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Separation of pressure signals caused by waves traveling in opposite directions

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ABSTRACT

Hydraulic transient analysis allows the condition assessment of pipeline systems by the measurement of a system's transient pressure response subject to input pressure excitations. The detection of a pressure wave's arrival time and amplitude at one or more sections can be used to detect unexpected anomalies, such as leaks, blockages, or corroded sections. Wave separation approaches, based on signal processing techniques involving two sensors, enable a directional attribution to any measured pressure perturbations. Being able to determine the direction of origin of a perturbation through a signal-splitting approach greatly facilitates anomaly detection through the resolution of this ambiguity. The signal-splitting procedure can be sensitive to the analysis conditions (i.e. the signal processing procedure used, the presence of noise within the signal, and the spacing of the sensors) and, as a result, produce spurious results. This paper explores this issue and proposes, and analyses, a range of strategies to improve the signal-splitting results. The strategies explored involve the consideration of alternative time- and frequency-domain formulations; the use of filters and wavelet to condition the signal; and processing the time-shifted differenced signal as opposed to the original raw signal. Results are presented for a range of numerical and laboratory systems.

Key words: diagnosis, pressure waves, pressurized pipes, separation, transients, wavelet

HIGHLIGHTS

- The pressure signals acquired at two measurement sections can be separated, pointing out positive and negative traveling wave components.
- The separation procedure can be helpful in the transient-based diagnosis in complex systems.
- Different techniques are developed in time and frequency domains and tested on numerical and laboratory experiments.
- Wavelet transform of separated signals is also derived.

1. INTRODUCTION

Water distribution system infrastructure inherently deteriorates with age due to corrosion, weathering, malfeasance, or the build-up of sediments and microfilms inside the pipe (Colombo *et al.* 2009; El-Zahab & Zayed 2019; Duan *et al.* 2020). This is an important problem as extreme deterioration can have significant implications for the effective operation of such pipeline systems (e.g. reliability of water supply), the functioning of metropolitan environments (e.g. road or building closure due to pipe bursts) and society's health and well-being (i.e. the intrusion of pathogens into the networks through cracks and leaks) (Karim *et al.* 2003; Snider & McBean 2020). As such, it is important for water utilities to monitor the condition of their pipeline infrastructure and proactively maintain the health and integrity of their pipeline infrastructure.

A range of invasive and non-invasive methods for anomaly detection in pipelines exist (El-Zahab & Zayed 2019), but a promising method for the assessment of pipeline infrastructure condition is through the use of hydraulic transient analysis (Colombo *et al.* 2009; Duan *et al.* 2020). Hydraulic transient analysis couples the measurement of hydraulic signals (typically pressure) with either model-based (e.g. Zecchin *et al.* 2013; Gong *et al.* 2014; Capponi *et al.* 2017; Zhang *et al.* 2019) or statistical (e.g. Motazed & S. 2018) signal processing approaches, with the aim of identifying condition faults within a pipeline (e.g. leakages, bursts, blockages, or corroded sections). Hydraulic transients are pressure and flow perturbations that propagate throughout a pipeline system at near the speed of sound and result either from rapid changes in boundary conditions

(i.e. a valve maneuver) or can be induced in the system (e.g. through a pressure wave generator) for active hydraulic transient analysis methods (Colombo *et al.* 2009). Similar to radar, or sonar applications, hydraulic transients are useful as a diagnostic tool as they are very sensitive to the system conditions, resulting from the fluid structure interactions. For example, a pipeline burst will induce a negative pressure wave that can be measured at a great distance from the burst location. Similarly, a pressure wave induced into a pipeline system for the purposes of interrogation will reflect at leaks, blockages, or even corroded sections, enabling the reflected wave to be measured and analyzed (Covas & Ramos 1999).

One of the problems with hydraulic transient analysis has been that it is not always possible to directionally attribute a measured pressure perturbation to its direction of origin within the pipeline. That is, as the pressure response at a point is the superposition of pressure waves traveling from both the upstream and downstream directions, a single measurement of a perturbation will not enable the analyst to determine whether it came from an upstream or downstream location. This directional attribution is important, as it can greatly assist the analyst in locating the perturbation source unless simple systems with pressure measurements at pipe ends are considered.

To address this problem, attention has recently shifted to the use of signal-splitting techniques, which involve decomposing a measured pressure perturbation into its upstream and downstream traveling waves (Zecchin *et al.* 2014). That is, the signal-splitting methods are able to reconstruct the independent wave forms that are traveling from both the upstream and downstream directions. This is achieved through the use of two closely spaced sensors, and a signal separation algorithm, which is based on the physics of the system, that takes the two pressure measurements and determines the associated positive and negative traveling waves. This technique was first applied to a frictionless numerical system in Gong *et al.* (2012), where reflections from pipe wall corrosion points were effectively reconstructed. This was then extended to a system including friction by Zecchin *et al.* (2014) where it was shown to effectively determine the form of a reflected wave in a noisy pipe-reservoir-valve system. The method was then applied to a laboratory system in Shi *et al.* (2017), and in combination with an optical fiber pressure sensor in Shi *et al.* (2019), where wave reflections within a real system were effectively reconstructed.

An acknowledged potential issue with the signal-splitting approach is that, under some circumstances, the algorithm can become unstable and yield results with significant numerical artifacts. This is potentially problematic, as it reduces the reliability, and hence utility, of the proposed method. The focus of this paper is to study the signal-splitting approach and find solutions to mitigate the introduction of numerical artifacts into the separated wave forms. The approaches explored in this paper are alternative frequency- and time-domain formulations of the signal-splitting algorithm; the use of a differenced signal as opposed to the original signals; the use of low-pass filters, to pre-filter the signals; the effects of noise, distance between measurement sections and pipe material on the signal-splitting algorithm performance; and the wavelet transform analysis directly in the separated signals. The proposed approaches are tested on a range of numerical and laboratory systems, where it is found that the most successful approach is a time-domain algorithm coupled with pre-filtering, even when the assumptions about the pipe material rheology are not correct.

2. METHODOLOGIES FOR THE SEPARATION OF SIGNAL COMPONENTS

The solution of the linearized partial differential equations governing transients in pressurized pipes is given by the sum of waves propagating along characteristic lines in the positive and negative directions. As a result, the variation in time and space of the pressure head, $h(x, t)$, or pressure signal, can be considered as the sum of two separated components

$$h(x, t) = h^+(x, t) + h^-(x, t) \quad (1)$$

where superscripts $+$ and $-$ denote the effects on the pressure signal of wave propagating along the x axis in the positive and negative direction, respectively. With reference to Figure 1, we consider the pressure signals acquired at two measurement sections, $h_1 = h(x_1, t)$ and $h_2 = h(x_2, t)$, with $x_2 = x_1 + l$, in a pipe with constant diameter D , area A , and wave speed a .

The Fourier transform of Equation (1) allows for the analysis of the two components in the frequency domain as

$$H(x, \omega) = H^+(x, \omega) + H^-(x, \omega) \quad (2)$$

where $H(x, \omega) = \mathcal{F}h(x, t)$, ω is the angular frequency, and $\mathcal{F}$ denotes the Fourier transform. Under the assumption of a pipe of

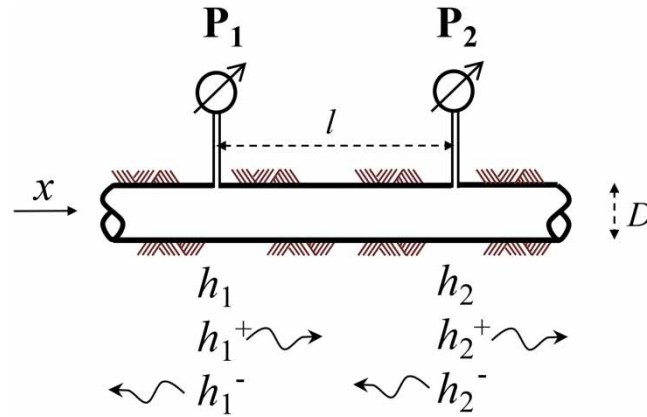


Figure 1 | Layout of the measurement sections.

an infinite length, the relationship between wave components at two cross sections is given by (see Appendix A in the Supplementary Material)

$$\begin{aligned} H_2^+ &= H^+(x_2, \omega) = G(\omega)H_1^+ \\ H_1^- &= H^-(x_1, \omega) = G(\omega)H_2^- \end{aligned} \quad (3)$$

where $G(\omega) = e^{-\Gamma}$ and $\Gamma = \Gamma(\omega)$ are the transfer function and the propagation operator of the trunk between the two measurement sections, respectively. For real fluids in viscoelastic pipe materials

$$\Gamma = l\sqrt{i\omega(C + 2iAV(\omega))(Li\omega + R)} \quad (4)$$

where $C = gA/a^2$ is the capacitance, $L = 1/(gA)$ is the inertance, $R = f q_0/(gDA^2)$ is the linearized resistance, q_0 is the mean discharge value used for the linearization of the equations in the frequency domain (Wylie & Streeter 1993; Chaudhry 2014), f is the friction factor, $V(\omega)$ is a function that takes into account the viscoelastic behavior of the pipe material (Ferrante & Capponi 2017, 2018b), g is the gravitational acceleration, and i is the imaginary unit.

