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Comparative study of instantaneous frequency based methods for leak detection in pipeline networks.

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ABSTRACT

Methods of pressure transient analysis can be seen as a promising, accurate and low-cost tool for leak and feature detection in pipeline various systems have been developed by several groups of researchers in recent years . Such techniques have been successfully demonstrated under laboratory conditions but are not yet established for use with real field test data.

The current paper presents a comparative study of instantaneous frequency analysis techniques based on pressure transients recorded within a live distribution network. The instantaneous frequency of the signals are analysed using the Hilbert transform (HT), the Normalized Hilbert transform (NHT), Direct Quadrature (DQ), Teager Energy Operator (TEO) and Cepstrum.

This work demonstrates the effectiveness of the instantaneous frequency analysis in detecting a leaks and other features within the network. NHT and DQ allowed for the identification of the approximate location of leaks. The performance TEO is moderate, with Cepstrum being the worst performing method.

Keywords leakage; pipelines system; pressure transient wave; Hilbert transform. Hilbert Huang transform; Direct quadrature; Teager energy operator; Cesptrum

1. Introduction

Leakage from water distribution networks has significant economic and environmental cost. Leaks may occur due to aging pipelines, corrosion, excessive pressure resulting from operational error and closing or opening valves rapidly, creating damaging transients (Ref?). According to a study performed by German Energy and Water Association (BDEW) [1] average water losses in public water networks in Europe vary from 6.5% to 24.6%. Water utilities normally employ wide range of leak detection methods but acoustic technology (e.g. noise correlators and geophones) are predominantly used for pinpointing repairs. Acoustic methods are typically labour intensive and often imprecise. Acoustic techniques become especially ineffective if the noise created by the leak is a small (which is the case for large leaks), attenuates quickly (as in non-metallic pipes), or is obscured by other background noise. There are numerous alternative methods for leak detection including: thermography, ground penetration radar, video inspection and tracer gas [4]. None of these methods has been proven reliable and they are currently not widely used.. Therefore, a more reliable and quick technique for detecting and locating leaks is currently desirable.

Many researchers have investigated transient based methods for leak detection. Pressure transients occur due to any sudden change of flow within the system (such opening a valve or stopping a pump) Transients propagate back and forth throughout the network and therefore can be shown to carry information of leaks or features within in the pipeline system [5]. Beside its potential low cost and non intrusive nature, this technique has the potential to locate leaks at greater distances from a measurement point than is currently possible. A number of hydraulic transient based techniques for leak detection are described in existing literature: inverse transient analysis [6,7] impulse response analysis [8,9], transient damping methods [10,11], frequency domain response analysis [12] and wavelet analysis [13,14]. However there are very few studies have been validated with real laboratory data [15] or field data [16].

These previous studies have successfully detected leakage size and location in a pipe from analysis of a transient signal. Here, in order to improve accuracy and make detection easier, a new signal analysis technique is proposed and compared with existing methods. The objective of the current paper is to explore and compare a proposed method of analysing non-stationary data called empirical mode decomposition (EMD) for instantaneous characteristics calculation for leak detection. The innovation of this technique is the analysis of instantaneous frequency (IF). This paper presents the results of the application of this technique.

2. Leak detection methods

2.1 Pressure waves and leaks in pipes

In a pipe system with constant steady flow, the pressure rise for instantaneous closure is directly proportional to the fluid velocity at cut off and to the velocity of the predicted surge wave but is independent of the length of pipe [17]. The well known Joukowsky equation has been applied for sudden closures in frictionless pipes and given as:

$$\frac{\delta p}{\delta t} = -\rho a \Delta \frac{\delta V}{\delta t} \text{ or} \qquad (1)$$

where $\frac{\delta p}{\delta t}$ is the rate of change in pressure (Pa), ρ is fluid density (kg/m^3), a is the characteristic wave velocity of the fluid (m/s), $\frac{\delta V}{\delta t}$ is the rate of change in fluid velocity (m/s)

For an instantaneous closure, the head produced ΔH (m) by the surge is:

$$\Delta H = -\frac{a}{g}\Delta V$$

This pressure surge starts to propagate along the pipe. At every discontinuity of the system, the wave is partially reflected, partially transmitted and some of it will also be absorbed [5]. Such discontinuities include features such as leaks, valves, junctions or changes in pipe diameter (see Fig 1.).

Figure 1 is about here

Generally, a leak induces a sudden pressure drop in a positive pressure surge, and also a reflection point; thus in the transient pressure signal this inflection can be used to identify the location of the leak. The distance of the leak from the measuring section, X_{leak}, can be calculated base on the travelling time, t_{tr}, of the transient to the leak and return back to the source, given as:

$$X_{leak} = \frac{a t_{tr}}{2} \qquad (2)$$

2.2 Signal processing for leak detection

The signal produced during transient process are mostly non-linear and non-stationary. The Sheffield University group have previously used a number of signal analysis techniques to analyse reflections of transient data in order to identify the features in pipelines systems for simulated and experimental systems. Initially cross-correlation analysis [18] was used to identify a number of reflections in simple pipe networks. This method worked, but was clumsy and tedious. Later, Al-Shidhani *et al.* [14] performed wavelet transforms on experimental and simulated transients in pipe systems. Whilst successful for simulated data, when the same analysis was applied to the experimental data, no useful results were produced. This is due to the fact that in real systems waves spread out due to dispersion [5] causing the outgoing and incident waves to become less sharp.

To overcome this problem, Beck *et al.* [19] used the cepstrum function to analyse pressure histories and identify leak positions in pipeline networks. Cepstrum detects periodic structures in the algorithmic spectrum (as explained by Randal [20]). This method not only detects the leaks but is also able to estimate their severity. More recently, the studies by Taghvaie *et al.* [21] using a combination of orthogonal wavelet transforms (OWT) and cepstrum confirm that this method is able to detect leakage size and location in pipelines. This method also utilises the wavelet filtering procedure in order to remove unwanted features such as noise or trends.

More recently, a new type of time-frequency analysis called the Hilbert-Huang transform (HHT) has become more popular for analysing non-linear and non-stationary signals. The HHT is totally adaptive and has been developed by Huang *et al.* [22]. This method consists of an empirical mode decomposition (EMD) to filter the signal, followed by a Hilbert transform analysis. The analysis presents the instantaneous amplitude and the instantaneous frequency as functions of time in a three dimensional plot. This frequency-time distribution of the amplitude is designated as the Hilbert amplitude spectrum, $H(\omega,t)$, or simply the Hilbert spectrum (HS). HHT techniques have been applied to various fields, such as structural damage detection [23], bioscience [24], and filtering and denoising [25]. The presence of leaks and features cause a phase change within a transient signal. This can be detected using analysis of instantaneous phase or frequency. Various method of calculating instantaneous frequency can be used. As a result, some researchers such as Bangfeng and Renwen [26] and Ghazali *et al.* [27] have started using HHT for leak detection.

