Multiple-fault detection in water pipelines using transient-based time-frequency analysis

Jilong Sun, Ronghe Wang and Huan-Feng Duan

ABSTRACT

Pipe faults, such as leakage and blockage, commonly exist in water pipeline systems. It is essential to identify and fix these failures appropriately in order to reduce the risk of water pollution and enhance the security of water supply. Recently, transient-based detection methods have been developed for their advantages of non-intrusion, efficiency and economics compared to traditional methods. However, this method is so far limited mainly to simple pipelines with a single known type of pipe fault in the system. This paper aims to extend the transient-based method to multiple-fault detection in water pipelines. For this purpose, this study introduced an efficient and robust method for transient pressure signal analysis – a combination of the empirical mode decomposition and Hilbert transform – in order to better identify and detect different anomalies (leakage, blockage and junction) in pipelines. To validate the proposed transient-based time-frequency analysis method, laboratory experimental tests were conducted in this study for a simple pipeline system with multiple unknown types of pipe faults including leakages, blockages and junctions. The preliminary test results and analysis indicate that multiple pipe faults in simple pipelines can be efficiently identified and accurately located by the proposed method.

Key words | empirical mode decomposition (EMD), Hilbert transform (HT), multiple-fault detection, pipelines, time-frequency analysis, transient-based method

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INTRODUCTION

Damage to pipeline systems can be divided into two categories: internal faults and external faults. Internal faults include corrosion and blockage on the internal pipe wall. Blockage distributed along pipelines reduces the transmission capacity and meanwhile increases energy cost (Świetlik *et al.* 2012; Scheidegger *et al.* 2013, 2015). Corrosion reduces the pipeline strength with imposing imminent risk to drinking water supply safety. Pipe leakage and burst can generally be attributed to external faults, which causes water and energy losses with significant environmental issues and economic cost (Aisopou *et al.* 2012; Wang *et al.* 2014; Jiang *et al.* 2015). Therefore, a reliable and efficient detection method is necessary for water pipeline systems such that these potential pipe failures and faults can be identified and maintained appropriately.

Urban water supply pipelines are usually concealed underground, and it is difficult and inconvenient to determine the instantaneous conditions of such pipelines by traditional physical and chemical methods (Sun *et al.* 2014). Among the commonly used methods, the acoustic diagnostic technique is time-consuming and labor-intensive. More importantly, the acoustic technique is sensitive to background noise for leakage detection, and this measurement for other types of pipe faults such as blockage and junctions is inaccurate or invalid (Lighthill 1997). Other traditional methods for pipe condition assessment are largely

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based on the local physical properties and thus become inefficient and intrusive to the system. In recent decades, the transient-based pipe fault detection methods have been proposed and widely developed in this field for noninvasive and efficient evaluation of water supply pipeline conditions (Colombo *et al.* 2009; Lee *et al.* 2013).

The principle of transient-based detection method is to examine and utilize the hydraulic characteristics of transient pipe flows to identify and determine the potential fault information (location and size) in the pipeline system (Duan *et al.* 2010; Stephens *et al.* 2012; Tuck *et al.* 2013). Plenty of system information can be contained and reflected in the transient pressure wave signal when it propagates along the pipeline and interacts with system components and devices as well as pipe faults. As a result, the transient pressure wave can be analyzed and utilized for evaluating the changes in the physical structure of a water pipeline system, such as unknown junction, blockage, ill-branch and leakage (Brunone 1999; Mpesha *et al.* 2001, 2002; Covas *et al.* 2005; Ferrante & Meniconi 2009; Duan *et al.* 2011a; Meniconi *et al.* 2011a, 2011b, 2015; Gong *et al.* 2012a, 2012b; Massari *et al.* 2014). Specifically, the results and findings of these previous studies have demonstrated that the pipe leakage may cause both additional reflection and damping for the time-domain pressure waves, and the pipe blockage and branch and junctions may result in different frequency shifting and damping patterns in the frequency domain (Ghazali *et al.* 2012; Lee *et al.* 2013; Duan *et al.* 2014). Accordingly, the transient response pattern for each type of these pipe faults has been derived and used in these studies for an inverse analysis and detection of pipe faults.

Current transient-based pipe fault methods can be classified into three different types according to the utilization ways of the transient responses (Duan *et al.* 2010): (1) time-domain transient response analysis (e.g. Meniconi *et al.* 2012, 2013, 2014; Hou & Zhang 2013); (2) frequency-domain transient response analysis (e.g. Mpesha *et al.* 2001; Gong *et al.* 2012c, 2013, 2015; Duan *et al.* 2013, 2014; Lee *et al.* 2013); and (3) transient calibration analysis (e.g. Liggett & Chen 1994; Kim 2014). These developed methods have been validated respectively through different numerical and experimental applications in these studies, and the obtained results from their applications have indicated the validity and applicability of these methods for identifying and detecting specific pipe faults in the system. However, current applications of these developed methods are mainly limited to simple pipeline systems such as single and multiple-series pipelines with knowing the originally intact system configurations. Most importantly, these methods are largely used and valid only for the pre-known or pre-assumed single type of pipe faults, and have not yet been extended to the relatively complex situations of multiple pipe faults with unknown types. It is also noted that the situation of multiple faults has been investigated in previous studies for the validations of these developed methods (e.g. Covas *et al.* 2005; Lee *et al.* 2006; Duan *et al.* 2011b; Gong *et al.* 2012c), but the considered multiple faults in these applications have to be specified (known or assumed) for the same type known in advance, while for the situation of multiple unknown types of pipe faults in the pipeline system, current transient-based methods will become inapplicable.

On the basis of previous applications and results discussion in the literature, the limitations of current transient-based pipe fault detection methods can be attributed to (but may not be limited to): (1) the difficulty of deriving and characterizing the transient responses to complex pipe configuration situations (branched and looped pipe junctions); and (2) the limitation of the currently used data analysis techniques (e.g. wavelet and Fourier analysis) for transient pressure waves to accurately distinguish the transient responses of different and multiple pipe faults and other system components. This study aims to explore the second aspect, that is, investigation. Actually, the study of Duan *et al.* (2014) demonstrated that the transient pressure waves propagating in complex pipeline systems under different faults (e.g. blockage) conditions are highly nonlinear and non-stationary (transient). On this point, it is necessary and significant to further explore different transient wave analysis techniques for the extension of current efficient and non-intrusive methods to more complex situations of pipe fault detection in practical water pipelines. This is the scope of the current study.