Under the assumptions of the Allievi-Joukowski theory, i.e. frictionless ($R = 0$) and elastic ($V = 0$) pipes, Equation (4) simplifies to $\Gamma = i\omega l/a = i\omega\tau$ (where τ is the time delay between sections) and the pressure waves move at a constant speed a without changing the shape (pure delay)

$$\begin{aligned} h_2^+ &= h^+(x_2, t) = h^+(x_1, t - \tau) = \mathcal{T}(\tau)h_1^+ \\ h_1^- &= h^-(x_1, t) = h^-(x_2, t - \tau) = \mathcal{T}(\tau)h_2^- \end{aligned} \quad (5)$$

The delay operator, $\mathcal{T}(\tau)$, operates the shift back in time of a function by the quantity τ .

2.1. Separation in the frequency domain

By means of simple algebraic manipulations (e.g. Shi *et al.* 2017), the Fourier transform of the positive and negative direction components at the two measurement sections can be evaluated by the Fourier transform of the measured pressure signals:

$$\begin{aligned} H_1^+ &= \frac{H_1 - GH_2}{1 - G^2} \\ H_1^- &= \frac{G(H_2 - GH_1)}{1 - G^2} \\ H_2^+ &= \frac{G(H_1 - GH_2)}{1 - G^2} \\ H_2^- &= \frac{H_2 - GH_1}{1 - G^2} \end{aligned} \quad (6)$$

It is worth noticing that in the evaluation of G and Γ in Equation (6), the assumption of a frictionless elastic system is not needed.

The separation procedure in the frequency domain is hence based on the Fourier transform of the pressure signals and the use of Equations (6). The solutions provided by Equation (6) can be directly used to determine the time-domain solutions by means of the inverse Fourier transform (denoted as $\mathcal{F}^{-1}$)

$$\begin{aligned} h_1^+ &= \mathcal{F}^{-1} H_1^+ \\ h_1^- &= \mathcal{F}^{-1} H_1^- \\ h_2^+ &= \mathcal{F}^{-1} H_2^+ \\ h_2^- &= \mathcal{F}^{-1} H_2^- \end{aligned} \quad (7)$$

2.2. Separation in the time-domain

Two kinds of separation procedures can be used in the time domain, based on the hypothesis of frictionless (pure delay), or linearized friction, elastic pipe systems, without the need for the direct and inverse transform of the signals required by Equations (6) and (7).

2.2.1. Pure delay

For the pure delay case, the algebraic manipulation of the frequency-domain separation formulae leads to different recursive time-domain solutions.

A first set of formulations can be determined from Equation (6) as

$$\begin{aligned} H_1^- &= G^2 H_1^- - G^2 H_1 + G H_2 \\ H_2^+ &= G^2 H_2^+ + G H_1 - G^2 H_2 \end{aligned} \quad (8)$$

and hence, by the inverse Fourier transform, the time domain is given by

$$\begin{aligned} h_1^- &= h^-(x_1, t) = w h^-(x_1, t - 2\tau) - h(x_1, t - 2\tau) + h(x_2, t - \tau) \\ &= w \mathcal{T}(2\tau) h_1^- - \mathcal{T}(2\tau) h_1 + \mathcal{T}(\tau) h_2 \\ h_2^+ &= w h^+(x_2, t) = h^+(x_2, t - 2\tau) + h(x_1, t - \tau) - h(x_2, t - 2\tau) \\ &= w \mathcal{T}(2\tau) h_2^+ + \mathcal{T}(\tau) h_1 - \mathcal{T}(2\tau) h_2 \end{aligned} \quad (9)$$

with $w = 1$. Values of $1 < w < 0$ can also be used to reduce the effects of noise and drift, as explained in the following sections. Once h_1^- and h_2^+ are evaluated by Equation (9), Equation (5) provides the values of h_1^+ and h_2^- , or alternatively, following through a similar process from Equation (6), a direct frequency-domain expression is given by

$$\begin{aligned} H_1^+ &= G^2 H_1^+ + H_1 - G H_2 \\ H_2^- &= G^2 H_2^- - G H_1 + H_2 \end{aligned} \quad (10)$$

providing the direct time-domain form as

$$\begin{aligned} h_1^+ &= h^+(x_1, t) = w h^+(x_1, t - 2\tau) + h(x_1, t) - h(x_2, t - \tau) \\ &= w \mathcal{T}(2\tau) h_1^+ + h_1 + \mathcal{T}(\tau) h_2 \\ h_2^- &= h^-(x_2, t) = w h^-(x_2, t - 2\tau) - h(x_1, t - \tau) + h(x_2, t) \\ &= w \mathcal{T}(2\tau) h_2^- - \mathcal{T}(\tau) h_1 + h_2 \end{aligned} \quad (11)$$

with h_1^- and h_2^+ evaluated by Equation (5).

An alternative solution, removing the recursion in (9) and involving an infinite series of backwards time-shifted raw signal terms, can be derived using the expansion $1/(1 - x^2) = 1 + x^2 + x^4 + \dots$ in the first and last expressions of Equation (6) as

$$\begin{aligned} H_1^+ &= (1 + G^2 + G^4 + \dots) H_1 - (G + G^3 + G^5 + \dots) H_2 \\ H_2^- &= (1 + G^2 + G^4 + \dots) H_2 - (G + G^3 + G^5 + \dots) H_1 \end{aligned} \quad (12)$$

For the pure delay case, the inverse Fourier transform of Equation (12) yields

$$\begin{aligned}
 h_1^+ &= h(x_1, t) + h(x_1, t - 2\tau) + h(x_1, t - 4\tau) + \dots + \\
 &\quad - h(x_2, t - \tau) - h(x_2, t - 3\tau) - h(x_2, t - 5\tau) - \dots \\
 &= [1 + \mathcal{T}(2\tau) + \mathcal{T}(4\tau) + \dots]h(x_1, t) - [\mathcal{T}(\tau) + \mathcal{T}(3\tau) + \dots]h(x_2, t) \\
 &= g_1 h(x_1, t) - g_2 h(x_2, t) \\
 h_2^- &= -h(x_1, t - \tau) - h(x_1, t - 3\tau) - h(x_1, t - 5\tau) - \dots + \\
 &\quad + h(x_2, t) + h(x_2, t - 2\tau) + h(x_2, t - 4\tau) - \dots \\
 &= -[\mathcal{T}(\tau) + \mathcal{T}(3\tau) + \dots]h(x_1, t) + [1 + \mathcal{T}(2\tau) + \mathcal{T}(4\tau) + \dots]h(x_2, t) \\
 &= g_2 h(x_1, t) + g_1 h(x_2, t)
 \end{aligned} \tag{13}$$

where g_1 and g_2 are the associated infinite series of time-shift operators, with h_2^+ and h_1^- evaluated by Equation (5).

The number of terms used in the expansion strongly affects the accuracy of the signal separation. Compared to the previously derived time-domain recursive formulae, Equation (13) only depends on the acquired pressure signal values at previous steps while Equations (9) and (11) require the use of both acquired and separated signal values at previous steps.

2.2.2. Linearized friction

For most civil engineering applications, the transfer function can be simplified taking into account the friction effects, although linearization is required. In this case (see Appendix B in the Supplementary Material), $G(\omega) \approx e^{-i\omega\tau} \mathcal{R}$ with $\mathcal{R} = e^{-\frac{1}{2}\sqrt{\frac{C}{L^R}}}$. Under this assumption, the inverse Fourier transform of Equation (8) yields

$$\begin{aligned}
 h_1^- &= \mathcal{R}^2 h^-(x_1, t - 2\tau) - \mathcal{R}^2 h(x_1, t - 2\tau) + \mathcal{R} h(x_2, t - \tau) \\
 &= \mathcal{R}^2 \mathcal{T}(2\tau) h_1^- - \mathcal{R}^2 \mathcal{T}(2\tau) h_1 + \mathcal{R} \mathcal{T}(\tau) h_2 \\
 h_2^+ &= \mathcal{R}^2 h^+(x_2, t - 2\tau) + \mathcal{R} h(x_1, t - \tau) - \mathcal{R}^2 h(x_2, t - 2\tau) \\
 &= \mathcal{R}^2 \mathcal{T}(2\tau) h_2^+ + \mathcal{R} \mathcal{T}(\tau) h_1 - \mathcal{R}^2 \mathcal{T}(2\tau) h_2
 \end{aligned} \tag{14}$$

Once h_1^- and h_2^+ are evaluated by Equation (14), Equation (5) provides the values of h_1^+ and h_2^- .

