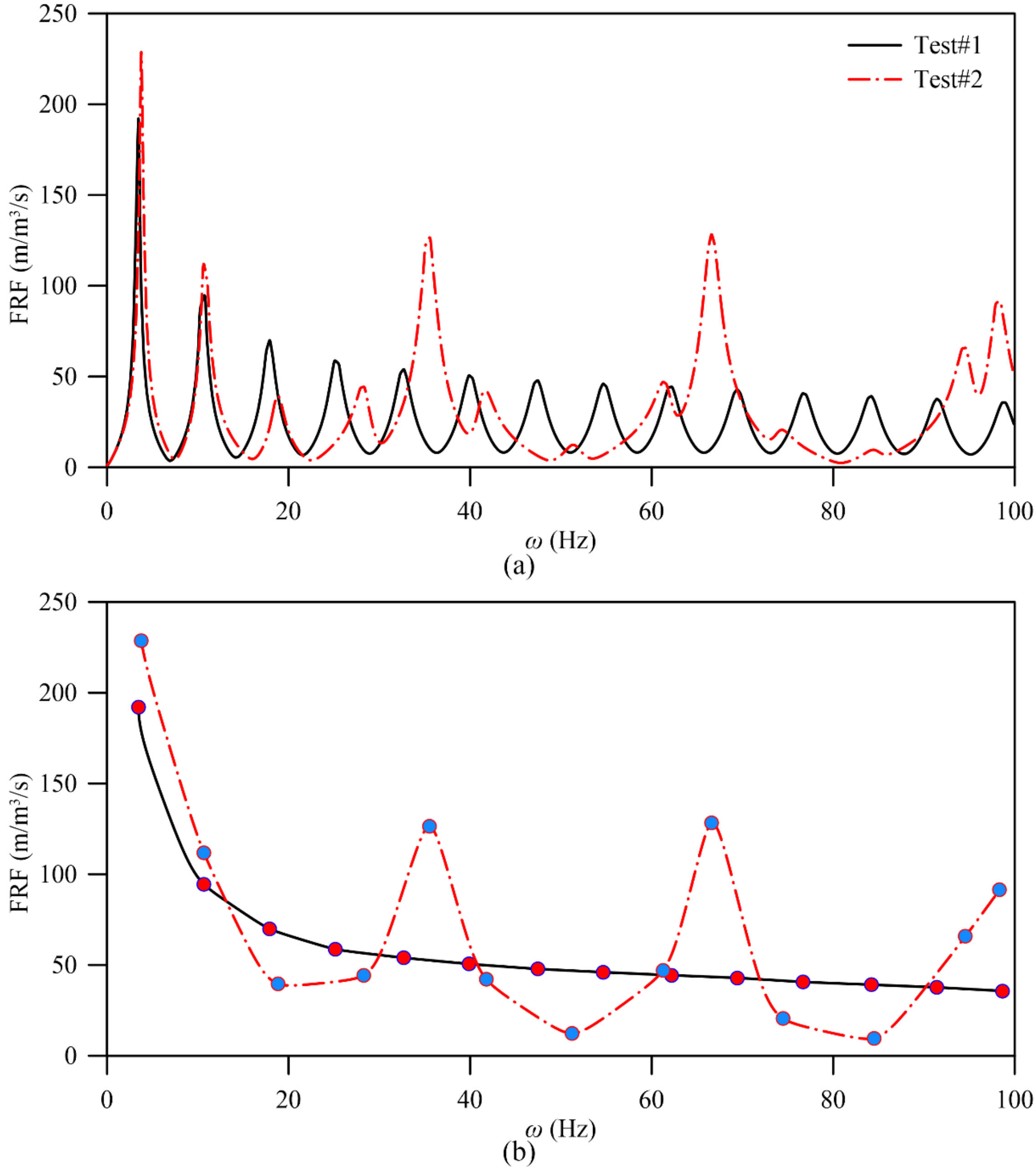


**Figure 4. Comparing the viscoelastic and elastic-viscoelastic series pipes (a) pressure signal in the frequency domain, and (b) resonance frequency amplitudes**

### 3.2. Effect of blockage length

In this subsection, the investigation focuses on the effect of blockage length. For this purpose, Tests #3 to #5 were conducted with blockage lengths of 22 m, 10 m, and 5 m, respectively. The inner diameter of the pipe used in these experiments was 2.71 cm. The blockages in these tests were made of elastic material, resulting in a blockage percentage of 46.33%.