This paper introduces an efficient and robust method for the transient pressure wave analysis, with the aim to extend the transient-based detection method to multiple-fault situations in simple pipelines, which thus provides preliminary progress and a useful basis for the further extension and application of this type of method to more complex and practical water pipe networks in the future. The combined method of the empirical mode decomposition (EMD) and Hilbert transform (HT) algorithms, which are proved to be more suitable and efficient for nonlinear and non-stationary signal analysis than the traditional analysis methods (e.g. wavelet and Fourier analysis) (Huang *et al.* 1998), is used in this study for the time-frequency analysis of transient pressure waves, so that the characteristics of different types of pipe faults can be decomposed and extracted from the original pressure wave signals. The detailed procedures of the transient signal decomposition and time-frequency correlation analysis for the detection of multiple-type pipe faults are provided in the paper. Thereafter, the proposed method and application procedure is validated and verified through the preliminary laboratory experiments conducted in this study. The pipe faults considered for this investigation include leakages, blockages, and junctions. Finally, the test results are analyzed and discussed in the paper.

METHODS

An efficient and robust transient wave analysis method is introduced in this study to characterize the transient behaviors of different types of pipe faults in the pipeline. Prior to presenting the application principle and procedure of pipe fault detection method, it is necessary to describe the key algorithms and methods used in this method.

Empirical mode decomposition

The EMD algorithm was firstly proposed by Huang *et al.* (1998), and was thereafter widely applied to different research and engineering fields for signal analysis. In principle, the objective signals, which can be complex in both temporal and spatial domains, are decomposed and separated into multiple simple and understandable signals, which are termed as the intrinsic mode functions (IMFs) in this method. From this perspective, the function of the EMD is very similar to traditional signal analysis methods (e.g. wavelet and Fourier analysis). However, through various theoretical analysis and engineering applications, the EMD has proved to be more suitable and efficient to nonlinear and non-stationary signals (Huang *et al.* 1998; Xue *et al.* 2013). It is known that the transient pressure waves in water pipelines are highly unsteady (transient) and nonlinear (reflections and transmissions), especially under conditions of complicated transient wave-fault-system interactions (Duan *et al.* 2014). As a result, current transient-based methods are so far mainly limited to simple situations of pipe fault detection in pipeline systems. To this end, the EMD is introduced in this study, with the perspective of implementing the multi-type pipe fault detection. The main steps of applying the EMD algorithm are as follows:

(1) Connect the local minima and maxima points of the objective signal $x(t)$ using a cubic spline curve to obtain the upper and lower envelope sequence, so as to evaluate the mean value of the signal, $m(t)$.
(2) Calculate the difference $h_1(t) = x(t) - m(t)$ to generate the IMF, checking the two following judgment criteria:
   (2.1) the difference between the numbers of extrema and zero-crossing over the entire signal series is not greater than one in an essentially oscillatory process;
   (2.2) the mean value of the envelopes for local minima and maxima is zero.

   If the obtained $h_1(t)$ above can meet these two criteria, then $h_1(t)$ is detected and used for the IMF; otherwise, the $h_1(t)$ is processed as the original signal $x(t)$ by repeating steps (1) and (2), until the above two conditions are satisfied. The obtained IMF is denoted as $c_1(t)$.
(3) Separate the obtained IMF, $c_1(t)$, from the objective signal $x(t)$ to obtain the residual sequence $r_1(t) = x(t) - c_1(t)$.
(4) Take the residual signal $r_1(t)$ in step (3) as a new objective signal $x'(t)$ to repeat the above steps (1)–(3), so that the new IMF is obtained.
(5) The above process continues until the predetermined stopping criteria are satisfied. Finally, the original signal $x(t)$ is decomposed into a series of IMFs (e.g. $c_1(t)$, $c_2(t)$, …, $c_n(t)$), and the last residual signal (e.g. $r_n(t)$).

In summary, any objective signal can be decomposed into different IMFs by the above EMD procedure with the following form:

$$x(t) = \sum_{j=1}^{n} c_j(t) + r_n(t) \tag{1}$$

Correlation analysis for signal reconstruction

By applying the above EMD algorithm, different physical behaviors from transient systems have actually been separated and contained into the resultant IMFs. Actually, the obtained IMF signal sequences are isolated from the high-frequency filter to the low-frequency one, i.e. the first IMF contains the highest frequency component, whereas the last IMF extracted contains the lowest frequency component. Inversely, the original signal may be reconstructed by the addition of the appropriate IMF components, excluding the noises (physical and non-physical), for the system analysis and evaluation (Huang *et al.* 1998).

In the process of data acquisition, the real signal is unavoidably subject to noise pollution, such as electronic noise, pipe wall vibration, sensor data acquisition errors and flow instability (Li *et al.* 2013). Based on the EMD based signal analysis, an appropriate reconstruction of the obtained IMFs is useful to reduce or filter the noises in original transient signals. To correctly and accurately reconstruct the physical transient wave signals while excluding the above-mentioned noises, the correlation analysis is applied. The application procedure of the correlation analysis for signal reconstruction is given as follows:

(1) Apply the EMD algorithm above to identify and separate the valid IMFs from the measured signals with containing the possible system and physical noises.
(2) Consider different combinations of the valid IMFs for signal reconstruction.
(3) For each combination situation, calculate the correlation coefficient (r_j) between the original signal and combined signal of the chosen IMFs.
(4) Rank the M correlation coefficients ($r_1, r_2, \ldots, r_j, \ldots, r_M$), and indicate the fault-containing importance of each IMF.
(5) Analyze the IMFs in the frequency domain according to their importance rankings (e.g. by the HT algorithm as described in the following section), in order to separate and find out different pipe faults information in the pipeline system.