Under the same assumptions, a second set of equations can be derived by the Inverse Fourier Transform of Equation (10) providing

$$\begin{aligned}
 h_1^+ &= \mathcal{R}^2 \mathcal{T}(2\tau) h_1^+ + h_1 + \mathcal{R} \mathcal{T}(\tau) h_2 \\
 h_2^- &= \mathcal{R}^2 \mathcal{T}(2\tau) h_2^- - \mathcal{R} \mathcal{T}(\tau) h_1 + h_2
 \end{aligned} \tag{15}$$

with h_1^- and h_2^+ evaluated by Equation (5).

3. COMPUTATIONAL PROCEDURES

Different procedures based on the derived formulae for the separation of the positive and negative direction components of pressure signals are used and compared in the following.

3.1. Frequency-domain signal splitting

The separation procedure in the frequency domain based on Equations (6) and (7) has been applied already (e.g. Shi *et al.* 2017). If either pressure signals are numerically simulated or acquired through measurement, h_1 and h_2 are data vectors sampled on a regular time grid and their transformation in the frequency domain is obtained by the Fast Fourier Transform.

Before the evaluation of the separated components by Equation (6) can be undertaken, signals must be filtered to avoid spurious oscillations as much as possible in the results. The filtering is obtained by the Hadamard multiplication of the transformed signals with a filter vector. As an example, for a sigmoidal filter, the terms of the filter vector are evaluated at the same frequencies of the transformed signals by Equation (16) as shown in the following sub-section.

Once the data are filtered, the separated signals can be evaluated in the frequency domain by Equation (6) and then transformed back into the time domain by Equation (7) using the inverse fast Fourier transform.

3.2. Time-domain signal splitting

Five different procedures can be used in the time domain.

The first two procedures are based on the pure delay hypothesis and Equations (9) and (11). In both cases, the vectors containing the separated signals in time are obtained by the linear combination of the measured or simulated signals at the previous time step. Since the separated signals at each time step depend on the same separated signals evaluated at previous time steps, the calculation must be recursive, cannot be parallelized, and may be numerically cumbersome.

The difference between the use of Equations (9) and (11) is only in the terms that are evaluated first, i.e. h_1^- and h_2^+ or h_1^+ and h_2^- . In both cases, Equations (5) allows the evaluation of the remaining terms.

Two further procedures are based on Equations (14) and (15), which are similar to those derived for the pure delay case but introducing the linearized friction term $\mathcal{R}$. The same considerations concerning the numerical efficiency and the equivalence of the results obtained by Equations (9) and (10), apply to these procedures also.

A fifth time-domain procedure is based on the pure delay hypothesis and Equation (12). In this case, the accuracy of the results strongly depends on the approximation introduced by the expansion order, which in turn corresponds to the number of the previous time steps needed for the evaluation of the separated signals. The increase in the number of the involved time steps also increases the computational burden.

3.3. Filtering

As noted out in the literature (e.g. Shi *et al.* 2017) and confirmed by the results shown in the following sections, when Equations (6) and (7) are used, signals must be filtered to avoid spurious oscillations in the separated components.

Filters with different functional forms have been tested and compared, such as Gaussian, Butterworth, and sigmoidal, with and without thresholds. For the sake of conciseness, only the results of the application of the sigmoidal filter are shown (as these are explicative of the capabilities of filtering effects in reducing the spurious oscillations), for which the filter is given by

$$F(\omega) = \frac{1}{\left[1 + 2^{(n-1)} e^{\frac{\omega - \omega_S}{\omega_\tau}}\right]^{1/n}} \quad (16)$$

where the parameters ω_S , ω_τ , and n in Equation (16), define the low-pass band.

When the signals are filtered, the products $F(\omega)H_1(\omega)$ and $F(\omega)H_2(\omega)$ are used instead of $H_1(\omega)$ and $H_2(\omega)$, respectively. Equation (6) show that the filter could also be applied not only to H_1 and H_2 , as in the following, but to their component H_1^+ , H_1^- , H_2^+ , and H_2^- before the inverse transform.

3.4. Wavelet transform

The wavelet transform of the separated signals can be obtained easily following the same procedure used in the frequency domain but using a wavelet function instead of the filter function. Wavelet transforms are commonly used for both filtering and denoising signals, and edge detection. All these aspects have been demonstrated to have utility for the diagnosis of pressurized pipes (Ferrante *et al.* 2009). The wavelet transform of a pressure signal can be evaluated as

$$\mathcal{W}h(\lambda, b) = \frac{1}{\lambda} \int_{-\infty}^{\infty} \Psi\left(\frac{t-b}{\lambda}\right) h(t) dt \quad (17)$$

where Ψ is the wavelet function, λ is the dilation parameter that allows the analysis at different time scales, and b is the translation parameter that allows the analysis in time. The Fourier transform of the wavelet transform of the signal for a given value of λ , or *voice*, is

$$\mathcal{F}\mathcal{W}h(\lambda, \cdot)(\omega) = \mathcal{F}\dot{\Psi}(\lambda\omega)H(\omega) = \Lambda(\lambda\omega)H(\omega) \quad (18)$$

with $\Lambda(\omega) = \mathcal{F}\dot{\Psi}(\omega)$ being the Fourier transform of the complex conjugate (denoted by the dot) of the wavelet function $\Psi(t)$. Hence, the wavelet transform of the pressure signal for a voice is a filtered signal, where the complex conjugate of the Fourier transform of the wavelet function is used instead of the sigmoidal filter.

Combining Equation (18) and the first of Equation (6), the Fourier transform of the wavelet transform of pressures propagating along the positive directions at measurement section 1 is

$$\begin{aligned}\mathcal{FW}h_1^+(\lambda, \cdot)(\omega) &= \mathcal{F}\dot{\Psi}(\lambda\omega)H_1^+(\omega) \\ &= \frac{\Lambda(\lambda\omega)H_1(\omega) - G(\omega)\Lambda(\lambda\omega)H_2(\omega)}{1 - G(\omega)^2}\end{aligned}\quad (19)$$

The same applies to the other formulae and hence to obtain a voice of the wavelet transform of pressure waves propagating in positive and negative directions, the same Equations (6) and (7) can be used, provided that the corresponding voices of the wavelet transform of pressure acquired at the measurement sections are used.

If the Haar wavelet is used, defined in the time-domain as

$$\Psi(t) = \begin{cases} -1 & \text{for } 0 \leq t < 1/2 \\ +1 & \text{for } 1/2 \leq t < 1 \\ 0 & \text{otherwise} \end{cases} \quad (20)$$

the corresponding Fourier transform

$$\Lambda(\omega) = 2 \frac{1 - \cos \omega}{\omega} e^{i(\omega + \pi)/2} \quad (21)$$

can also be used in Equation (19).

With respect to the frequency-domain procedures, different values of λ must be introduced in Equations (20) and (21), corresponding to the application of several filters at different time scales. The information content of the different voices, even limited to a few components (Ferrante *et al.* 2022), allows an easier discernment of pressure waves traveling in different directions in noisy signals.

4. NUMERICAL STUDY

To assess the applicability of the wave separation technique, the time- and frequency-domain procedures are tested on numerical and laboratory signals. The distance between the measurement sections, l , is varied in the tests from about 1 to 50 m. The effects of other parameters, such as the acquisition frequency, the noise disturbance and those related to the rheology of the pipe material, are also considered.

4.1. Measurement sections at about 1 m on an elastic pipe

As a first case, the separation procedure was tested considering the pressure signals at two nodes of a numerical model at a distance $l = 0.99$ m in a smooth pipe with $D = 0.103$ m, $a = 390.7$ m/s and an initial steady-state flow of $q_0 = 7.2$ l/s. The signals were computed at a frequency of 2^{12} Hz using a model based on the method of characteristics with a steady-state piezometric head operating point of about 20 m (note that the signals presented in the following sections show only the transient perturbations about this operating point).

4.1.1. Frequency-domain procedure

The results of the separation procedure in the frequency domain, shown in Figure 2, confirm the results of Shi *et al.* (2017), where two measurement sections about 1 m apart are also considered, i.e. the separation procedure in the frequency domain, based on Equation (6), leads to oscillating artifacts in the separated signals. The oscillations can be explained by the use of the discrete form of the denominator $1 - G^2$ in the numerical calculations, which causes spurious peaks in the transformed signals.

4.1.2. Comparison of the time-domain procedures

The application to the numerical signals of recursive formulations in the time domain based on Equations (9) or (11) with $w = 1$, leads to decomposed signals without appreciable oscillations. As an example, in Figure 3 the acquired signals and their components obtained by Equation (9) are shown. The use of Equation (11) instead of Equation (9) yields negligible

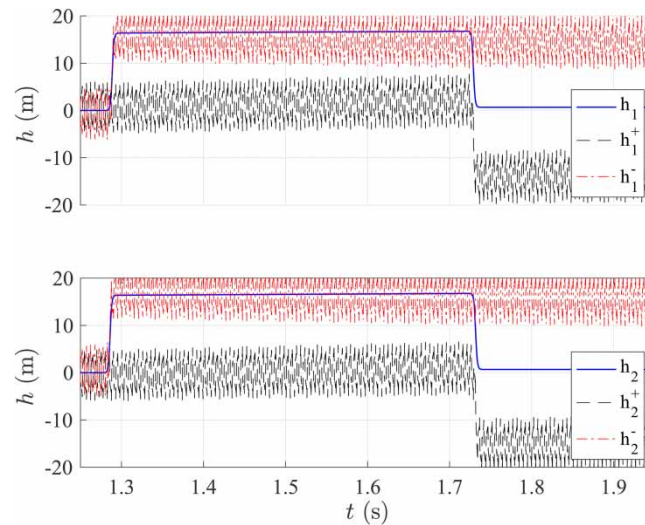


Figure 2 | Separation in the frequency domain by Equations (6) and (7) of the signals h_1 and h_2 simulated by a numerical model with a sensor spacing of 0.99 m on an elastic pipe. The superscript denotes the component propagating in the positive (+) and negative (–) directions.