3. Four signal processing algorithms

3.1 Empirical mode decomposition

Huang *et al.* [22] proposed using a empirical mode decomposition (EMD) technique to decompose any given signal as a set of nearly monocomponent signals. EMD is an adaptive decomposition (i.e. data-based) and suitable tool for nonstationary data analysis. A pressure transient in pipe system can be considered as a nonstationary signal. Nonstationary signals should be examined differently from stationary data since they have statistical properties that vary as a function of time. Ideally, EMD can be used to estimate a signal's instantaneous frequency (IF). To get a meaningful IF, each mode of decomposition signal should be nearly monochromatic (one frequency). Each basis function produced by EMD is called an Intrinsic Mode Function (IMF). IMF's represent the oscillatory modes embedded within the data where each IMF involves only one mode of oscillation with no complex riding waves present.

To achieve this, an IMF is defined as a function for which (1) the number of extrema and the number of zero crossings must either be equal or differ by one, and (2) at any point, the mean value of the envelope of signal defined by the local minima is zero [22]. Such definition attempts to ensure that meaningful instantaneous frequency can be obtained from each IMF. With the definition, a signal *X(t)* EMD algorithm works as follows [17]:

(1) Identify all the local extrema, *x(t)* from the given signal and then connected by cubic splines to form the upper envelope. Repeat for the minima.

(2) Compute the mean, *m(t)* of the two envelopes.

(3) Extract the detail, d(t) as an IMF, *d(t) = x(t) – m(t)*.

(4) Repeat the iteration on the residual *m(t)* until residual data is too small, meaning that residual becomes a monotonic function or a function with only one extremum from which no more IMF can be extracted. The residual represents the trend.

The above procedure has to be refined by a *sifting* process [22]. The purpose of this step is to enforce the definition of an IMF [28]. The original signal may be able to be reconstructed by summing all the IMF components. Preferably, all modes of IMF produce by abovementioned step should be nearly monochromatic and can be used to give a significant evaluation of the signal's instantaneous frequency.

3.2 Estimation of instantaneous frequency (IF)

a) Hilbert Transform (HT)

Generally, a signal is characterised by its frequency content. For nonstationary signals, in which frequency value changes at any moment it is more useful to characterise a signal in terms of its instantaneous frequency. The instantaneous frequency is the frequency that locally fits the signal. To get a well defined and physically meaningful instantaneous frequency, the signal must be analytic and it must be within a narrow band by means of Hilbert transform (HT). The Hilbert transform *y(t)* of signal *x(t)* is defined as [22]:

$$y(t) = \frac{PV}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau \qquad (3)$$

in which *PV* denotes the Cauchy principal value of the integral. *y(t)* is the convolution of *x(t)* with 1/πt. Coupling the *x(t)* and *y(t)* results in a complex conjugate pair, giving analytic complex signal *z(t)* of *x(t)* as

$$z(t) = x(t) + iy(t) = A(t)e^{i\phi(t)} \qquad (4)$$

Considering the last expression of the analytical signal in Eqn 4, A is an envelope of the signal and *φ(t)* is a phase angle. The instantaneous frequency, *ω(t)* of the analytical signal, is simply:

$$\omega(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt} \qquad (5)$$

As explained by Boashah [29] the Hilbert transform produces a more physically meaningful result for monocomponent or nearly monocomponent (i.e. narrow band) functions. As a result, the effectiveness of EMD decomposition is particularly suitable for the evaluation of instantaneous frequency by means of the subsequent Hilbert transform.

To demonstrate the calculation of IF, consider a chirp signal as shown in Fig.2. It is shown that when using the decomposition of signal the frequency properties of the chirp signal are revealed.

Figure 2 is about here

b) Normalized Hilbert Transform (NHT)

Huang *et al*. [30] found that the analytical signal obtained from a Hilbert transform only produces meaningful instantaneous frequency if the conditions of Bedrosian [31] theorems are met. Vatchev [32] also discussed the mathematical problems associated with Hilbert transform of IMFs. As a result, Huang *et al*. [30] introduced normalized Hilbert transform (NHT) which empirically separates the amplitude modulation (AM) and frequency modulation (FM). Through a normalization scheme, the signal has to be normalized using the envelope of signals produced through spline fitting. This can be written as:

$$n_1(t) = \frac{x_1(t)}{e_1(t)} \tag{6}$$

where $n_1(t)$ is the normalized signal, $x_1(t)$ is the signal and $e_1(t)$ is the empirical envelope of the signal. The details of normalization can be found in Huang *et al*. [30]. After n^{th} of iteration, the normalized signal, then becomes

$$n_n(t) = \frac{x_n(t)}{e_n(t)} \tag{7}$$

The iteration can be stopped when all values of $n_n(t)$ are less or equal to unity and it is assumed that empirical FM is part of data, F(t) as:

$$n_n(t) = \cos\phi(t) = F(t) \tag{8}$$

As a result, with FM part determined, AM is then

$$A(t) = \frac{x(t)}{F(t)} \tag{9}$$

Re-written Eqn. 8 and Eqn. 9

$$x(t) = A(t) * F(t) = A(t)\cos\phi(t) \tag{10}$$

The normalized FM component of an IMF is suitable for Hilbert transform since it has satisfied the Bedrosian theorem.

c) Direct Quadrature (DQ)

Additionally, Huang *et al*. [30] also applied the direct quadrature method to the normalized IMFs to get an exact instantaneous frequency. This proposes method eschews any Hilbert transform by means of a 90 degree shift of phase angle. After the normalization the FM signal produced, *F (t),* is the carrier part of the signal. By assuming signal to be a cosine function, its quadrature is given as:

$$\sin \phi(t) = \sqrt{1 - F^2(t)} \qquad (11)$$

Using arctangent we can calculate the phase angle and defined simply as:

$$\phi(t) = \arctan \frac{F(t)}{\sqrt{1 - F^2(t)}} \qquad (12)$$

Instantaneous frequency can be defined as the derivative of the phase function from Eqn. 12

d) Teager Energy Operator (TEO)