Hilbert transform

After obtaining the IMFs by the EMD operation and their relevant importance rankings by the correlation analysis, it is necessary to analyze each IMF so that the transient behaviors of different system components (including devices and faults) can be understood and identified for its influence range and intensity. To better represent the non-stationary (transient) signals, the concept of the instantaneous frequency was introduced for the HT algorithm and then combined with the EMD algorithm (termed as EMD-HT method in this study) for the transient signal analysis (Cheng *et al.* 2008). By using this instantaneous frequency, the HT becomes more suitable and preferable to the non-stationary signal analysis than the traditional analysis techniques such as Fourier transform and Wavelet analysis which were originally developed for a relatively stationary signal (Huang *et al.* 1998). The principle is provided as follows:

For any time-domain sequence $x(t)$, the HT response $y(t)$ is obtained by:

$$y(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{x(t)}{t-\tau} d\tau \tag{2}$$

which results in the following analysis function $z(t)$:

$$z(t) = x(t) + iy(t) = a(t)e^{i\phi(t)} \tag{3}$$

where i is the imaginary unit; $a(t)$ and $\phi(t)$ are amplitude and phase of the complex function. Hence, the instantaneous frequency is given by:

$$\omega(t) = \frac{d\phi(t)}{dt}, \tag{4}$$

where $\omega(t)$ is the instantaneous angular frequency. This HT process is applied to each IMF obtained from the EMD method, so that the instantaneous properties (frequency and amplitude) of the specified transient responses are obtained.

Numerical illustration of the EMD-HT based time-frequency analysis

In order to better understand the EMD-HT based transient signal analysis, a numerical example is adopted herein to illustrate the application procedure and validity of this technique. For simplicity, the testing objective signal $s(t)$ is shown in Figure 1, which is composed of: (1) two series of single frequency signals, $x(t)$ and $y(t)$, which represent the system and pipe fault information respectively; and (2) random signal, $r(t)$, which represents the noises in the system. By applying the above EMD-HT method, this signal $s(t)$ can be decomposed into five IMFs as shown in Figure 2(a) in the time domain, and Figure 2(b) in the frequency domain. The correlation analysis indicates that the first and second IMFs are dominant for their influences on the original objective signal. In other words, the other three IMFs are mainly due to the noises, which thus can be neglected in the pipe fault analysis. As a result, the original objective signal can be decomposed into two sub-signals as:

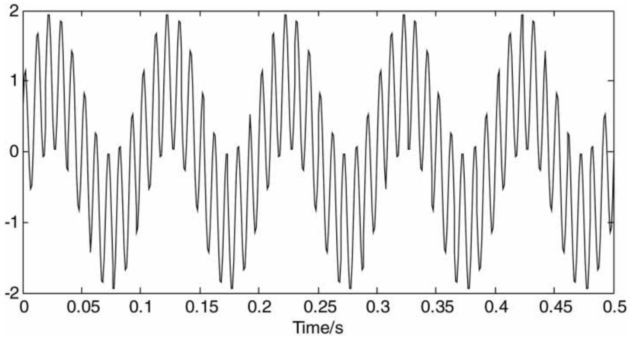

Figure 1 | The testing objective signal trace s(t).

$$s(t) = x(t) + y(t) = \sin(20\pi t) + \sin(200\pi t) \quad (5)$$

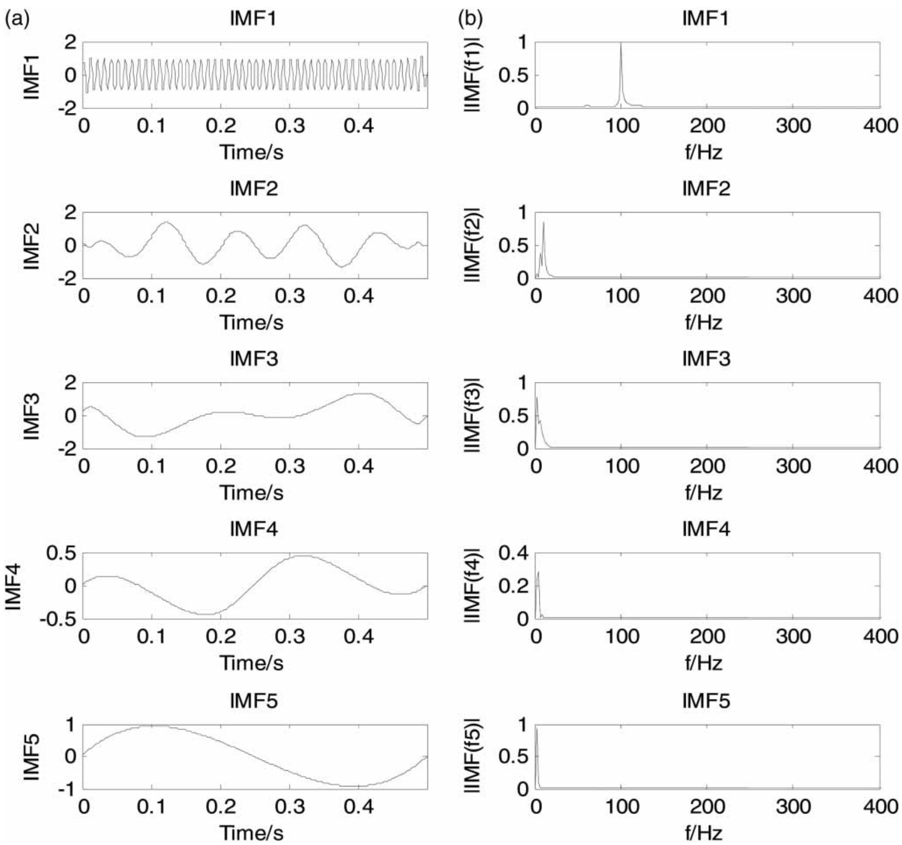

Figure 2 | EMD decomposition results. (a) IMF signals in the time domain; (b) IMF signals in the frequency domain.

Detection of pipe faults based on time-frequency analysis

To locate the pipe faults based on the transient wave analysis, the parameter of wavespeed (a) becomes especially crucial since it directly relates to the characteristics of the wave reflection and transmission in the pipeline (Brunone 1999). In this study, the wavespeed of the pipeline under investigation is pre-calibrated based on the classic *Joukowsky* formula. In typical fast transient events such as by rapid valve operations (with $T_c < 2L/a$), the resultant transient pressure head (ΔH) is dependent on pipe wavespeed as well as initial flowrate (or velocity) at this source location, which can be described as:

$$\Delta H = \frac{\pm a \Delta V_0}{g} \quad (6)$$

where ΔV_0 is the change of initial velocity magnitude; $\pm$ indicates the direction of the generated transient wave; g is gravitational acceleration; T_c is the valve operation time; and L is the length of the pipeline. Therefore, the wavespeed quantity (a) of the studied pipeline can be inversely calibrated by measuring the initial velocity change (ΔV_0) and the resultant transient pressure head (ΔH).