Figure 5a displays the pressure signals from these three tests in the time domain. Additionally, Figure 5b provides a closer look at the first half-cycle of these signals. The results indicate that the phase of the signal changes with variations in the blockage length, directly proportional to the length of the blockage. Moreover, as the blockage length increases, the pressure increase caused by the blockage in the first half-cycle also increases. As shown in Figure 5b, with an increase in blockage length, the decreasing trend of the peak becomes slower and extends over a longer interval. This is because a longer blockage leads to a greater wave reflection from the blockage towards the longer section of the pipe, resulting in a larger pressure increase and a longer time interval for the crest and trough.

Figure 6a presents the frequency response of Tests #3 to #5 in the frequency domain. This figure illustrates that the frequency response changes as the blockage length varies, and the signal undergoes a noticeable phase change. With an increase in blockage length, the amplitude of the signal at resonance frequencies also increases. Furthermore, according to Figure 6b, the results indicate that some of the resonance frequencies change with variations in the blockage length, and the three tests do not share the same resonance frequencies.

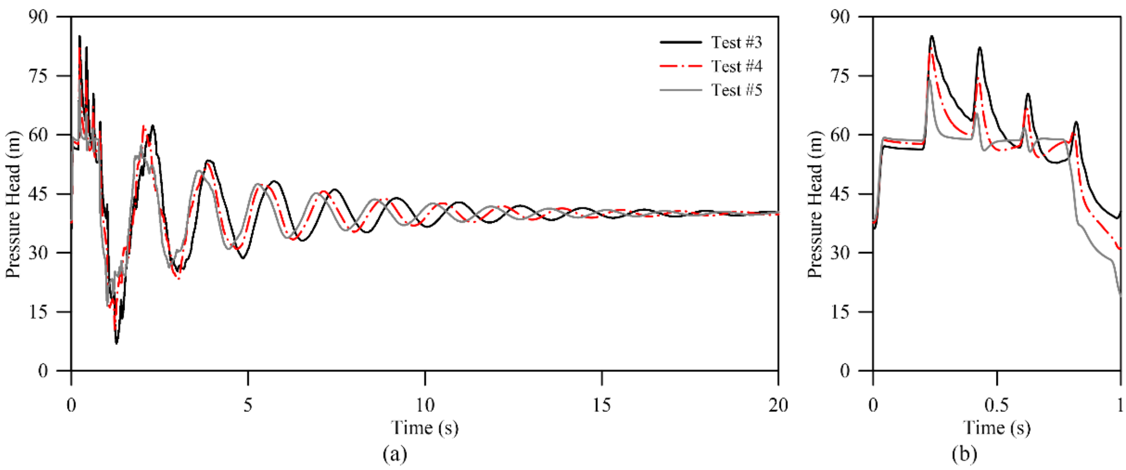


**Figure 5. Comparing the pressure signals for three tests with different blockage lengths in the time domain**

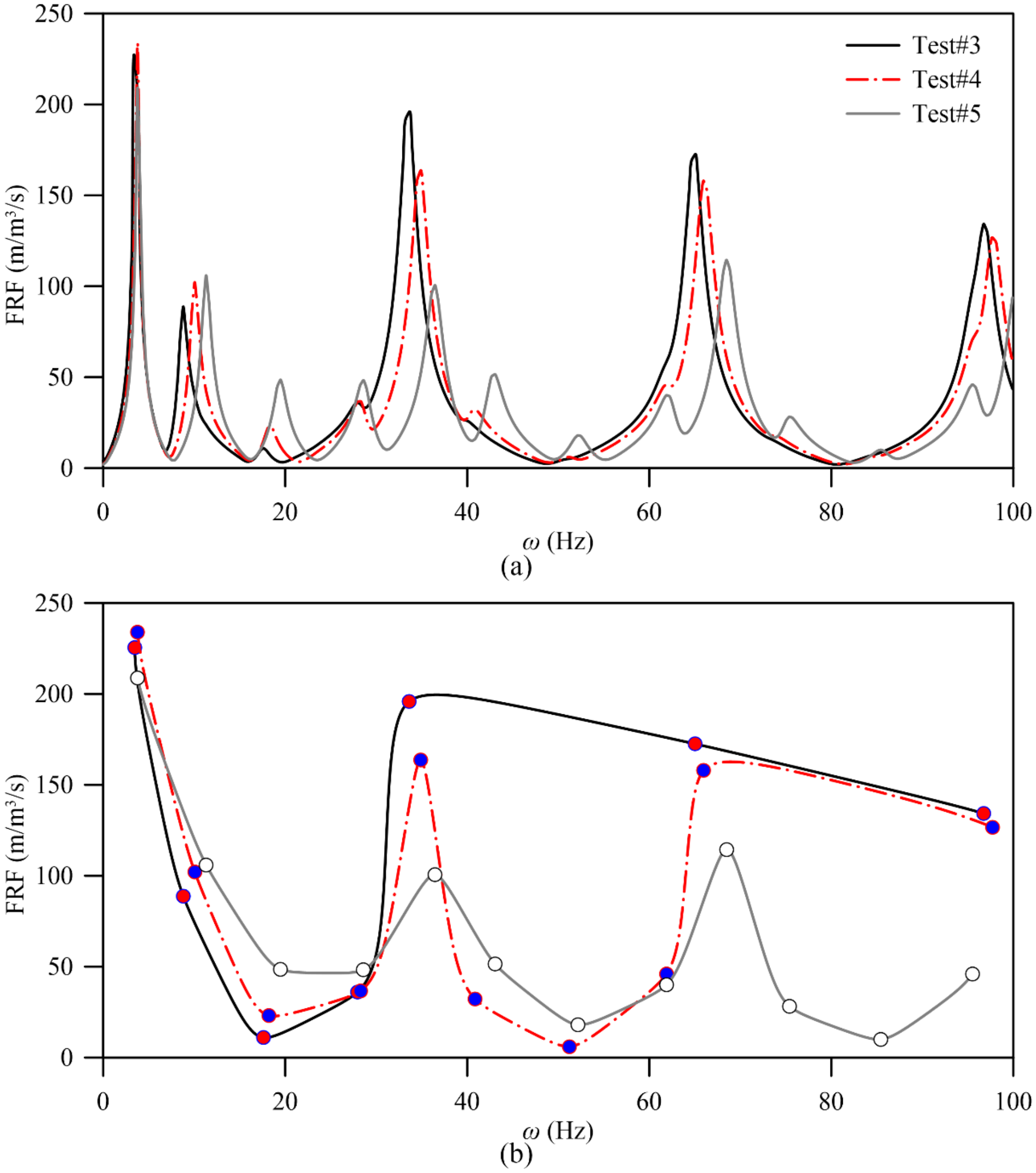


**Figure 6. Comparing the three tests with different blockage lengths (a) pressure signal in the frequency domain, and (b) resonance frequency amplitude**

### 3.3. Effect of blockage percentage

In the investigation of pipe blockage, the percentage of blockage is another parameter that has been examined. Tests #6 and #7 were conducted to explore this aspect. In both tests, a constant length of 10 m was considered at a distance of 57 m from the upstream boundary of the pipeline. The blockage percentages in these two experiments were 46.33% and 23%, respectively.

Figure 7 compares the pressure signals from these two tests in the time domain. Figure 7b provides a closer look at the first half cycle of these experiments. The results reveal that variations in the blockage percentage lead to changes in the phase of the signal. As time progresses from the beginning of the transient flow, this phase change becomes more pronounced. Additionally, according to Figure 7b, a less severe blockage exhibits a stronger and delayed reflection with an increase in the blockage percentage.

Figures 8a and 8b present a comparison of the two signals in the frequency domain. Figure 8a demonstrates that changes in the blockage percentage also affect the phase of the signal in the frequency domain and influence the amplitude at different frequencies. However, the intensity of these changes is not as prominent as the changes observed when varying the blockage length.