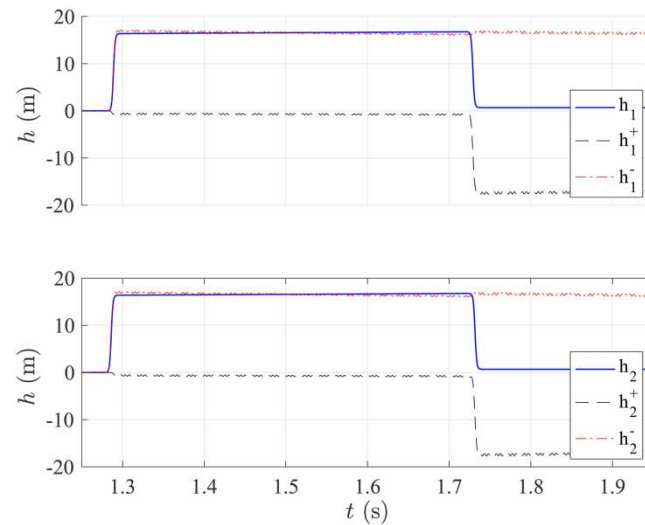


Figure 3 | Separation in the time domain, by Equation (9), of the same signals h_1 and h_2 of Figure 2. The superscript denotes the component propagating in positive (+) and negative (–) directions.

differences in the results. Similarly, the results of Equations (14) or (15) are almost coincident and very similar to those shown in Figure 3 for the same duration.

The time-domain recursive procedure based on Equation (12) does not yield comparable results unless a large number of terms in the expansion are used (e.g. more than 500), with a resulting large increase in computational burden with respect to the other two procedures. Based on these findings, only results of the application of Equation (9) for the pure delay and (14) for the linearized friction are shown in the following, as they are representative of the time-domain procedures.

One of the main issues in the use of the time-domain procedures is the drift of the signal over long durations. As an example, in Figure 4, the same data as that in Figure 3 is shown for a longer duration of time. Although pressure wave arrivals in the two directions are correctly separated at cross sections, the distance between separated and measured signals' mean values continues to increase with time.

The results of the separation procedure accounting for the linearized friction (i.e. Equation (14)) are plotted in Figure 5. The comparison of Figures 4 and 5 shows that the introduction of the linearized friction term causes a reduction in the drift.

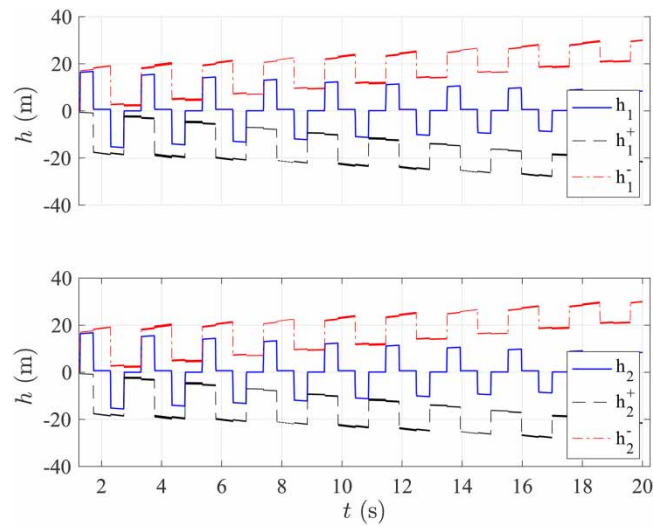


Figure 4 | Separated signals of Figure 3 over a longer duration.

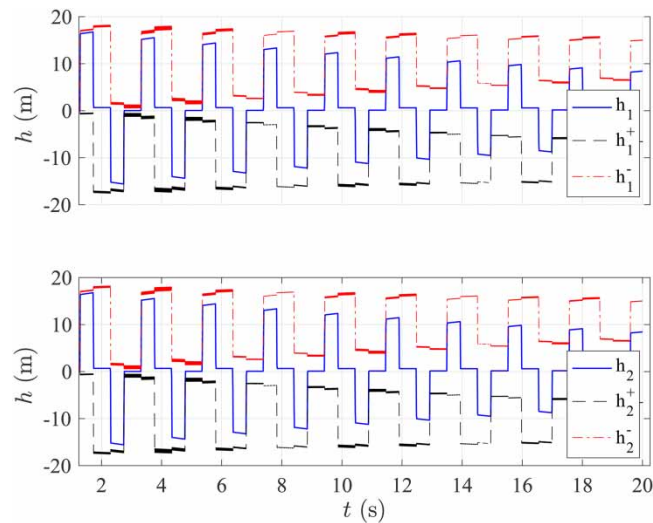


Figure 5 | Separated signals obtained by Equation (14) (the splitting procedure accounting for the influence of linearized friction) from the same signals h_1 and h_2 used in Figure 2. The superscript denotes the component propagating in positive (+) and negative (–) directions.

In this application, $\mathcal{R}$ is very near unity, with a value of $\mathcal{R} = 0.9998$. The behavior over a shorter duration (not shown) is very similar to Figure 3.

The derivative of the acquired signal reveals the amplitudes of pressure waves passing through a measurement section. For this reason, the numerical differences in time of the signals of Figure 3, shown in Figure 6, are effective in revealing the passage of positive and negative waves through the measurement sections. Even if the use of the numerical differentiation enhances the oscillations of the signals and of their components, the pressure waves propagating in the positive and negative directions are clearly discerned in Figure 6. Furthermore, the differences are less affected by the drift effects (as seen by the longer-term behavior as shown in Figure 7).

4.1.3. Filters in the frequency domain

As to be demonstrated, the use of filters reduces the amplitudes of the oscillations shown in Figure 2 and improves the separation of the numerical signals in the frequency domain by Equations (6) and (7). By way of an example, Figure 8

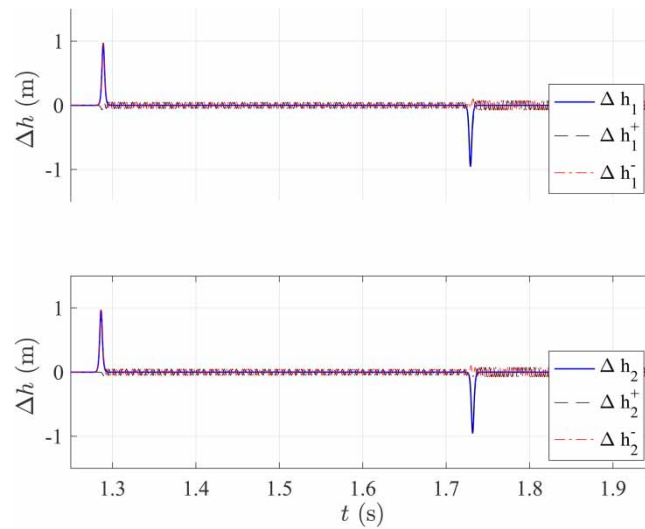


Figure 6 | Numerical differences of the separated signals of Figure 3 obtained by Equation (9). Superscript denotes the component propagating in the positive (+) and negative (−) directions.

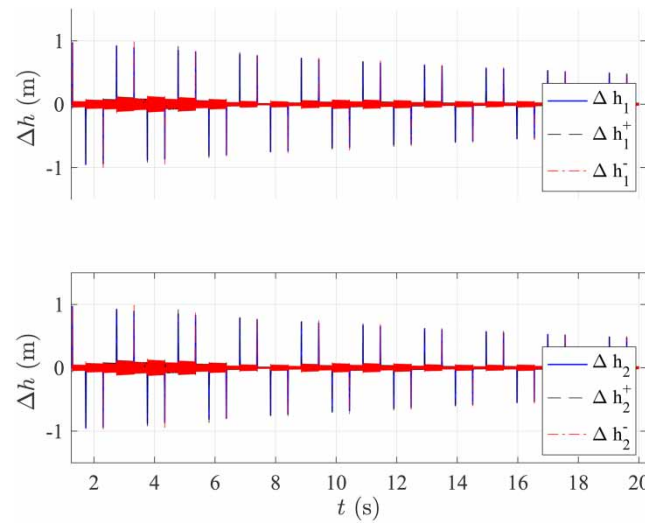


Figure 7 | The numerical differences of the separated signals of Figure 6 are shown for a longer duration.

shows the results of the same procedure used for Figure 2 when a sigmoidal filter with $\omega_s = 0.0093$, $n = 1$, and $\omega_r = 3$ is applied to the signals. These values are a trade-off between the need of avoiding spurious oscillations and the need of preserving the shape of the signals and were obtained by a preliminary parametric study. In fact, the filters modify the pressure wavefront shape reducing the slopes and introducing a bias in the separated signals between the arrival times of the pressure waves.