Accordingly, the distance of each pipe fault to the transient measurement (i.e. pressure transducer/sensor) location, x_f, can be calculated by:

$$x_f = \frac{a(t_2 - t_1)}{2} \quad (7)$$

where t_1 and t_2 are transmutation time, which are determined by the instantaneous frequencies from the EMD-HT analysis. It is also noted that this pipe fault location principle and procedure of Equation (7) is similar to the traditional analysis methods (e.g. Wavelet in Ferrante & Meniconi (2009), and Fourier transform in Gong *et al.* (2012b)), but the determination of the reflection/transmission times (t_1 and t_2) of pipe faults by the instantaneous frequencies from the EMD-HT analysis method is the innovative contribution of this study. The EMD-HT based time-frequency analysis method may become another alternative and useful tool for complex pipe fault detection in water pipeline systems, which is demonstrated and validated in the following experimental applications.

EXPERIMENTAL SETUP

For demonstrating and validating the EMD-HT based pipe fault detection method, the transient pressure data were collected from laboratory experiment tests, which were conducted at the Graduate School at Shenzhen, Tsinghua University, China. The experimental pipeline system is shown in Figure 3, consisting of a single pipeline with galvanized steel material that is bounded by the water supply and drainage tanks, pressure measurement system and flow control devices. The details of the data acquisition devices and different pipe faults for testing in this experimental system are shown in Figure 4. The internal pressure of water supply tank is adjusted by an electronic pressure switch, and the initial discharge is adjusted by the inline valve installed at the end pipeline (close to the downstream drainage/storing tank). A recycling pump is used to maintain the steady water level in the tanks. For clarity, the parameters of the system operation are given as follows:

- Total pipeline length $L = 79.15$ m.
- Internal diameter and pipe-wall thickness: DN = 40 mm and $e = 4$ mm.
- Recycling pump type: CHL2-50, with flow rate 2 m^3/h and head = 50 m.
- Pressure tank volume: 1 m^3.
- High-frequency data acquisition card: with sampling frequency (1–250 K Hz) and output voltage (0–5 V).
- Pressure transducer: MIK-P300-1581256, with pressure range (0–1.6 MPa) and output voltage (0–5 V).

The details of system settings and parameters for testing are shown in Tables 1 and 2, respectively. The transients in the system are generated by the fast and complete closure of the inline valve from initial full open state. The transient data are collected at the two ends of the pipelines (S1 and S2), with S2 used for the calibration of wavespeed of the test pipeline, and S1 (close to the inline valve) for the pipe fault detection and analysis later in this study.

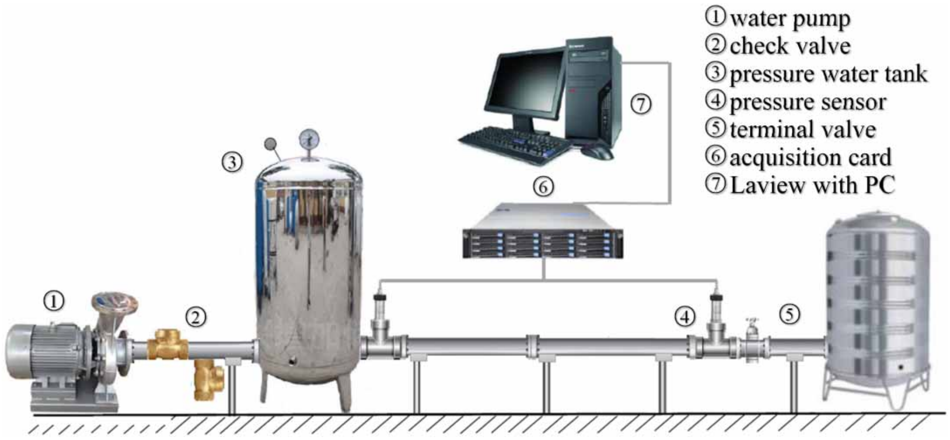

Figure 3 | Schematic of experimental test system.

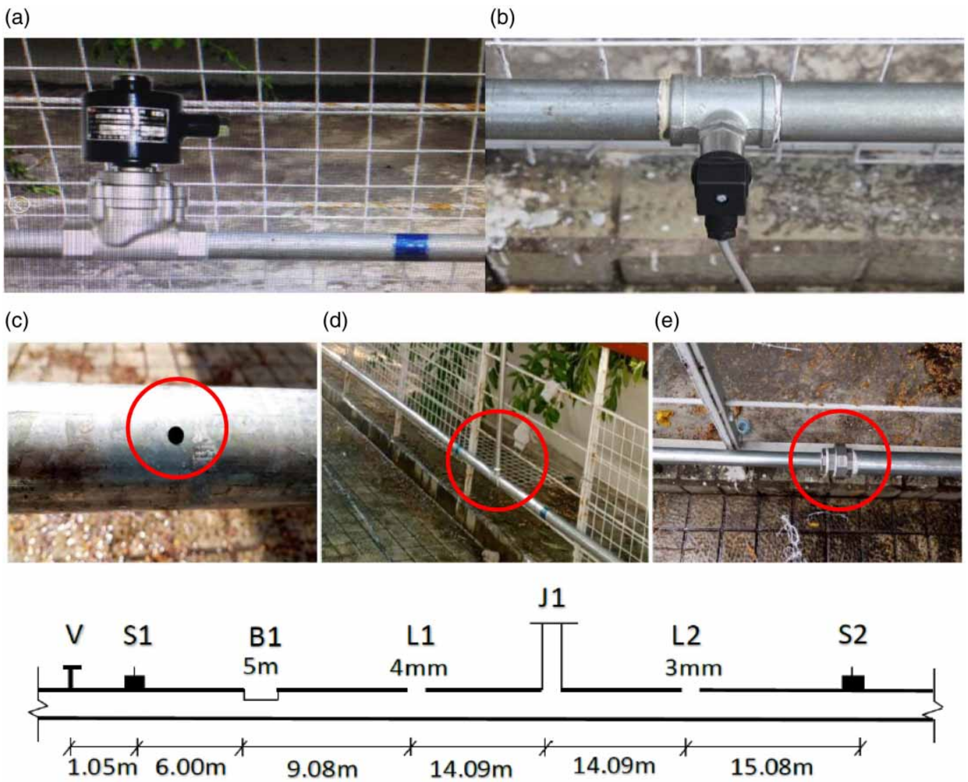

Figure 4 | Different pipe faults and facilities used for the tests: (a) control valve (V); (b) pressure sensor (S1 and S2); (c) leakage hole (L1 with 3 mm diameter and L2 with 4 mm diameter); (d) junction (J1 with 1 m height); (e) blockage (B1 with DN25).