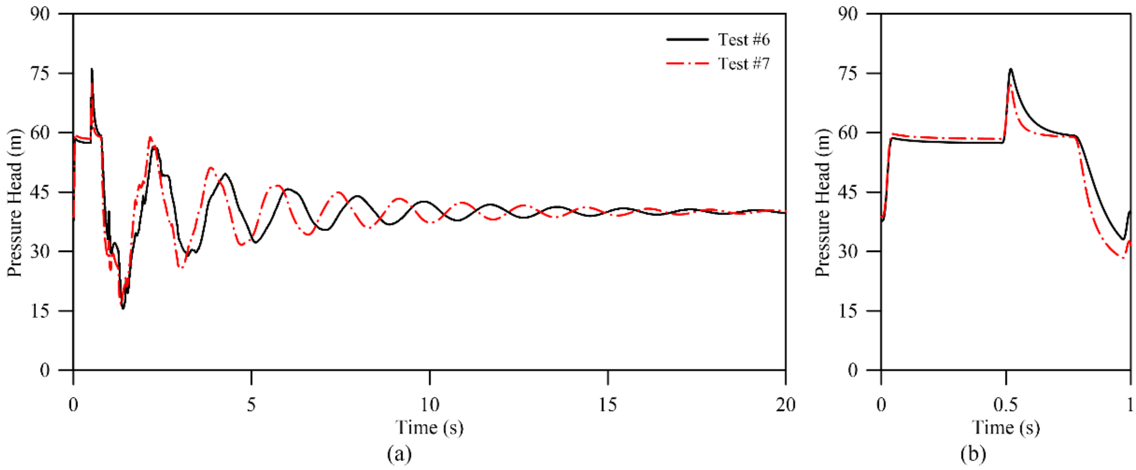


**Figure 7. Comparing the time domain pressure signal for two tests with different blockage percentages**

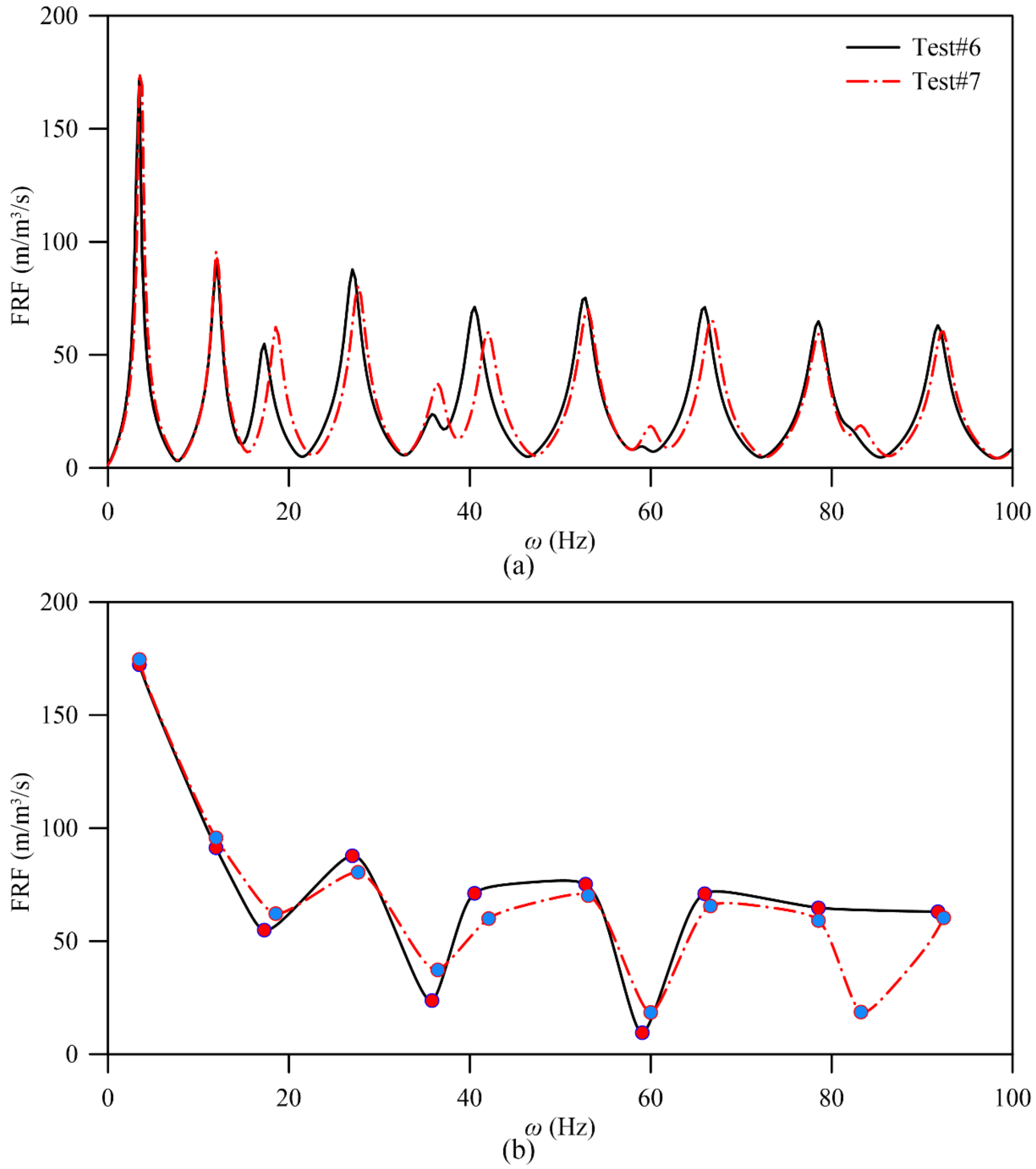


**Figure 8. Comparing the different blockage percentages (a) pressure signal in the frequency domain, and (b) resonance frequency amplitude**

### 3.4. Effect of transient intensity

The impact of transient flow intensity on a fixed blockage was investigated in Test#7 and Test#8. These tests utilized blockages with a percentage of 23% and were located 57 m from the upstream boundary of the pipeline. The blockage length was fixed at 10 m. The flow rates for these two tests were 0.5 l and 1 l, respectively.

Figure 9 compares the pressure signals from these two tests in the time domain, while Figure 9b provides a closer look at the first half-cycle. The findings indicate that changes in transient flow intensity do not result in significant phase shifts in the signal; they primarily affect the amplitude of the transient flow. Higher-intensity signals exhibit larger amplitudes in the reflection caused by the blockage.

Figure 10a compares the frequency response of Test#7 and Test#8, while Figure 10b illustrates the amplitudes of these two signals at resonance frequencies. The results reveal that changes in transient flow intensity only affect the signal's amplitude and do not alter its phase. Furthermore, Figure 10b demonstrates that the frequency response pattern remains consistent at resonance frequencies, regardless of variations in transient flow intensity.