The effect of the signal sampling frequency, f_d , was analyzed in the range between 2^9 and 2^{14} Hz. The oscillation amplitude of the downsampled unfiltered signals was comparable and the filter effects were the same provided that the pass-band and stop-band edge frequencies were both scaled by f_d .

4.1.4. Effects of noise

The effect of the noise was analyzed by adding a white noise to the signals h_1 and h_2 of Figure 2 with a standard deviation of 0.2% of the maximum of the simulated values, which is assumed to be representative of the total error band of a pressure

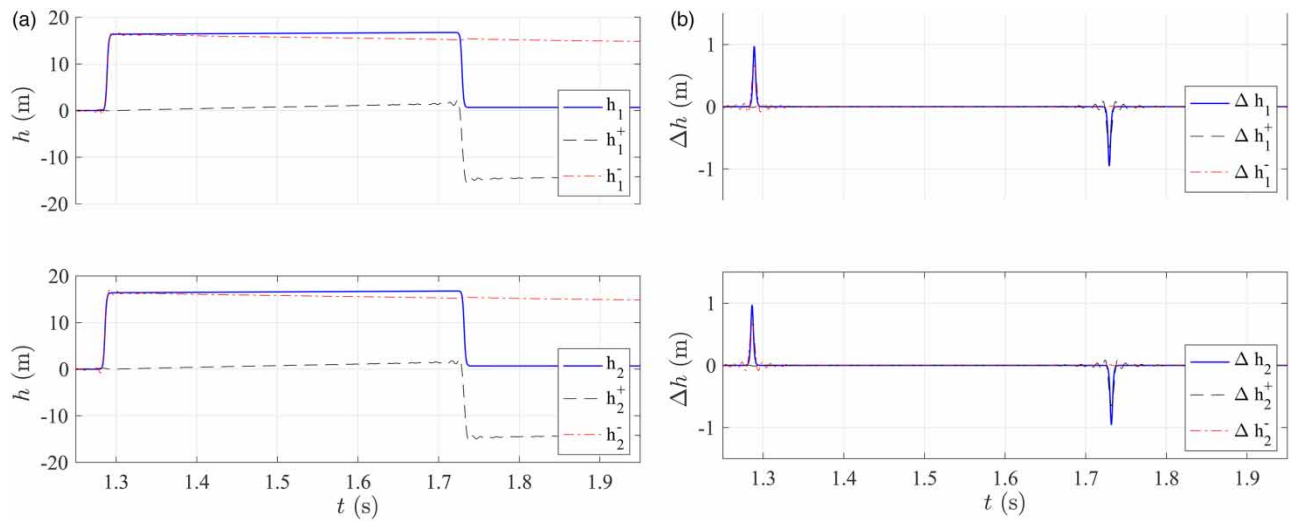


Figure 8 | Separation in the frequency domain, by Equations (6) and (7), of the same signals h_1 and h_2 from Figure 2, filtered by a sigmoidal low-pass filter. Both (a) the original signals and (b) their derivatives are shown.

transducer. The noise affects the results when both frequency- and time-domain separation procedures are used (Figures 9(a) and 9(b)).

The results of the time-domain formulations are less affected by noise on shorter time scales, but due to the recursive procedure, the standard deviation of the separated signals increases in time.

The weight term $w < 1$ in Equations (9) and (11) can be used to reduce both the drift and the noise effect increase on the long-duration behavior for the time-domain separation procedures. As an example, Figure 10 shows the results for the same case of Figure 9(b) with $w = 0.999$. Even such a small variation with respect to unity eliminates the drift and the increase of the noise in time.

The use of the linearized friction can be considered similar to the use of the weights $\mathcal{R}^2$ and $\mathcal{R}$ applied to the terms in the recursive formulation. For this reason, it is not surprising that the separation procedure with $\mathcal{R} = 0.9998$ corresponds to a drift and noise effect reduction comparable to that of Figure 10.

As expected, the noise, being singular everywhere, has a great impact on the numerical differences of the signals.

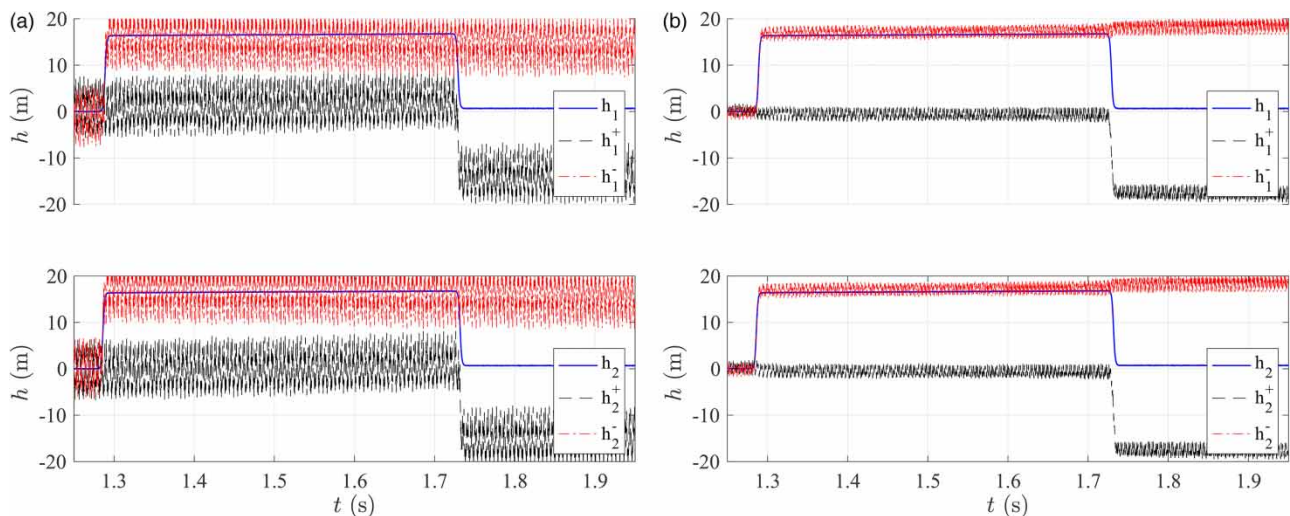


Figure 9 | Separation of noisy signals in (a) the frequency-domain; (b) or by the recursive formulations in the time domain.

4.1.5. Wavelets

For noisy signals, the wavelet transform is very effective in determining the pressure wave arrival at a measurement section and can be directly used for diagnosis. With reference to the same numerical signals of Figure 9 corrupted by noise, the result of the signal filtering by a Haar wavelet with time scale of $\lambda = 2^2, 2^4, 2^6$, and 2^8 samples is shown in Figure 11. The larger the voice scale, the less the noise effect, and the smaller the local maxima number. Voices with large scales, with peaks emerging from the noise band can point out the discontinuity in the noisy signal introduced by the pressure wave arrival, while voices at lower scales can be used to determine the accurate location of the wave arrival.

4.2. Measurement sections with a near 50 m on an elastic pipe

As a further step in the investigation, pressure signals at the two measurement sections are simulated at a distance of $l = 51.02$ m apart using the same numerical model used in Figure 9 with added noise as specified in the previous sub-section.

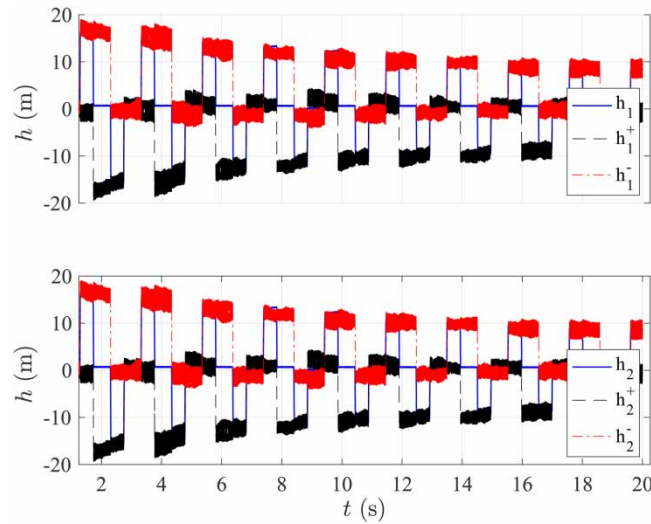


Figure 10 | Separation in the time domain, by Equation (9) with $w = 0.999$, of the same signals h_1 and h_2 of this figure. The superscript denotes the component propagating in the positive (+) and negative (−) directions.