The alternative method to compute instantaneous frequency is the energy operator (TEO) [33]. A distinctive advantage of TEO is its outstanding localization property, a property unsurpassed by any other method. In determining the location of leaks and other features in a pipeline system time localization plays important part. The TEO is totally based on differentiations without involving integral transforms. Taking Newton’s law of motion for an oscillator with mass, *m* and spring constant *k* states that

$$\frac{d^2x}{dt^2} + \frac{k}{m}x = 0 \tag{13}$$

the solution of the signal of the form $x(t) = a\cos(\phi(t))$. The sum of kinetic and potential energy is the system's total energy E, given by:

$$E = \frac{1}{2}kx^2 + \frac{1}{2}m\dot{x} \Rightarrow E = \frac{1}{2}m\omega^2 a^2 \tag{14}$$

where $\omega = d\phi(t)/dt$, then an energy operator is defined as:

$$\psi(x) = \dot{x}^2 - x\ddot{x} \tag{15}$$

With constant frequency and amplitude we will have

$$\psi(x) = a^2\omega^2 \text{ and } \psi(\dot{x}) = a^2\omega^4 \tag{16}$$

By manipulating the two terms in Eqn. 16, we have

$$\omega = \sqrt{\frac{\psi(\dot{x})}{\psi(x)}} \text{ and } a = \frac{\psi(x)}{\sqrt{\psi(\dot{x})}} \tag{17}$$

As a result, one can obtain both the frequency and amplitude with the energy operator.

3.3 Cepstrum

Cepstrum is a good tool for detection of singularities because…. In addition to studies of instantaneous frequency, cepstrum also will be used with the combination of EMD to detect any reflection of the selected IMF. Generally, cepstrum is defined as the Fourier transform of the logarithm of the Fourier transform [20] and suitable for non linear signal processing technique. It is defined as:

$$C_A = F^{-1}(\log A\{f\}) \tag{18}$$

where $A\{f\}$ is the complex spectrum of where $a\{t\}$. It can be represented in term of amplitude and phase at each frequency by

$$A\{f\} = F\{a(t)\} = A_R + jA_I\{f\} \qquad (19)$$

Taking the complex algorithm of Eqn. 19 gives

$$\log A(f) = \ln|A(f)| + j\phi(f) \qquad (20)$$

where $j = \sqrt{-1}$ and $\phi(f)$ is the phase function.

4. Leak detection scheme outline

4.1 Implementation

The proposed leakage detection methods have been evaluated by the following steps:

- Use an previously acquired transient signal from field tests conducted in a real distribution network.
- Decompose the data into set of monocomponent signals, i.e IMF by using EMD, as described in section 3.1.
- Filter the signal by discarding some of irrelevant IMF.
- Compute instantaneous frequencies using HT, NHT, DQ, TEO and Cepstrum as described in section 3.2
- From extracted signals calculate the distance of leak and other features using Eqn. 2.
- Compare and evaluate results of the analysed methods

The operation procedures can be summarized in the flowchart as shown in Fig. 3

Figure 3 is about here

4.2 Numerical simulations to test leak detection algorithm

Toevaluate the proposed method consider following synthetic signal:

$$s(t) = x(t) + v(t) \qquad (21)$$

Where $x(t)$ and $v(t)$ are the background signal and the impulse representing reflection of leaks or features, respectively. The background signal can be chosen as:

$$x(t) = \sin(0.027\pi t) - \sin(2(0.027\pi)t + \pi/2) + \sin(4(0.027\pi t)\,. \qquad (22)$$

Fig 4(a). shows 300 samples of *x(t)* and Fig. 4(b) indicates two spikes with an amplitude of 0.1, with *v(t)* at instants 120 and 240 respectively. The combinations of these are shown in Fig. 4(c). The algorithm has been applied to the simulated signal; it has yielded five IMFs as shown in Fig. 5. Applying all methods proposed to IMF1, instantaneous frequency has been calculated and the results are shown in Fig. 6. As it can be seen, for the clean signal, all methods indicate the reflection at the correct occurrence times.

Figure 4, 5 and 6 is about here

For further analysis, white noise has been added, and hence Eqn. 21 becomes:

$$s_{noise}(t) = x(t) + v(t) + noise \qquad (23)$$

The white noise is normally distributed with mean 0 and standard deviation 1, as generated using MATLAB version 7. The signal has then been decomposed into eleven IMFs as shown in Fig. 7. IMF1-IMF7 consists most of the noise. IMF8-IMF10 have been chosen for further analysis while the rest of IMF’s are considered irrelevant. Using the same method of calculating instantaneous frequency as described above, the results of this analysis are shown as Fig. 8. Again all the method successfully detect the reflection at their correct occurrence time. The TEO method shows the worst result since it only performs well in the absence of noise (as previously explained by Huang *et al.* [30]). EMD also works as a filter bank [25] hence it is possible to remove all unnecessarily noise in the signal.

Figure 7 and 8 is about here

5 Experimental details

The analysed test data presented in this paper was obtained during fieldwork experiments conducted within a live distribution system..A schematic map of the site is shown in Fig.9. The pipeline is constructed of 4 inch diameter cast iron. A leak of size 3.5 l/s (size obtained by comparing water company flow database before and after leak repair) is located 40m from hydrant 2 (H2). The hydrants and leak location are shown as “H” and “L” signs respectively in Fig. 9. In this case the testing was conducted from hydrant 2 (H2). There is also a pressure reducing valve (PRV) located near to the hydrant 1 (H1).

Figure 9 is about here

The transient event was generated by rapidly opening and closing a small solenoid valve fitted to the testing hydrant (see Fig.10). A small diameter pipe has been used for the connection between the valve and the hydrant in order to limit the transient pressure such that system creates. This method has been previously described in Taghvaei *et al.* [34]. The resulting transient was measured using a a pressure transducer attached to the hydrant cap. The main advantage of this device is that it is able both create a pressure pulse and acquire the system response data from only a single, standard access point. As it always extracts water from the pressurised system, it thus has no health or contamination issues. A simple data acquisition system which captured the resultant pressure signal at a frequency of 5 kHz was used Fig.11. A total of four repeat tests were conducted at the site. To accurately locate each feature or leak, the wave speed of the pipeline has to be calibrated by measuring the time taken for generated transient wave to travel from the measurement point to the boundary of the pipeline and back to the measurement point. The theoretical speed of wave propagation in this pipe is 1310 m/s and the calibrated value was 1090 m/s. This difference may be due to deterioration of the pipe condition since its installation. Table 1 shows field test details for this work.