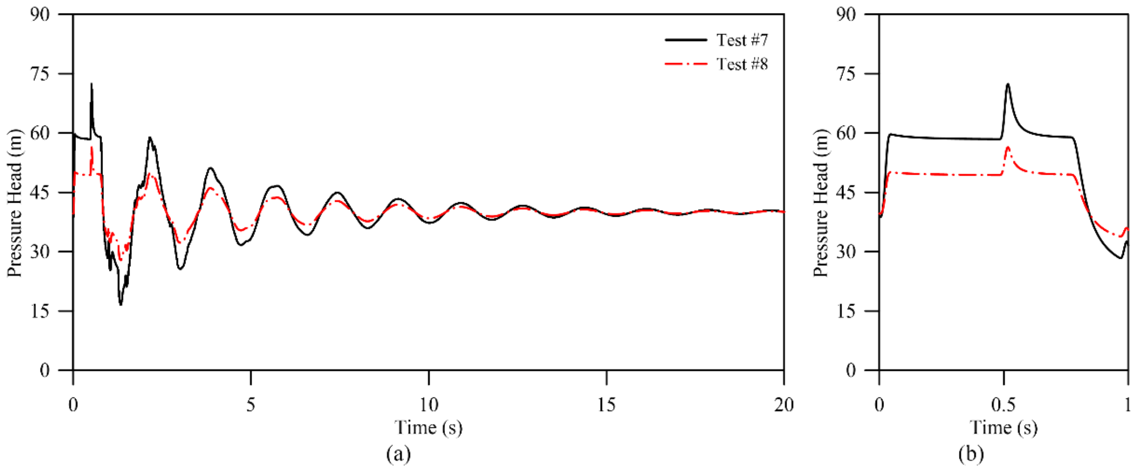


**Figure 9. Comparing the time domain pressure signal for two tests with different hydraulic transient intensities**

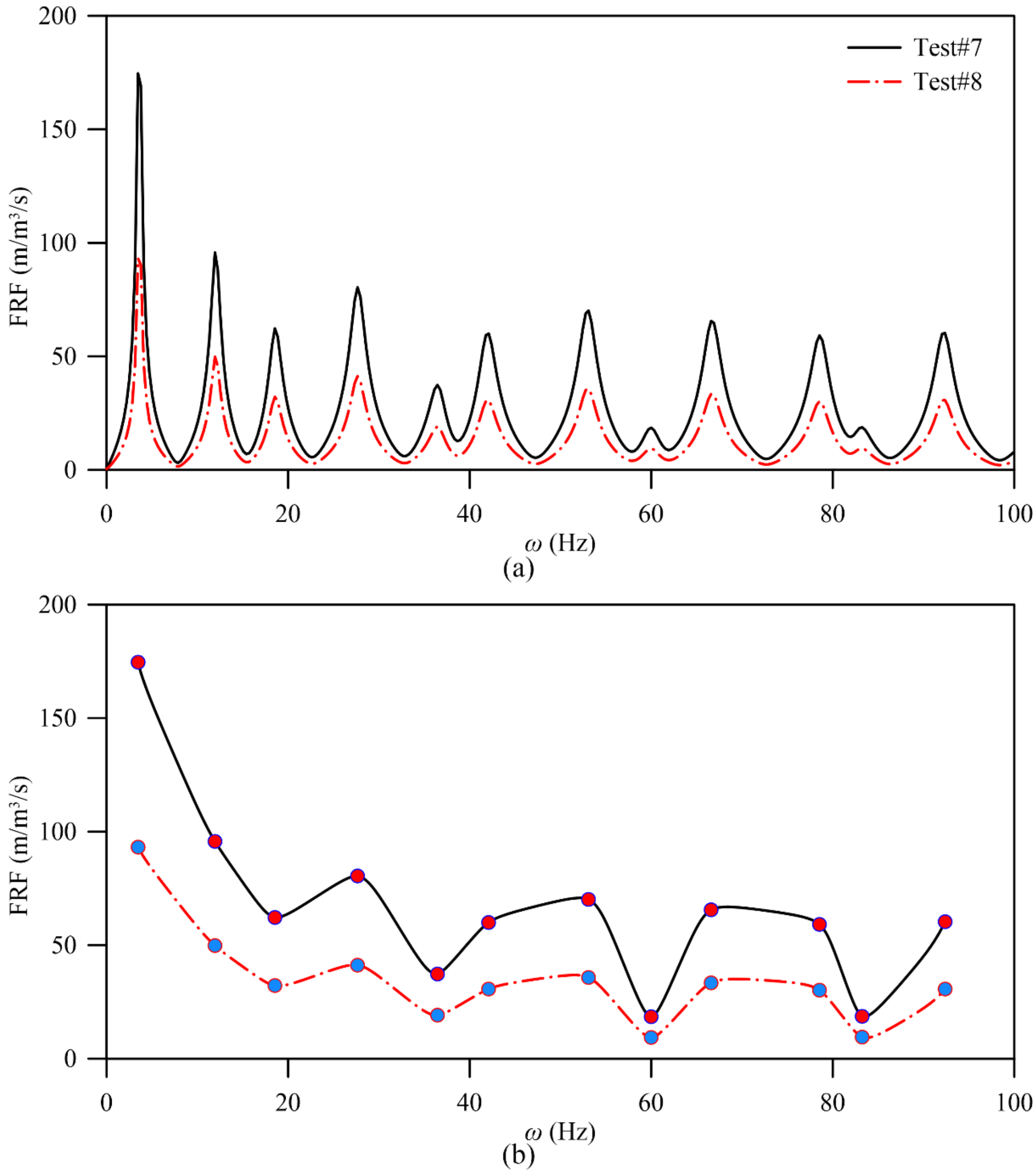


**Figure 10. Comparing the two hydraulic transient intensities (a) pressure signal in the frequency domain and (b) resonance frequency amplitude**

### 3.5. Effect of transient location

The location of the blockage is an important and influential parameter in determining the characteristics of the pressure signal. In this section, the effect of blockage location on the pressure signal was investigated using two experiments: Test#4, located 117 m upstream of the pipeline, and Test#6, located 57 m upstream of the pipeline. Both tests had a blockage percentage of 46.33% and a length of 10 m.