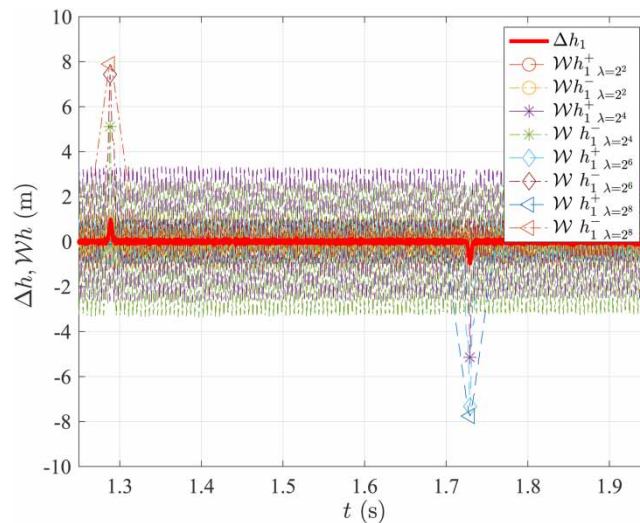


Figure 11 | Differences of the signals Δh_1 of Figure 9 compared with the wavelet transform voices for $\lambda = 2^2, 2^4, 2^6$, and 2^8 samples of positive and negative components.

The separation procedures in the frequency domain show that noise and distance between sections induce artifacts in the separated signals that can hide the information content (Figure 12(a)), while the time-domain separation procedures are very effective in the separation of the simulated noisy signals (Figure 12(b)).

Interestingly, the use of a sigmoidal filter (results not shown) in this case neither reduces the noise effect nor improves the results.

4.3. Measurement sections on a viscoelastic trunk

The separation procedure in the frequency domain does not require any particular assumptions concerning the pipe material, provided that its rheology can be modeled by Equation (4). By way of contrast, the separation procedures in the time domain are based on the pure delay or linearized friction assumptions, which apply only to an elastic pipe material. For this reason, the separation procedures in the frequency domain should perform better than their counterparts in the time domain when a viscoelastic pipe is considered.

To explore this issue, a viscoelastic pipe system (i.e. $V(\omega) \neq 0$) was simulated using the method of characteristics with a sensor spacing of about 50 m. The pipe material rheology is fully described by the series composition of a spring with a Kelvin–Voigt element, which is made by a damper with viscosity η in parallel with spring with Young modulus E . In this case, $V(\omega) = k_m(E + \omega\eta)^{-1}$ where $k_m = k_\lambda \rho g D / (2e)$, k_λ is the pipe constraint coefficient, ρ is the water density, and e is the pipe wall thickness. For the simulations shown $e = 6.6$ mm, $\eta = 3.047 \times 10^9$ Pa·s, and $E = 7.376 \times 10^{10}$ Pa. A white noise was added to the signals as in the previous cases, and the sigmoidal filter was used.

As a general result, if a transfer function accounting for the viscoelastic properties of the pipe material is used, the introduced oscillations are less noisy. For example, the separated signals obtained for an unfiltered noisy pressure signal on a viscoelastic pipe by the frequency domain (Figure 13(a)) and the time-domain (Figure 13(b)) procedures are more clear than those of Figure 12(b) for an elastic pipe. It is surprising that even when applied outside of the assumed elastic pipe material case, the use of the time-domain recursive formulations produces even smoother results (Figure 13(b)) than the frequency-domain based procedures (Figure 13(a)) that assume the correct viscoelastic pipe material.

5. EXPERIMENTAL DATA

In the following, the separation procedures are tested on experimental signals acquired during transient tests.

5.1. The experimental apparatus

The tests were carried out at the Water Engineering Laboratory at the University of Perugia, Italy, on a series of two polymeric pipes, with an air vessel (R) at the upstream end and a hand-operated ball valve discharging into the air (DV) at the

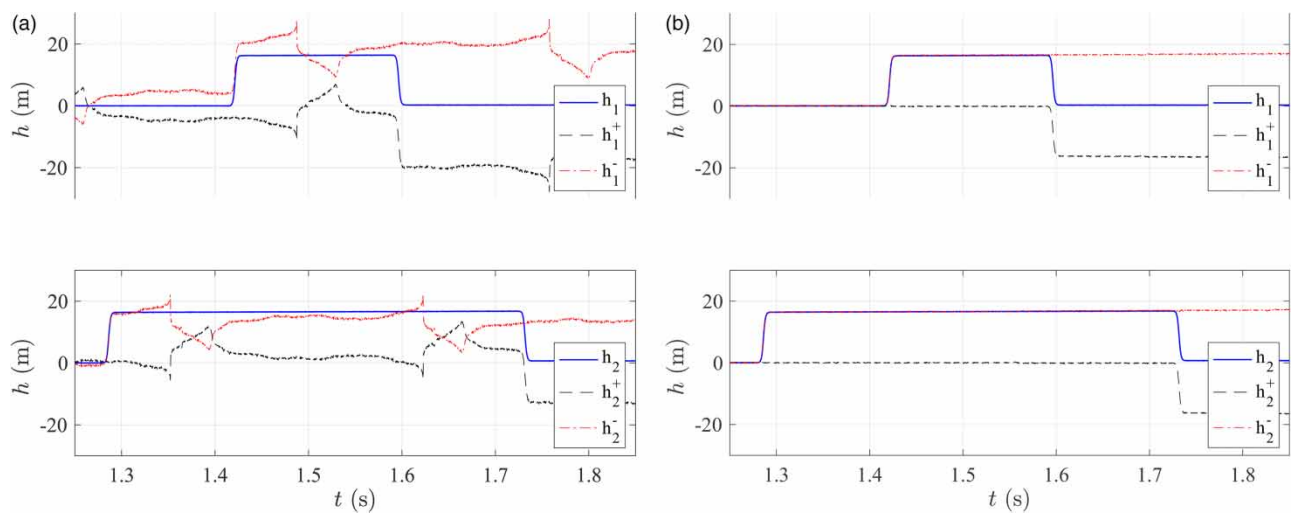


Figure 12 | Separation in (a) the frequency and (b) time domains of the numerical signals h_1 and h_2 with a sensor spacing distance of 51.02 m with added noise.

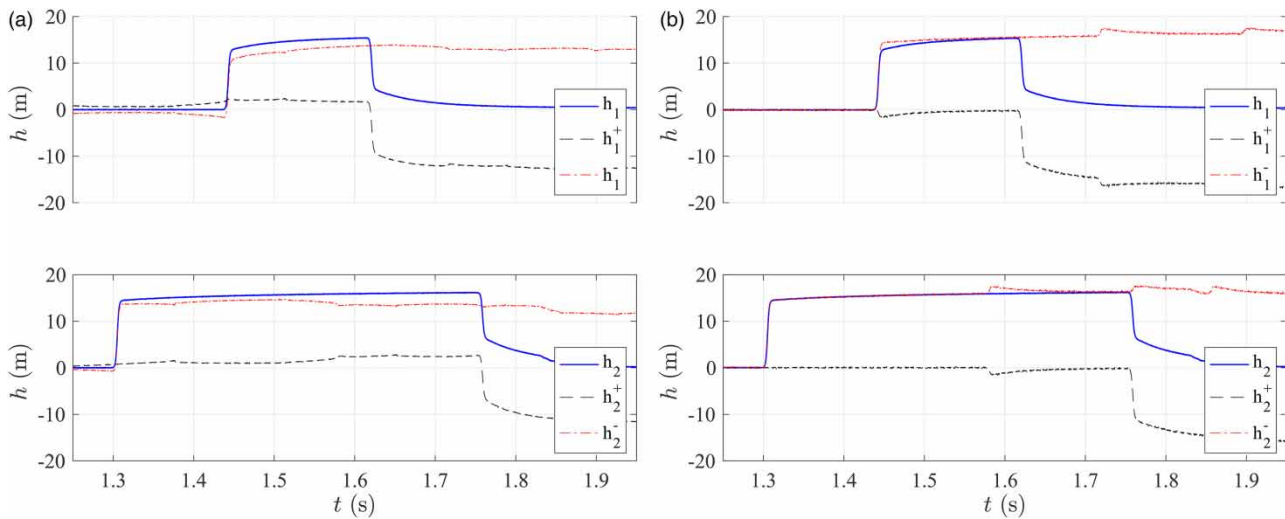


Figure 13 | Separation (a) in the frequency domain by Equations (6) and (7), and (b) in time domain by Equation (9), of numerical signals h_1 and h_2 at a distance of 51.02 on a viscoelastic pipe with added noise, not filtered.

downstream end, as depicted in Figure 14. Directly upstream of DV, an automatically controlled butterfly valve (MV) was used to generate the pressure transients in the system. This test rig is described in more detail in Ferrante & Capponi (2018a, 2018b).

Two polymeric pipes were used. The oriented polyvinyl chloride (PVC-O) DN110 PN16 upstream pipe, with the total length $L_{TO} = 99.18$ m, an internal diameter of $D = 103.0$ mm, and a wall thickness $e = 2.7$ mm, was joined to the high-density polyethylene (HDPE) DN110 PN10 pipe, with a total length $L_{TE} = 92.79$ m, $D = 96.8$ mm, and $e = 6.6$ mm.