RESULTS AND DISCUSSION

Figure 5 plots the measured transient pressure traces at S1 in the above test system, which shows complex oscillations and attenuations of the transient wave propagation process in the pipeline. For generality, five cases of initial flow conditions (Re) are conducted and shown in Figure 5, which provides very similar trends of the oscillation and

Table 1 | Setting of geometric information

Number	Fault and instrument	Value	Distance to valve (m)
1	Pressure sensor1 (S1)	–	1.05
2	Blockage1 (B1)	5 m	7.05
3	Leakage1 (L1)	3 mm (0.35 L/s)	16.13
4	Junction (J1)	2 m	30.22
5	Leakage2 (L2)	4 mm (0.47 L/s)	44.31
6	Pressure sensor2 (S2)	–	59.39

Table 2 | Experimental test condition

Basic properties	Value
Pipe material	Galvanized steel material
Pipe diameter(mm)	DN40
Calibrated wave speed (m/s)	1014.10
Sampling frequency (Hz)	5,000
Closure valve time (s)	0.2
Initial Reynolds number (Re)	2.1×10^3–5.1×10^4
Friction coefficient (f)	0.0135
Tank pressure (mH_2O)	28

attenuation. It is also noted that similar analysis results have been obtained for these five datasets based on the EMD-HT method, and therefore, only the result for the first dataset of transient pressure wave is presented and discussed in the following study.

Results and analysis by the EMD technique

Based on the previously introduced principle and application procedure of the EMD method, the transient pressure signal in Figure 5 (first dataset) can be decomposed into nine different IMF signals (IMF1–IMF9) and one residual signal (denoted as IMF10 here), which are shown in the left columns of Figure 6 for IMF1–IMF5 and Figure 7 for IMF6–IMF10, respectively. Meanwhile, the frequency domain results of these ten decomposed signals (IMF1–IMF10) are shown in the corresponding right columns of Figures 6 and 7 for comparison.

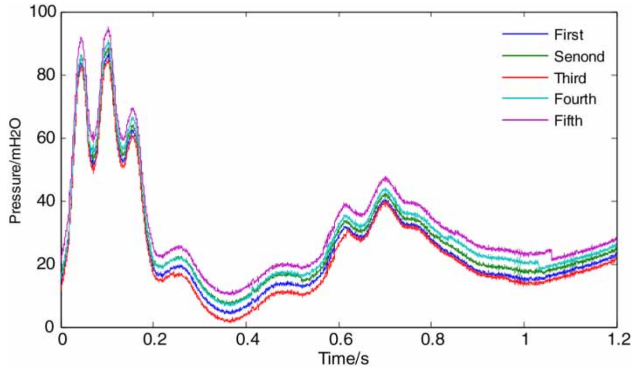

Figure 5 | Measured transient pressure traces at S1.

Clearly, the comparative results indicate the different frequency bandwidths of these decomposed signals. Specifically, the first three signals (IMF1–IMF3) contain much higher frequencies but much smaller magnitudes than the others. Based on the principle and explanation of the EMD method as indicated in Huang et al. (1998), these first three signals are mainly due to the physical disturbances such as turbulence and flow instabilities in the system. Therefore, only the signals of IMF4–IMF9 are valid and used for the pipe fault analysis for this pipeline system.

Furthermore, the dominant frequencies of the valid signals IMF4–IMF9 are easily identified from the frequency domain results in Figures 6 and 7, as follows: IMF4 (14.69 Hz), IMF5 (10.49 Hz), IMF4 (14.69 Hz), IMF5 (10.49 Hz), IMF6 (1.82 Hz), IMF7 (1.23 Hz), IMF8 (1.21 Hz) and IMF9 (0.63 Hz). These results clearly indicate the four groups of the dominant frequencies, which are actually relating to different potential pipe faults in the system. The detailed detection and analysis of these potential pipe faults by the correlation analysis and HT method are given in the following sections.

IMF signal reconstruction and correlation analysis

Based on the EMD results and analysis, the high-frequency noise signals of IMF1–IMF3 are filtered and the appropriate combinations of IMF4–IMF9 are used to reconstruct reduced-noise signals. The five reconstructed signals are plotted in Figure 8, which are much smoother than the original signals in Figure 5 due to the noise reduction or