Figure 11a displays the pressure signals from these two tests in the time domain, while Figure 11b provides a closer look at the first half-cycle of these signals. The results show that the distance of the blockage from the transient valve also affects the phase of the signal. As the distance from the valve increases, the amplitude of the reflected blockage decreases. Additionally, the phase change of the signal increases with time from the start of the transient flow in these tests.

Figure 12a presents the frequency response of these two experiments. The figure clearly illustrates the phase change in the signal due to the variation in blockage location. Furthermore, as the distance from the transient flow generation location increases, the signal amplitude decreases at specific frequencies and increases at other frequencies. According to Figure 12b, the amplitudes of the signal frequencies have also changed with the variation in blockage location.

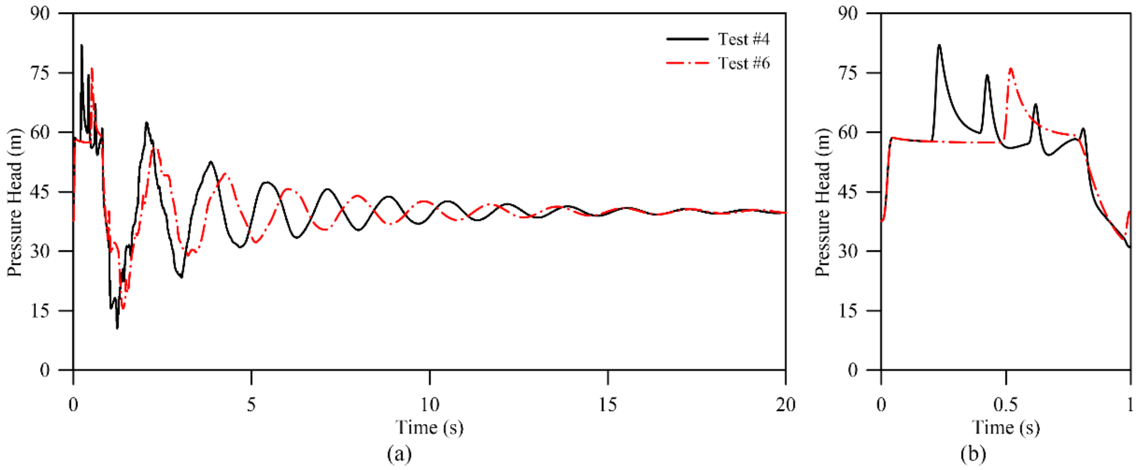


**Figure 11. Comparing the time domain pressure signals for tests with blockage at different locations**

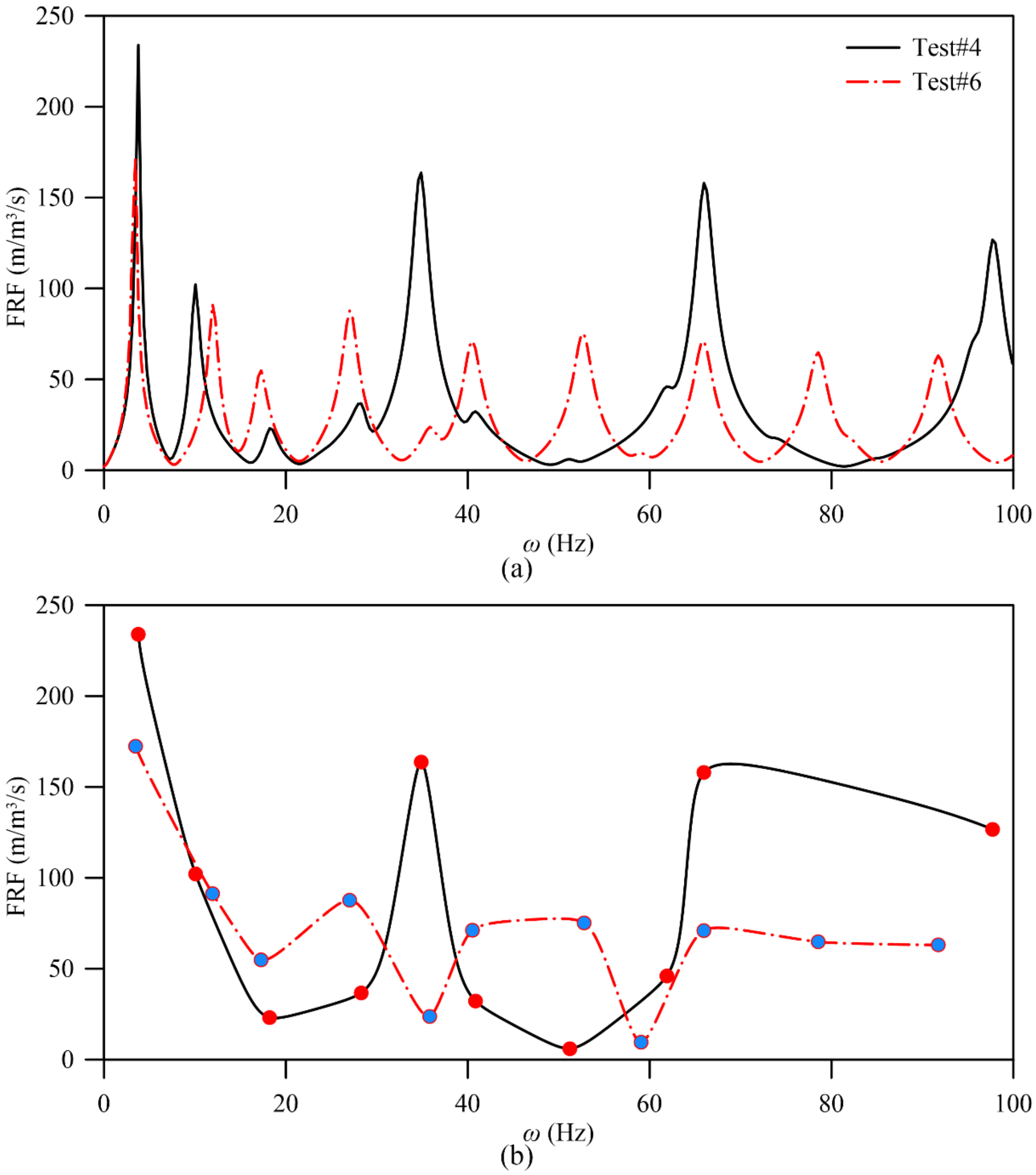


**Figure 12. Comparing the tests with blockage at different locations (a) pressure signal in the frequency domain, and (b) resonance frequency amplitude**

## 4. Conclusions

This study focused on investigating the impact of extended elastic blockages on the characteristics of transient pressure waves in viscoelastic pipelines, with a particular emphasis on the time and frequency domains. Eight experimental tests were conducted, involving blockages with different diameters and lengths at two distinct locations. Several properties of the pressure signal were analyzed, including phase shift, resonance frequency, and changes in the frequency domain.

The findings of the study are as follows:

- An elastic blockage in a viscoelastic pipeline induces a phase shift in the pressure signal, both in the time and frequency domains. The reflections caused by the elastic blockage are particularly prominent in the first cycle of the signal.
- Increasing the length of the blockage leads to a more significant phase shift in the time domain and intensifies the wave reflections. The increase in pressure due to the blockage is delayed due to damping effects.
- A higher percentage of blockage results in a phase shift and amplitude wave reflections. Over time, the phase shift of the pressure wave in the time domain increases during transient flow.
- The intensity of the transient flow does not affect the phase of the wave but only impacts the amplitude of the pressure signal in the time and frequency domains. The reflection caused by the blockage is more pronounced during high-intensity transient flows.
- Comparisons between blockages at different locations demonstrate that the blockage's location influences the phase of the pressure signal and alters the distribution of amplitude frequencies. The amount of wave reflection decreases with an increased distance between the blockage and the transient source.
- Geometric changes in the pipeline induce phase shifts in the pressure signal and alter the amplitude frequencies. On the other hand, hydraulic characteristics such as the intensity of the transient flow solely affect the amplitude of the pressure signal in the time and frequency domains.
- The results of this research can serve as a foundation for the development of methods to detect blockages in viscoelastic pipelines. Feature extraction from pressure signals can be employed to identify and analyze the desired phenomena in pipeline systems.

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