An electromagnetic flow meter (FM) was used to measure the discharge during the initial steady-state conditions, with an accuracy of 0.2% of the measured value. Four piezoresistive pressure transducers, with a full scale (f.s.) of 6 bar and an absolute and accuracy of 0.25% f.s., were connected to the HDPE pipe at P_{E1} and P_{E2} , and to the PVC-O pipe at P_{O1} and P_{O2} . The acquisition frequency was 1 Hz for the FM and 2,048 Hz for the pressure transducers.

5.2. Separation of positive and negative pressure waves

The separation procedures are tested on the pressure signals measured at two pairs of measurement sections, i.e. P_{O1} and P_{O2} with a spacing distance of 50.02 m along the PVC-O pipe and P_{E1} and P_{E2} with a spacing of 48.90 m along the HDPE pipe. The viscoelastic parameters used to evaluate Γ were calibrated in Ferrante & Capponi (2017).

Figure 15(a) shows both the signals acquired at the pressure transducers P_{O1} and P_{O2} and the separated signals obtained by the frequency-domain procedure. The results seem to be even better than those obtained by the same separation procedure applied to numerical signals, with reduced oscillations and influence of noise. This is most probably to the signal smoothing resulting from the polymeric pipe material rheology.

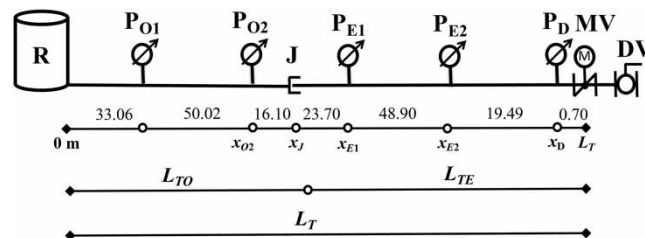


Figure 14 | The laboratory set-up. R is the upstream air vessel, J is the spigot junction between the upstream PVC-O pipe and the downstream HDPE pipe. P_{O1} , P_{O2} , P_{E1} , P_{E2} , and P_D are pressure transducers, FM is the flow meter, MV and DV are the remotely controlled butterfly valve and the hand-operated ball valve, respectively. Distances are in meters.

The results of the time-domain procedure for the separation of the same signals of Figure 15 are shown in Figure 16. The time-domain procedure is able to evaluate the separated signals with reduced oscillations even when the assumption of pure delay (i.e. a frictionless and elastic pipe) is incorrect, which is quite a remarkable result. For the results shown, a value of $w = 0.95$ is used based on a preliminary parametric study. Similar results (not shown) are obtained in the linearized friction case, where the value of $\mathcal{R} = 0.98$ can be evaluated by an estimate of q_0 and f . It is worth noting that the separated signals for the experimental results do not suffer from long-term drift (Figure 16(b)), as was the case for the numerical results. This result is unexpected since the damping typical of the viscoelastic effect should be more evident and the conditions far from those of pure delay and elastic pipe assumption embedded within the time-domain method.

As further validation, the separation procedure in time- and frequency domains are applied to the pressure signals acquired at the measurement sections P_{E1} and P_{E2} during the same transient as that in Figures 15 and 16.

The results of the frequency-domain procedure (not shown) confirm those found in Figure 15 for the PVC-O pipe, while the results of the time-domain procedure shown in Figure 17 are even further improved in terms of reduced oscillations and the noise effect. The same value of $w = 0.95$ is also used in this case.

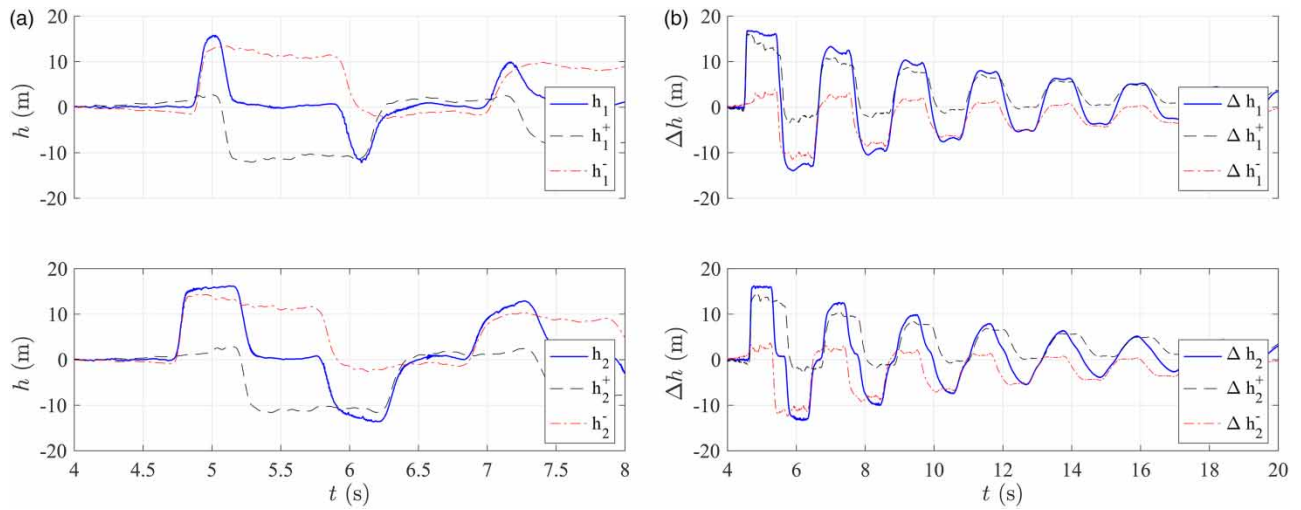


Figure 15 | Separation in the frequency domain by Equations (6) and (7) of the experimental signals h_1 and h_2 acquired at P_{O1} and P_{O2} , respectively, on the system of Figure 14. The same signals in (a) are also shown in (b) for a longer duration.

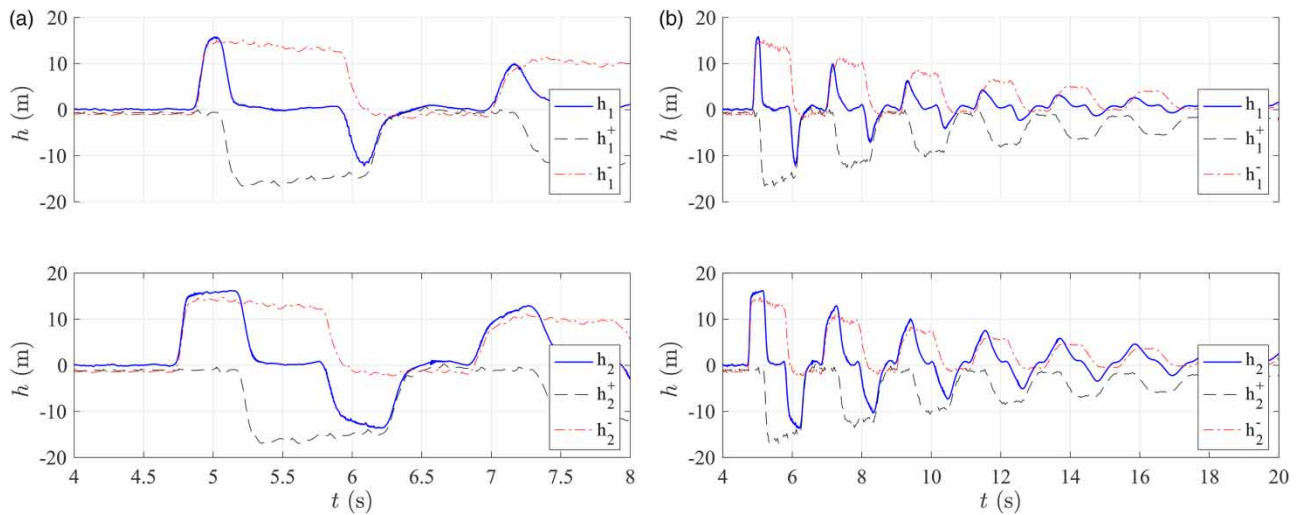


Figure 16 | Separation in the time domain by Equation (9) of (a) the experimental signals h_1 and h_2 acquired at P_{O1} and P_{O2} , respectively, on the system of Figure 14; and (b) the same signals of (a) but for a longer duration.