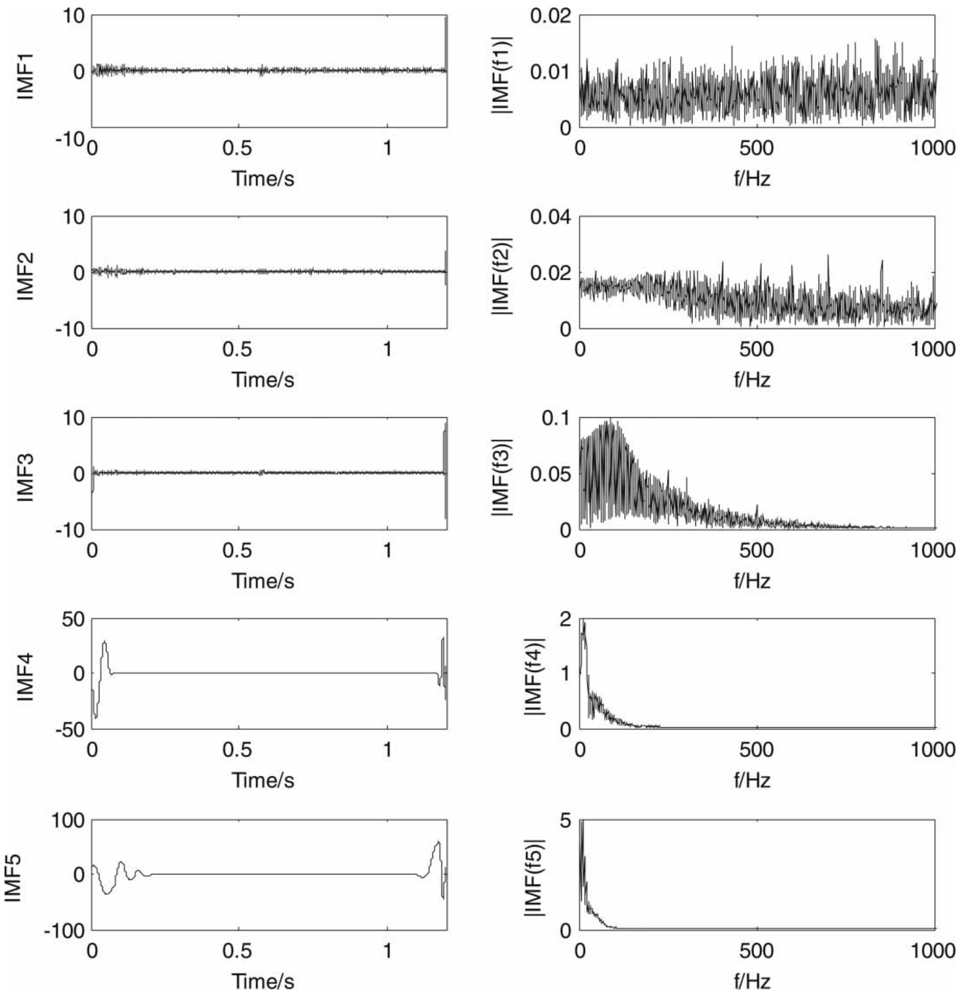

Figure 6 | The results of IMF1–IMF5 signals by the EMD method in the time domain (left column sub-figures) and the frequency domain (right column sub-figures).

exclusion. Accordingly, the correlation coefficient (r) between each of these reconstructed signal and original signal can be figured out to express their different similarities with the original signal. The correlation coefficients for the five cases of Figure 8 are obtained as follows: (a) 99%; (b) 93%; (c) 89%; (d) 84%; and (e) 41%. On the one hand, the result of case (a) that excludes the first three high frequency signals (i.e. IMF1–IMF3 in Figure 6) confirms again the noise-induced results of these signals. On the other hand, the result of case (e) in Figure 8 implies the great loss of system information (including pipe faults) by removing the IMF8 and IMF9 signals. Furthermore, the larger difference between cases (d) and (e) than that between cases (a) and (d) indicates the greater importance of IMF8 than IMF9. In the following study, the detailed information of each IMF and the combination is analyzed by the HT method for identifying different pipe faults in the system.

Fault location and type detection

The HT method is applied to perform the transient time-frequency analysis so as to characterize different faults in this system. The five reconstructed results in Figure 8 are transformed by the HT method and shown in Figure 9, where each sharp peak corresponds to the moment of the pressure wave passing through the specific pipe fault. Based on Equation (7), the total number of pipe faults and the locations of the faults in the system can then be predicted and the results are given in Table 3. Meanwhile, the relative

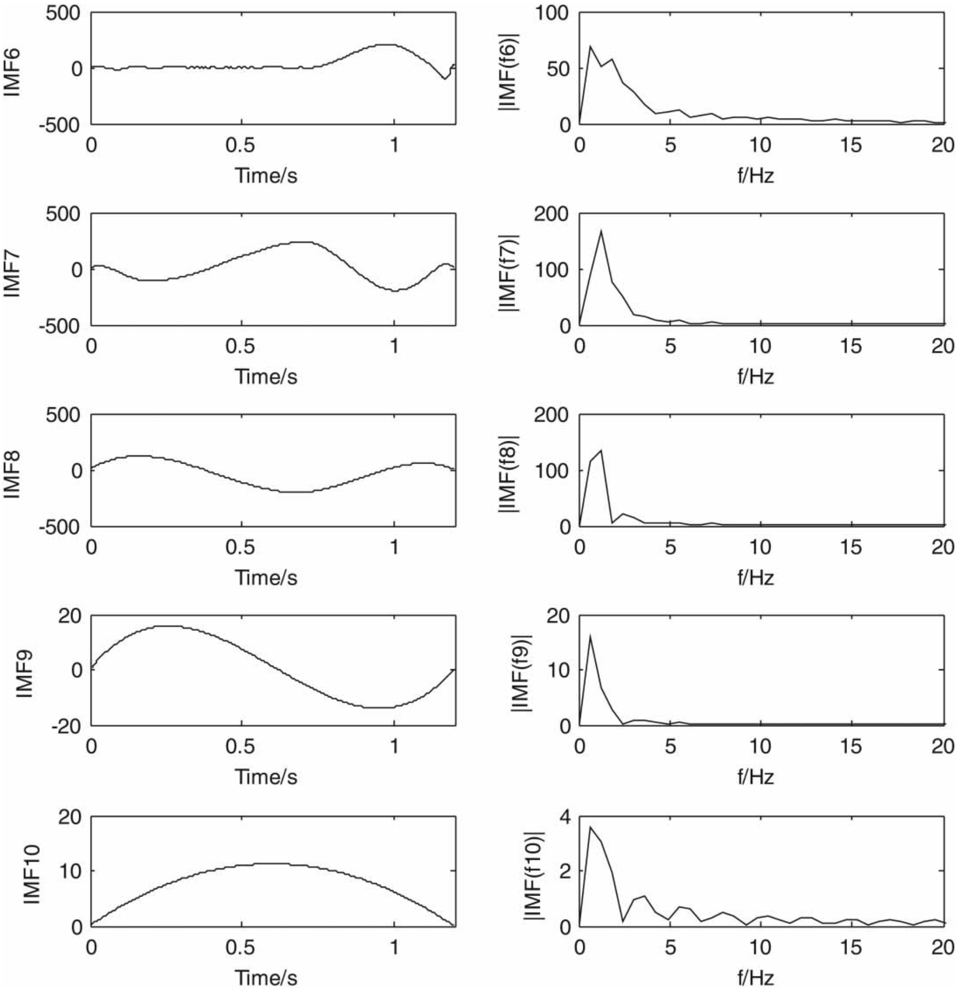

Figure 7 | The results of IMF6–IMF10 signals by the EMD method in the time domain (left column sub-figures) and the frequency domain (right column sub-figures).

errors of the prediction, which is defined by the difference between the predicted and real values normalized by the real value, are calculated and also listed under the location results in Table 3.

The predicted results of the pipe fault locations demonstrate the validity and accuracy of the proposed time-frequency analysis method for identifying and locating all potential pipe faults in the test system. Particularly, the prediction errors of all pipe fault locations are within 5% for case (a) with full reconstruction signal, which is more accurate than other cases in Table 3. This is reasonable because case (a) contains more information (IMF4–IMF9) for the analysis.