Figure 10 is about here

Figure 11 is about here

Table 1 is about here

6 Results and Discussion

Fig. 12 shows the recorded transient after each of the four tests. As we can see from the figure, the closing valve occurs approximately at t = 0.08s. The pressure rises rapidly immediately after the valve is closed. This shows that the transient signal produced is transmitted and reflected around the pipe system, all the while being attenuated through both friction and various features in the pipe network. The analysis of the signal starts immediately after the valve is closed.

Figure 12 is about here

To filter the signal and remove any offset, the data is decomposed into seven IMFs and its residue as shown in Fig. 13. This splits the signal into different frequency bands from high to low frequency. IMF1-IMF2 contained highest frequency which mostly consists of noise. Meanwhile, IMF7 and the residue contain the basic response of the network. All of these IMF were therefore discarded. The rest of IMFs (i.e IMF3-IMF6) have been recombined to produce a signal without noise as displayed in Fig. 14. The instantaneous frequency of this filtered data was then calculated using the abovementioned methods (Fig. 15).

Figure 13, 14 and 15 is about here

There are four main features in the network that that reflect transients (leak, junction, hydrant and pressure reducing valve). The peaks shown in the analysed results correspond to the time taken by the wave to travel along the pipe and return back to measuring point (after wave speed calibration). The distance of the leak and features from the source of transient (H2) can be estimated simply by multiplying the time delay data corresponding to the each peaks by the calibrated speed of sound (i.e a=1090 m/s) in the pipe system and halving this value for the return journey. The results then can be compared with the distances on the schematic map. The summary of this analysis along with the errors can be found in the Table 2.

Table 2 is about here

It can be seen that all methods can identify the leak which occurs approximately at t= 0.072s (hence 39.24m) from the measurement point with acceptable range of error (within x%). The HT method can capture most of the features except for the reflection from pressure reducing valve (PRV). This suggests that the instantaneous frequency calculated is able to capture the discontinuity produced by the leak and other features. The improvement of HT called NHT and DQ [30] are able to identify most of the features within a reasonable accuracy. The missing feature by HT has been recovered by both NHT and DQ.

The TEO method gives an acceptable result but it also produces other irrelevant peaks which may lead to miscalculation the distance of the features or false results. This is probably caused by the wave profiles having intrawave modulations or harmonic distortions. TEO is also very sensitive to the presence of the noise [30]. The combination of EMD and Cepstrum gives the worst result since it only shows the peak corresponding to the leak point. It also indicates the hydrant 3 (H3) and junction 2 (J2) with a very small amplitude peak and fails to locate the other features in the pipeline. As explained by Huang *et al.* [17] the common problem with the EMD is frequent appearance of mode mixing, which is defined as either a single IMF consisting of widely disparate scales, or a signal residing in different IMF components. As a comparison, the result produced are also compared with the method proposed by Taghvaie *et al.* [21] as they used the combination of wavelet and cepstrum. The result is shown in Fig. 11(f). Most of the features are detected except for H1. It also produces irrelevant reflections which may be caused by the noise present in the filtered data using OWT.

Conclusions

In this paper, the instantaneous frequency of pressure waves through fluid-filled pipelines of a real life system signal were analyzed in order to identify leaks and other features. Firstly, collected transient data was decomposed and filtered by empirical mode decomposition (EMD). Then, the different methods of calculating instantaneous frequency such as HT, NHT, DQ and TEO have been evaluated and compared. The analysis using EMD and Cesptrum also has been studied. Neither method had previously been applied in a systematic way to the problem of identifying features in real life pipeline systems. The features that were identified as causing a reflections were a leak (of size 3.5 l/s), hydrant, junction and pressure reducing valve. The process results confirmed that the instantaneous frequency calculation by NHT and DQ analysis can reveal most of the features and Cepstrum analysis gives the worst result.

The current study is not immediately expected to be a panacea for leakage, i.e. able to identify the features at any position and in complex pipeline systems. Further real life tests are necessary in order to evaluate the operational range. Furthermore, this work shows that the combination of empirical mode decomposition and instantaneous frequency analysis is promising tool for leak and features detection. Work is continuing to test these techniques on more complicated systems under a variety of operating conditions.

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Figures:

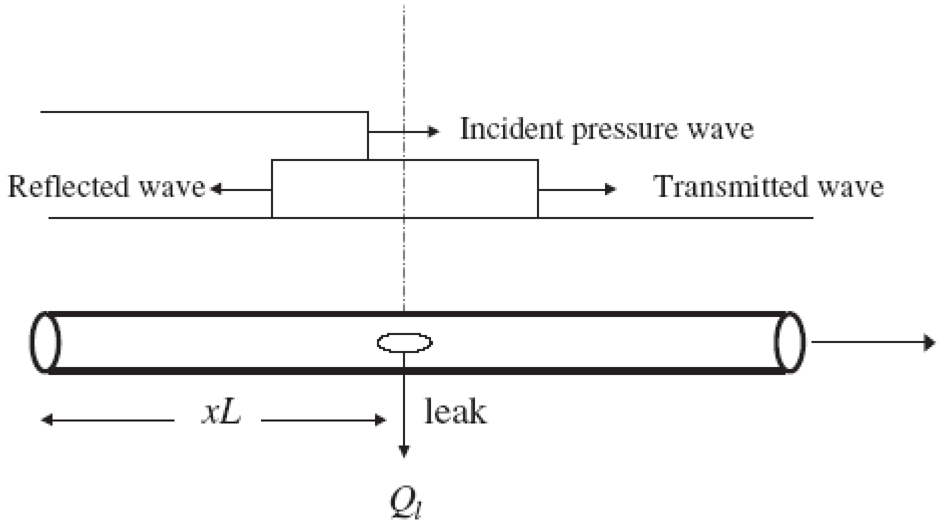
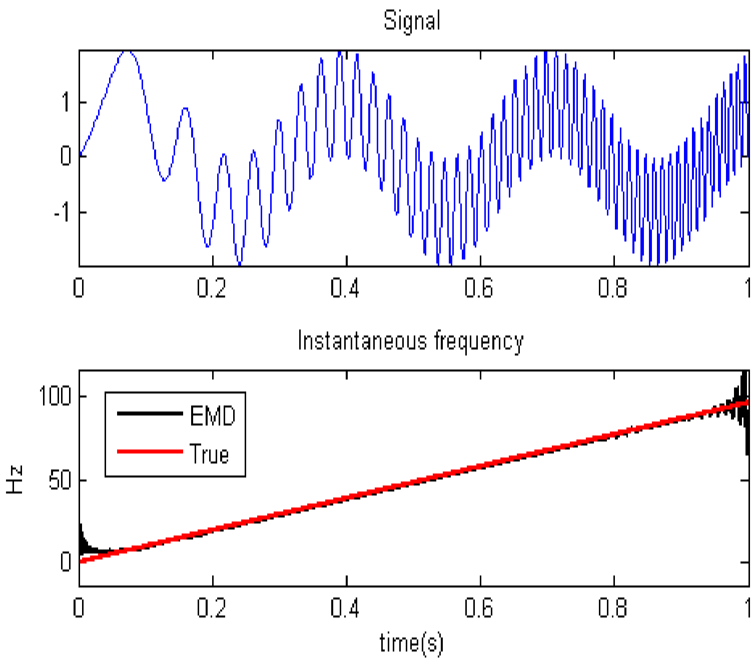
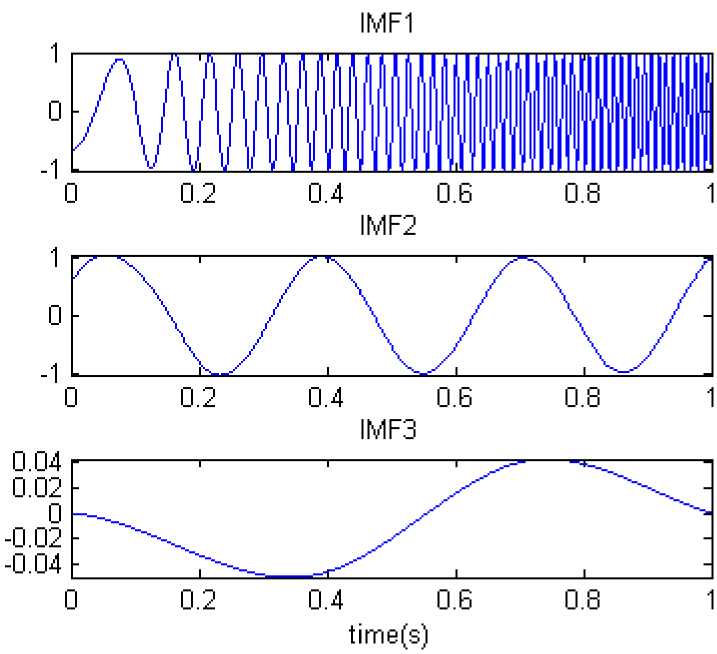


Fig.1 Conceptual wave reflections at a leak [1]



(a) Instantaneous frequency estimation using Hilbert transform



(b) IMFs of chirp signal produce by empirical mode decomposition

Fig. 2 The instantaneous frequency estimation and IMFs

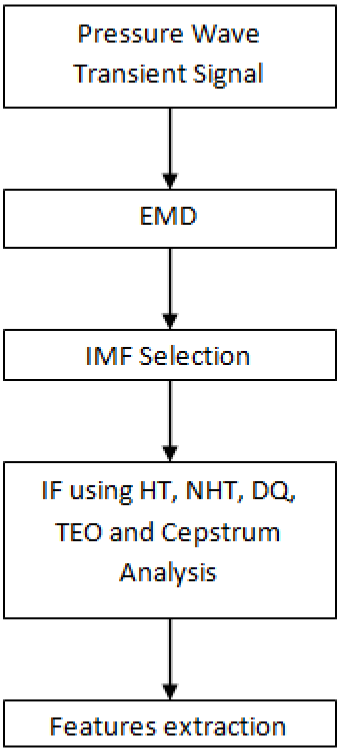


Fig. 3 The operation procedure of the proposed method.