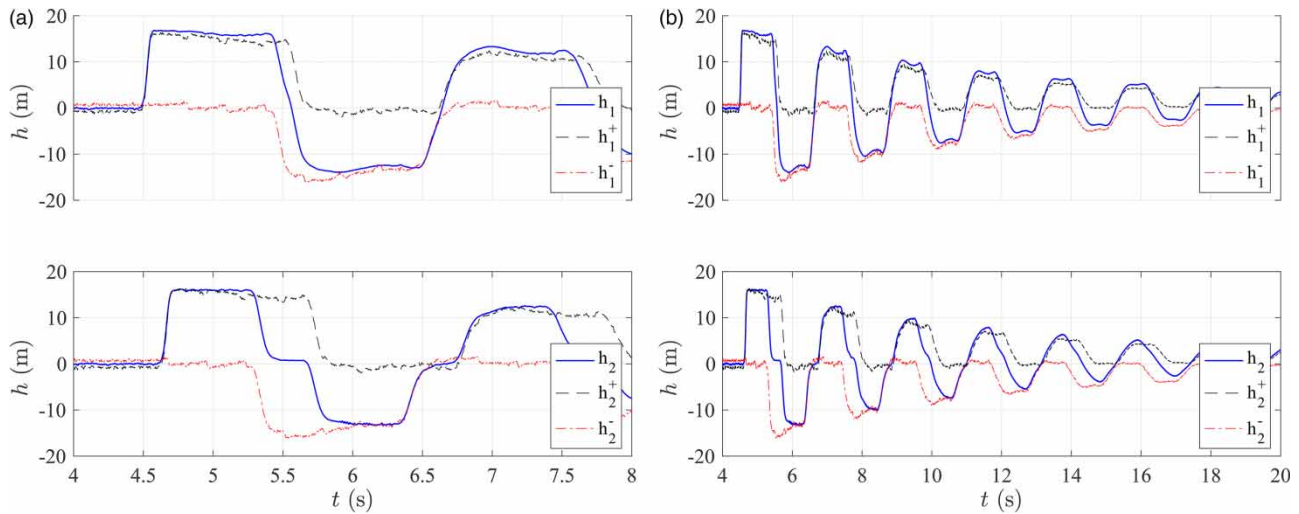


Figure 17 | Separation in the time-domain by Equation (9) of (a) the experimental signals h_1 and h_2 acquired at P_{E1} and P_{E2} , respectively, on the system of Figure 14; and (b) the same signals as in (a) but for a longer duration.

These results appear to confirm that the viscoelastic effects generally improve the results for both time- and frequency-domain separation procedures since the HDPE material can be considered to have a greater viscoelastic effect than PVC-O. A measure of the viscoelasticity of the two materials is provided in Ferrante & Capponi (2017) where the use of the fractional derivatives allows for this kind of evaluation.

5.3. The wavelet analysis of the separated signals

The Haar wavelet filter has also been applied to the pressure signals acquired at P_{O1} and P_{O2} . In Figure 18, the voices of the separated signals for $\lambda = 50, 100, 200$, and 500 samples are shown. The sequences of maxima and minima along voices around a given time, or ‘chains’, are effective in pointing out the discontinuities. The higher peaks corresponding to large values of λ are not affected by noise and allow the detection of discontinuities, while peaks of the same chain corresponding to small values can be used for an accurate location in time.

Similar results are obtained when the pressure signals acquired at P_{E1} and P_{E2} are considered (Figure 19).

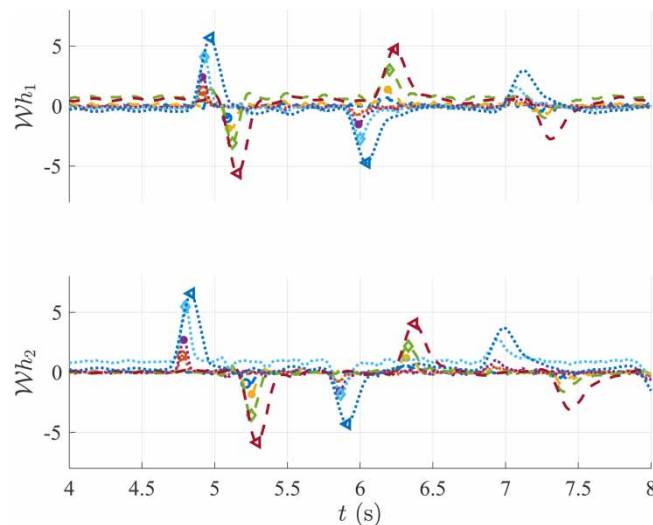


Figure 18 | Wavelet transform voices of the signals from Figure 16 compared with the wavelet transform voices for $\lambda=50$ (circle), 100 (asterisk), 200 (diamond), and 500 (triangle) samples of the wavelet filter of the positive (dashed lines) and negative (dotted lines) wave components.

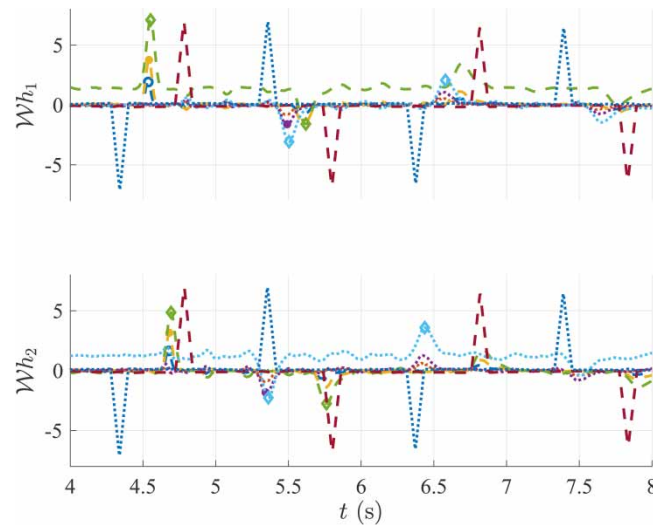


Figure 19 | Wavelet transform voices of the signals of Figure 15(b) for $\lambda = 50$ (circle), 100 (asterisk), 200 (diamond), and 500 (triangle) samples of the wavelet filter of the positive (dashed lines) and negative (dotted lines) wave components.

6. DISCUSSION AND CONCLUSIONS

Techniques for separating the effects of pressure waves traveling in opposite directions have the interesting feature of helping diagnose parts of complex systems. The information carried by waves about their causes and encountered singularities can be associated with a location within the system without the need to model the system in total, boundary conditions included.

As demonstrated within this paper, the separation of pressure signals acquired at two measurement sections into their respective positive and negative traveling wave components can be obtained by different procedures, and under different conditions. Procedures available in the frequency domain have been revised, and other procedures entirely in the time-domain are proposed (without the need for transformation to and from the frequency domain). The performance of all these procedures has been tested using numerical and experimental signals, considering different distances between sections and different pipe materials.

6.1. Discussion

The procedure obtained by the Fourier transform of the signals, their algebraic manipulations in the frequency domain, and then by the inverse transform, has been seen to be significantly affected by spurious oscillations that can hide the information content of the separated signals. The oscillations do not depend on the sampling frequency of the signals and are also present in noise-free signals. These oscillations can, however, be partially removed by a low-pass filter but their tuning for specific applications can be onerous. The choice of the filter parameter values requires a trade-off between the reduction of the oscillations and the ability to retain the sharpness of step wave fronts in the pressure signals.

The wavelet transform of the separated pressure signals can be obtained if a wavelet function is used instead of a filter. This accomplishes two tasks, i.e. detecting pressure waves propagating in the two opposite directions and avoiding the need to filter out oscillations introduced by the separation procedure or noise.

The procedures obtained by the time-domain recursive formulations were also tested. Two recursive-based procedures requiring the values of the separated signals at previous time lags yield near identical results. A procedure requiring only historic values of the original pressure signals was also tested; however, its efficiency and reliability were found to be limited by the large number of terms needed (results not shown). The time-domain procedures are affected by two main issues that become more relevant over long time durations. The first issue is the drift of the separated signals, which is an increase in the mean absolute values of the two wave components. The second issue is the noise error compounding in time caused by the terms involving the previous time steps, which propagate and add noise from one time step to the next.

The use of a weight factor (like a relaxation coefficient) applied to the historic terms in the time-domain formulations can reduce the drift and the noise aggregation observed in the separated signals. The use of a linearized friction term to account for frictional losses can be considered equivalent to that of the weight factor, with the difference being that the former is

applied to all terms of the recursive formulation and, most important, being physically based it depends on parameters of the system that can be measured or estimated (such as the geometry, the reference flow q_0 and the friction factor). A filter applied to the acquired signals can also be used if needed to reduce the impact of noise.

The distance of the measurement sections appears not to be a limiting factor. Separation procedures can provide similar results for sections 1 or 50 m apart, as long as the pipe section between the measurements is uniform. The separation procedures are also effective for pipes of a viscoelastic material. Those signal-splitting procedures derived in the frequency-domain yield signals less affected by oscillations, while those derived in the time-domain perform well, even despite the fact that they are based on the assumption of an elastic pipe material.

6.2. Conclusions

In conclusion, separation procedures are a promising tool application in transient-based diagnosis. Their use in subsections of a complex system is one of the most interesting features, as the methods do not require a full model of the pipeline system to interpret the measured signals. Findings show that time-domain procedures appear to be more accurate and reliable when numerical or experimental signals are used, both in elastic and viscoelastic pipes, especially when friction effects are modeled. In general, the results of the proposed investigation can be considered a necessary preliminary step in assessing these techniques. Field tests in functioning systems are the natural and necessary continuation of this research activity.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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