For practical applications, after obtaining the predicted locations of the pipe faults in the system, it is easy to identify the types of these pipe faults by on-site investigation. Nevertheless, it is more convenient and significant if the type of each fault can be characterized in advance, which is another advantage of the proposed time-frequency analysis in this study. For this purpose, the comparative analysis of the prediction results from different IMFs combinations shown in Table 3 and Figure 9 becomes useful. Specifically, the pipe fault types can be evaluated by the comparison and analysis of different IMFs in Figures 6 and 7 and the obtained HT results in Figure 9. For the test system of interest in this study, the analysis procedures and results are as follows:

(1) The difference between cases (b) and (c) in Figure 9 indicates that the IMF5 represents the information of the fourth pipe fault. Therefore, the type of this fault can

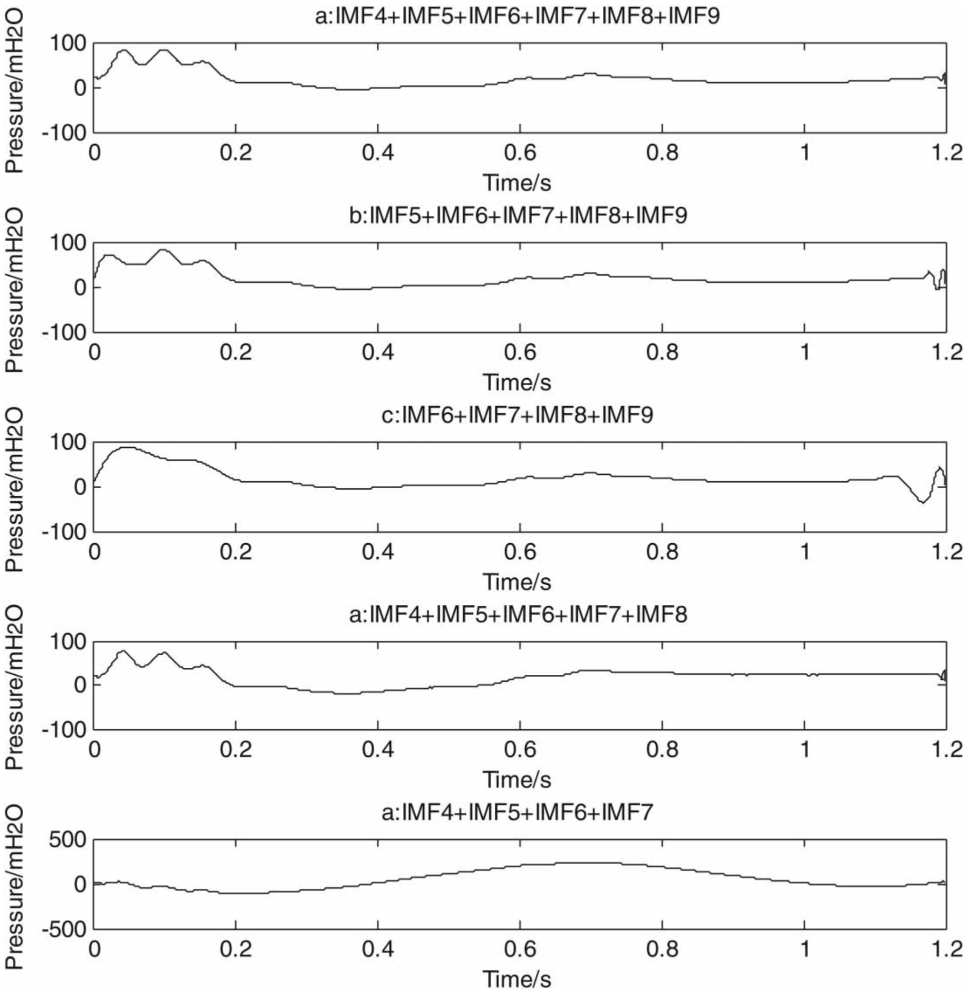

Figure 8 | Reconstruction results of the IMF signals.

be analyzed from the IMF5 in Figure 6, which indicates the leakage type because of the small frequency shift and negative reflection (Ferrante & Meniconi 2009; Lee *et al.* 2013; Gong *et al.* 2015).

(2) The difference between (d) and (e) in Figure 9 gives that the IMF8 contains the information of the third and fourth faults. By taking IMF8 as the objective signal, and repeating the similar EMD-HT analysis, then IMF8 can be decomposed into two sub-signals where one is for the leakage type and the other is for the junction type (frequency shift and negative reflection) (Meniconi *et al.* 2011a; Duan & Lee 2016). According to the result from (1), the third fault is identified to be the junction type.

(3) Similar analysis of (1) and (2) is applied for other comparisons of the results in Figure 9, and the types of first and second faults can be identified to be blockage (frequency shift and positive reflection) and leakage respectively (Gong *et al.* 2012c; Duan *et al.* 2014).

Based on the above time-frequency analysis procedure, the types of the four identified pipe faults in the test system of this study can be accurately obtained and the results are listed in Table 3. Consequently, the EMD-HT based time-frequency domain analysis is valid and accurate to detect both the types and locations of multiple pipe faults in water pipelines.

Practical implications and future work

The proposed time-frequency analysis based on the EMD-HT method for multiple-fault detection in the pipeline is