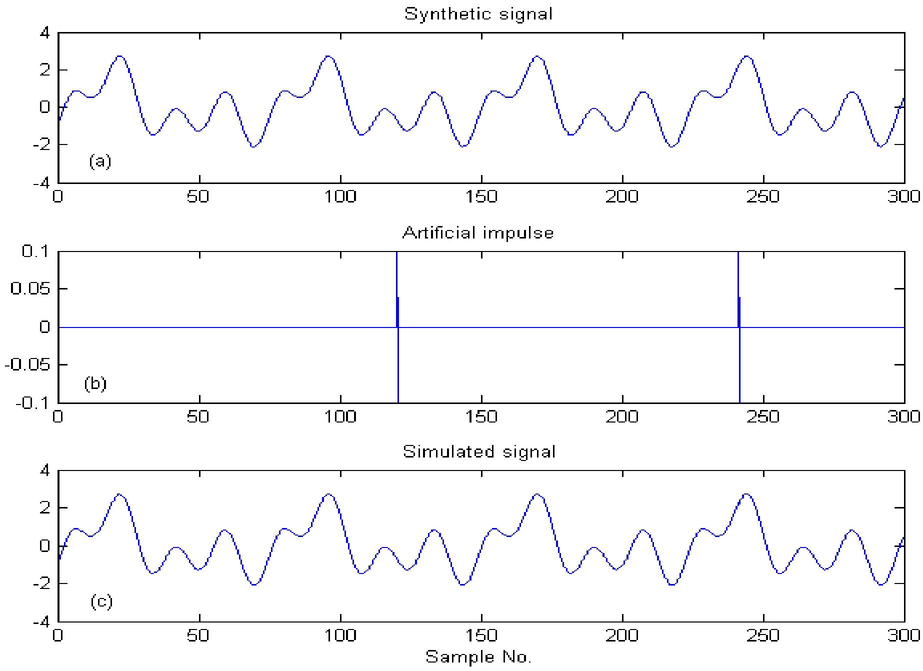


Fig. 4 The synthetic signal with the present of artificial impulse

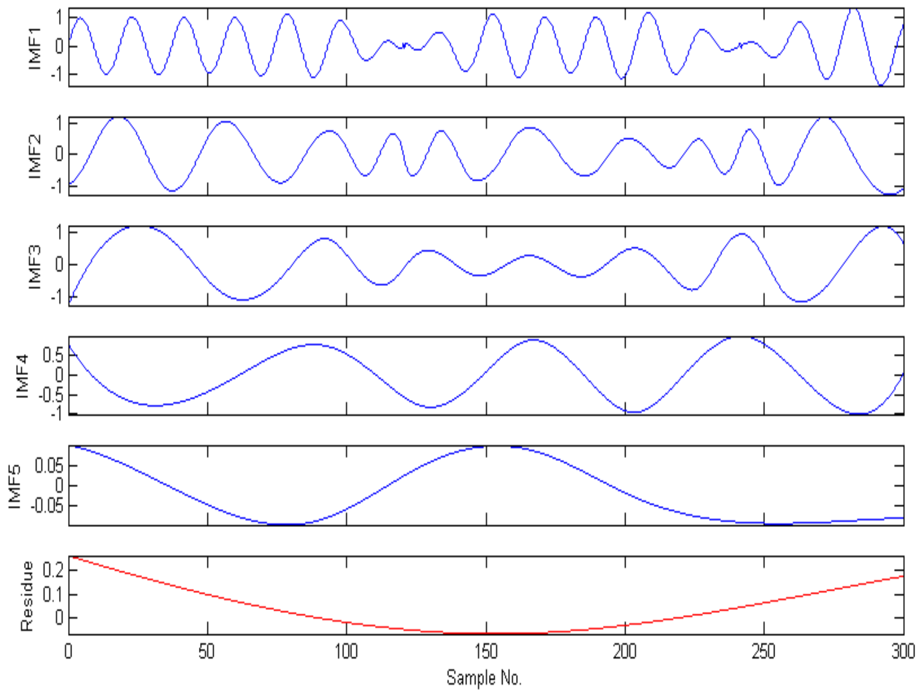


Fig.5 The 5 IMFs component with its residue for the $s(t) = x(t) + v(t)$

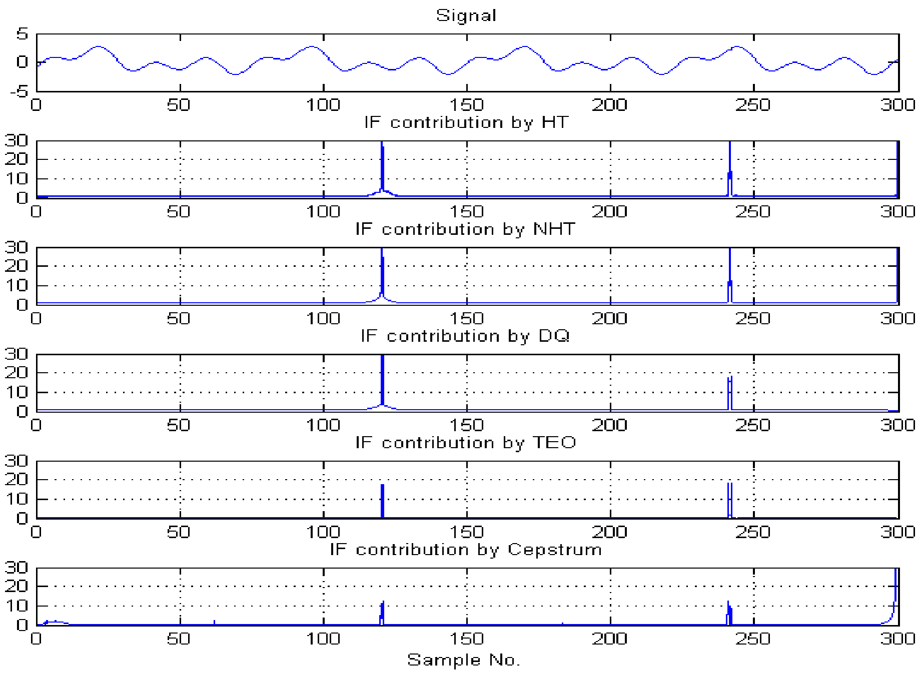


Fig.6 The simulated signal with instantaneous frequency by HT, NHT, DQ, TEO and Cesptrum

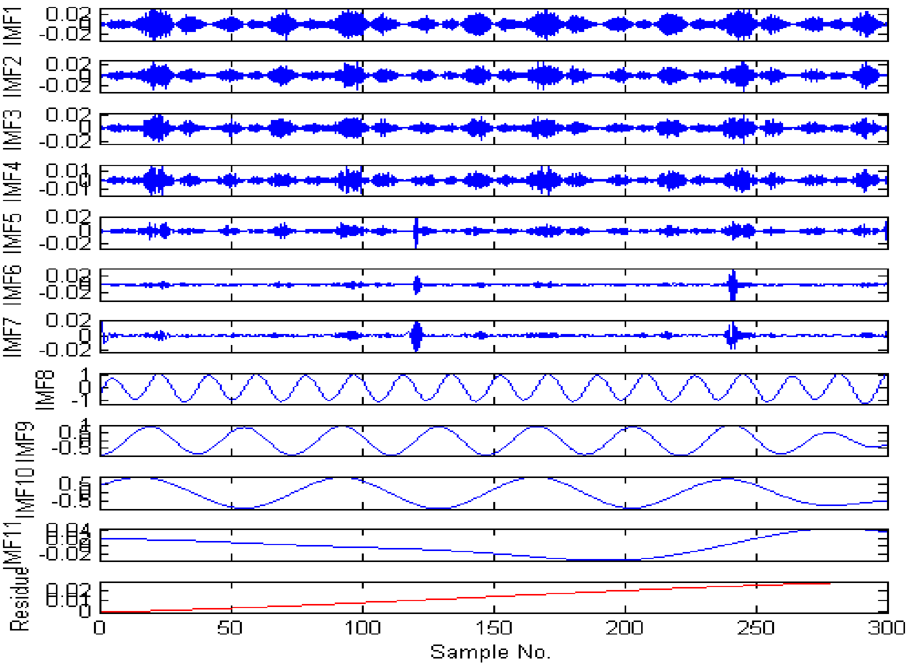


Fig.7 The 11 IMFs component with its residue for the $s(t) = x(t) + v(t) + noise$

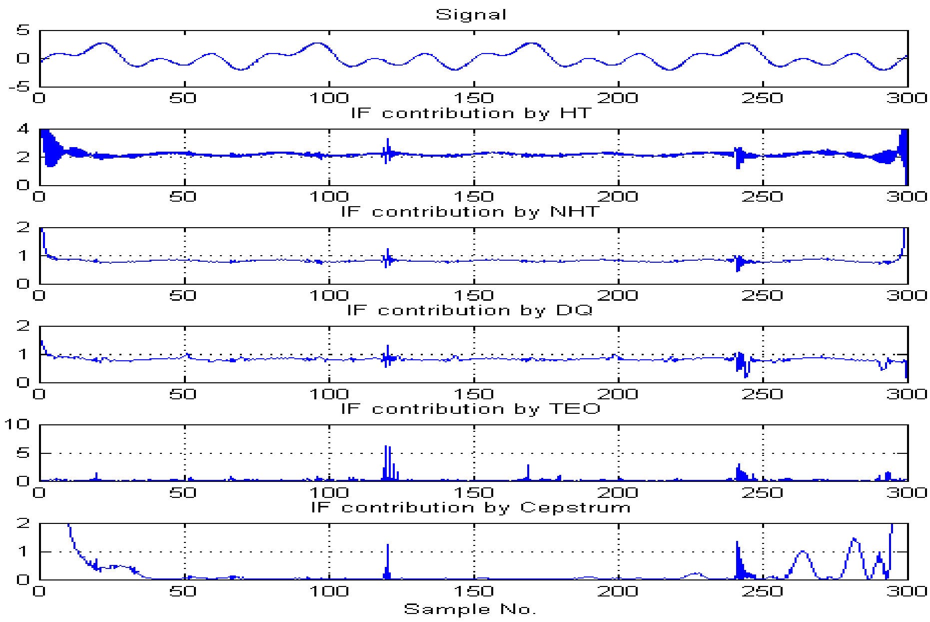


Fig.8 The simulated signal with noise and instantaneous frequency contribution by HT,NHT,DQ,TEO and Cesptrum

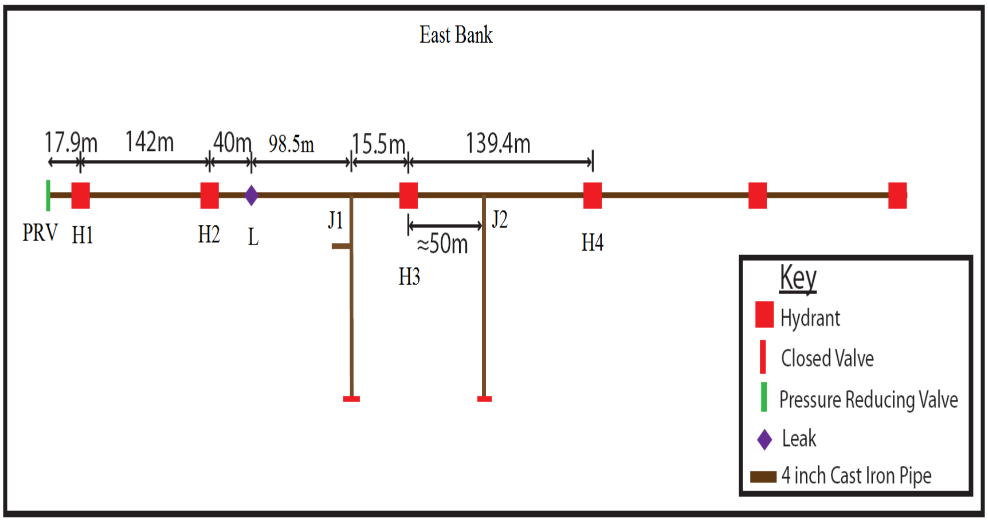


Fig.9 Schematic map of a section of the Yorkshire Water's distribution network used in this paper