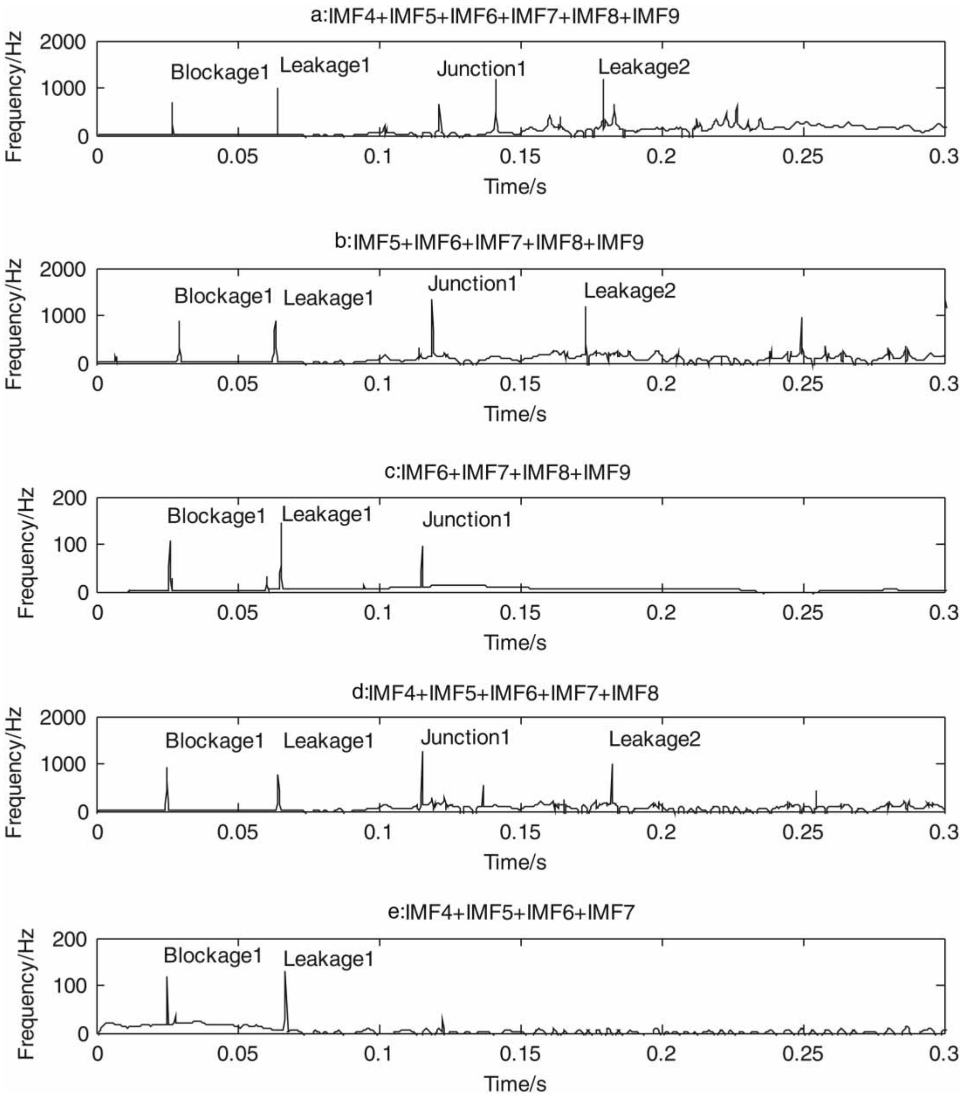

Figure 9 | Instantaneous frequency analysis by different combinations of IMF signals.

successfully applied to the experimental test system in this study. The results and analysis demonstrate the validity and accuracy of this method for identifying the locations and types of pipe faults in the pipeline. From the perspective of theoretical development, this study has made substantial progress on the transient-based pipe fault detection method, with extending the simple situation of single and/or known type of pipe fault(s) to the relatively complex situation of multiple and unknown types of pipe faults. From the perspective of engineering application, this study has provided a comprehensive tool for pipeline condition assessment and fault detection, and meanwhile, a feasible way to deal with and reduce the noises and uncertainties (physical and non-physical) for pipe fault detection in the practical pipeline systems. Consequently, the results and findings of this study may have significance for the development and application of transient-based pipe fault detection methods.

It is also worthwhile pointing out the potential limitations of the introduced method in the current study for practical applications, which requires more future work. These limitations may include (but are not limited to) the following:

(1) Only the simple pipeline system is tested and applied for examining the proposed method in current study, and

Table 3 | Location results of the pipe faults by the time-frequency analysis

Reconstructed signal Number Fault type Real distance	Detection results 1st Blockage1 7.05 m	 2nd Leakage1 16.13 m	 3rd Junction1 30.22 m	 4th Leakage2 45.30 m
(a) IMF4 + IMF5 + IMF6 + IMF7 + IMF8 + IMF9	7.02 m 0.4%	16.28 m 0.9%	30.80m 1.9%	46.75 m 3.2%
(b) IMF5 + IMF6 + IMF7 + IMF8 + IMF9	7.44 m 5.5%	16.08 m 0.3%	30.13m 0.3%	43.99 m 2.9 %
(c) IMF6 + IMF7 + IMF8 + IMF9	6.62 m 6.1%	16.54 m 2.5%	29.21 m 3.3%	– –
(d) IMF4 + IMF5 + IMF6 + IMF7 + IMF8	6.36 m 9.8%	16.33 m 1.2%	29.21 m 3.3%	46.23 m 2.1%
(e) IMF4 + IMF5 + IMF6 + IMF7	6.36 m 9.8%	17.05 m 5.7%	– –	– –

more complex and practical system situations such as branched and looped systems are essential to be explored in future work.

(2) Three common types of pipe faults (i.e. leakage, blockage, junction) are investigated for the type identification, with knowing their basic transient characteristics (reflection and frequency shift) in the literature. Further study is needed for understanding and characterizing the transient behaviors of other potential types of pipe faults in water pipelines so that the proposed method can then be extended to these cases.

(3) The proposed time-frequency domain method is mainly applied to identify the locations and types of pipe faults, and the detection of the sizes/extents for different types of pipe faults is worthy of further investigation.

Finally, it is necessary to further validate the proposed time-frequency analysis method of this study through more laboratory experiments and field tests so that this method can be eventually extended and improved to practical water pipeline systems.

CONCLUSIONS

In this paper, a time-frequency analysis method is proposed to identify fault locations and types in pipelines. The combination of the EMD and HT algorithms are used for the analysis of transient (non-stationary) and nonlinear pressure wave signals, and then the decomposed IMFs signals can be used for the pipeline condition assessment. The correlation analysis is used for examining the relative importance of the obtained IMFs so that the appropriate combinations of such IMFs can be determined for the analysis. The principle and application procedure of the proposed detection method are presented in detail in the paper and are also validated for the preliminary experimental tests conducted for a simple pipeline system in this study. The multiple pipe faults used for investigation include leakage, blockage and junction.

The application results demonstrate the validity and accuracy of the proposed time-frequency analysis method for identifying the types and locations of the multiple pipe faults. Specifically, the numbers and types of the pipe faults used in this study can be exactly identified and the locations of these faults can also be detected with relative errors within 5% for the test system. Meanwhile, the proposed method can separate and reduce the noises from the original measured transient pressure wave signals, and therefore the influence factors of system uncertainties and flow instabilities can be greatly reduced or excluded from the analysis.

The results and findings of this study may provide significance and useful implications to extend the transient-based pipe fault detection to more complex and practical pipeline systems. The results discussed in this study also suggest that further validations and necessary improvements are required for the extension of the proposed method to practical applications in future work.

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