Fig. 10 Connection of solenoid valve to hydrant to generate pressure transient

Fig. 11 Typical connection of pressure transducer to the hydrant

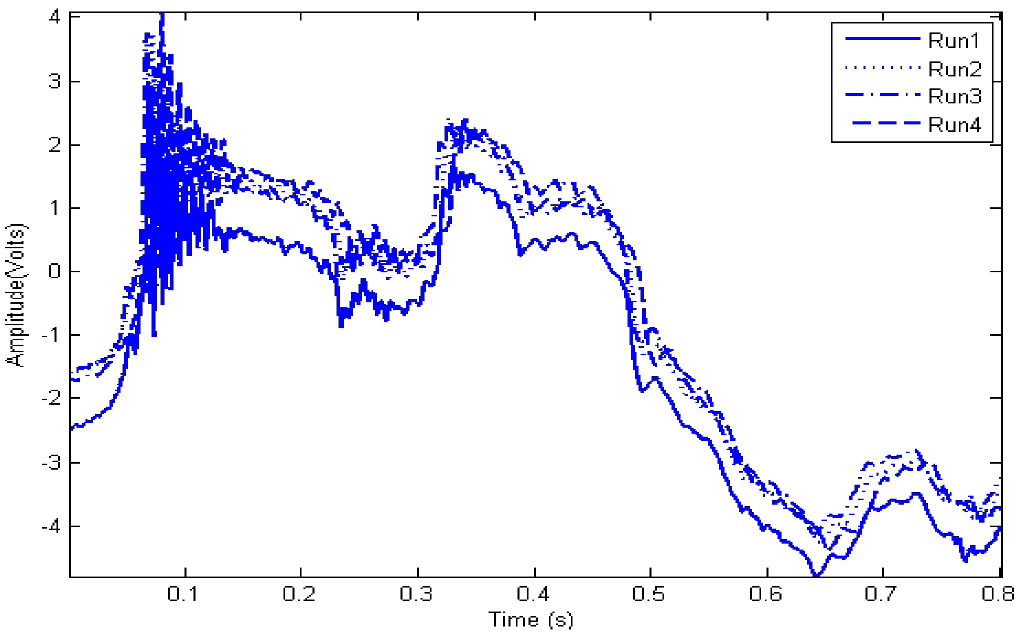


Fig.12 Transient data from field site with a leak at 40m from measurement point

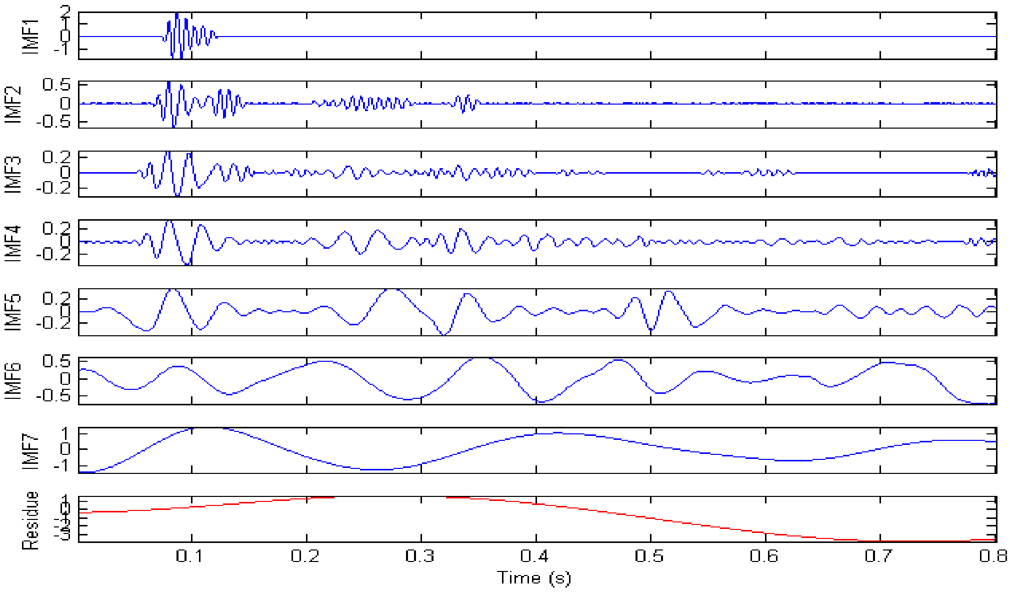


Fig.13 The IMF's and its residue of field test data

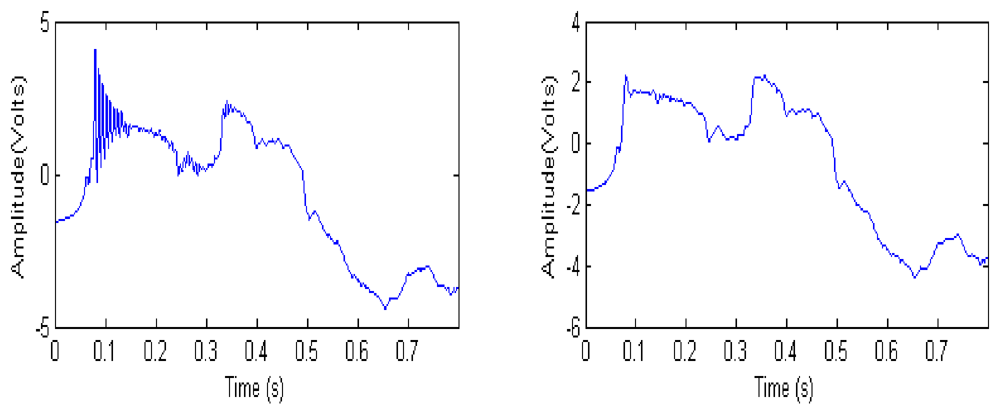


Fig.14 Typical set of transient signal before (left) and after (right) filtering

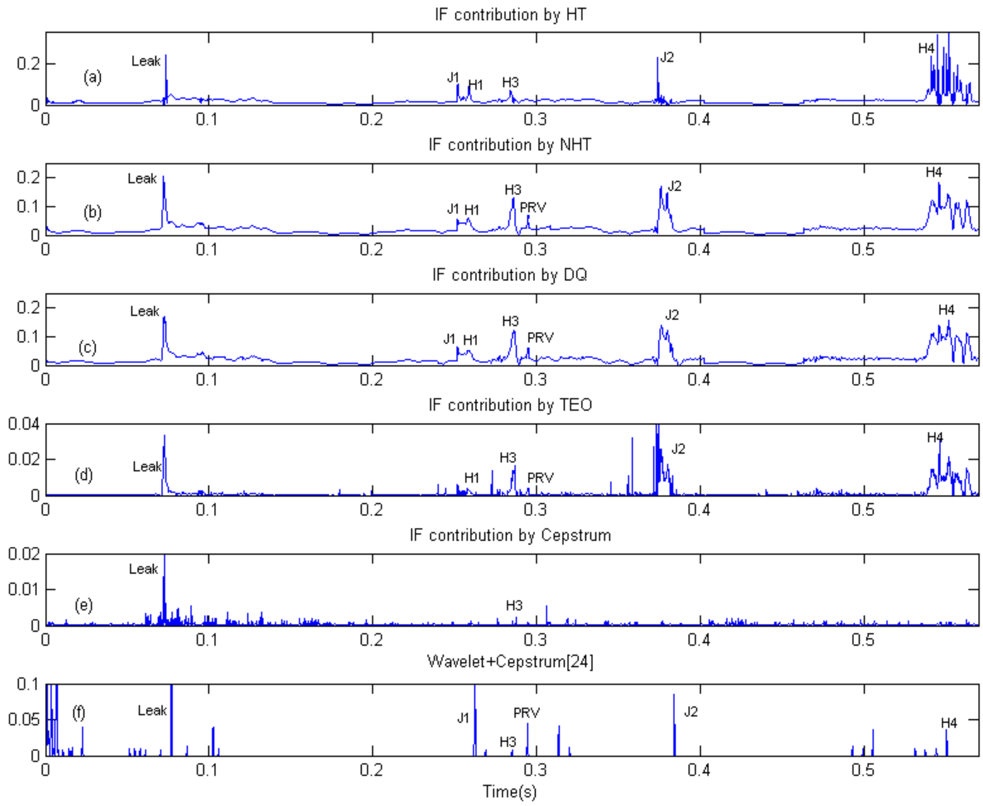


Fig.15 Instantaneous frequency analysis by HT,NHT,DQ,TEO and Cesptrum and Taghvaei [21] of the field test data

Tables:

Table 1. Field test condition

Pipe material	Cast iron
Pipe diameter	4 inch
Calibrated speed of wave	1090 m/s
Leak size	3.5 l/s
Testing point	Hydrant 2 (H2)
Sampling frequency	5 kHz

Table 2. Summarised result of field test data for different instantaneous frequency analysis

Features	Analysed Distance (m)					Measured Distance (m)	Error (%)				
	HT	NHT	DQ	TEO	Cepstrum		HT	NHT	DQ	TEO	Cepstrum
Leak(L)	40.22	39.46	39.57	39.68	39.567	40	0.55	1.36	1.08	0.81	-1.08
Junction 1(J1)	137.4	137.3	137.2	137.2	-	138.5	0.79	0.87	0.94	0.94	-
Hydrant 1(H1)	141.3	141	140.8	140.6	-	142	0.49	0.70	0.85	1.00	-
Hydrant 3(H3)	154.9	155.7	155.8	156.2	156.7	154	0.58	1.10	1.17	1.43	1.75
PRV	-	165.9	165.8	166	-	160		3.69	3.63	3.75	-
Junction 2(J2)	203.1	204.9	205.2	205.4	205.7	204	-0.44	0.44	0.59	0.67	0.83
Hydrant 4(H4)	300.9	297.6	297.7	297.9	-	293.4	2.56	1.43	1.47	1.53	-