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An improved cross-correlation method based on wavelet transform and energy feature extraction for pipeline leak detection

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Abstract. Early detection and precise location of leakage is of great importance for life-cycle maintenance and management of municipal pipeline system. In the past few years, acoustic emission (AE) techniques have demonstrated to be an excellent tool for on-line leakage detection. Regarding the multi-mode and frequency dispersion characteristics of AE signals propagating along a pipeline, the direct cross-correlation technique that assumes the constant AE propagation velocity does not perform well in practice for acoustic leak location. This paper presents an improved cross-correlation method based on wavelet transform, with due consideration of the frequency dispersion characteristics of AE wave and the contribution of different mode. Laboratory experiments conducted to simulate pipeline gas leakage and investigate the frequency spectrum signatures of AE leak signals. By comparing with the other methods for leak location identification, the feasibility and superiority of the proposed method are verified.

Keywords: acoustic emission; pipeline leak detection; cross-correlation analysis; wavelet transform; energy feature

1. Introduction

As a major lifeline infrastructure to deliver water, gas and other energy media, pipelines play an important role in modern society. A serious issue existing in the daily operation of the pipeline system is leakage, which may cause considerable economic loss and even pose a threat to public safety. Early detection and precise location of leakage is of great importance for life-cycle maintenance and management of widely-distributed pipeline system.

In the past few years, acoustic emission (AE) techniques have demonstrated to be an excellent tool for on-line leakage detection given the fact that the leakage can release elastic energy in form of transient stress waves and generate the signals representative of the abnormal AE events (Dipen 2005). Many efforts have been made to investigate acoustic features of leakage source, propagation characteristics of acoustic waves along pipelines, and the relation of AE signals with different parameters like leakage rate, propagating distance, material and geometric properties of

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pipelines, operating conditions etc. (Muggleton and Brennan 2004, Brunner and Barbezat 2006, Juliano *et al*. 2013). It is validated that AE signals generated by pipeline leakage are continuous signals generally with a wide frequency range even up to hundreds of kHz.

To determine AE source location, further research work have been reported based on cross-correlation analysis of the continuous AE signals acquired at different locations. The early work uses the observed raw signals for direct time delay estimation and cross-correlation analysis (Kosel *et al.* 2000). Simple as it is, the straightforward method sometimes cannot achieve good identification accuracy due to the disturbance of measuring noise. Some advanced signal processing techniques are then employed to improve the identified results (Gao *et al.* 2004, 2006). In view of good resolution in both time and frequency domains, wavelet transform is regarded as one of the most reliable tools for studying signals with sudden changes of phase and frequency. Compared with the other time-frequency methods, wavelet transform is capable of a multi-scale analysis of the signal via the operations of dilation or translation and is particularly suitable to deal with the non-stationary signals such as those due to pipeline leakage. Given this, the applications of wavelet transform in AE testing have been reported in succession and it has been validated that the wavelet based time-frequency analysis is indeed powerful to identify the singular AE signals and the leakage location (Ding *et al.* 2004, Ahadi and Bakhtiar 2010).

A particularly noteworthy feature in AE signals propagating along a pipeline is the multi-mode and frequency dispersion characteristics, which leads to the propagation velocity of AE wave varying with the mode frequency. For this reason, the direct cross-correlation technique that assumes the constant AE propagation velocity does not perform well in practice for acoustic leak location. In this work, an improved cross-correlation method based on wavelet transform is proposed, considering the frequency dispersion characteristics of AE wave and the contribution of different mode. Focusing on the pressurized pipes in which leakage yields turbulent flow, laboratory experiments are designed and conducted to simulate gas leakage and investigate the frequency spectrum signatures of AE leak signals. By comparing with the other methods for leak location identification, the feasibility and superiority of the proposed method are verified.

2. Cross-correlation analysis for leak locating

Due to the features of multi-modes, wide frequency range covering hundreds of kHz, attenuation and dispersion nature in propagation, AE signal generated by pipeline leak is generally characterized as a continuous, time variant and non-stationary signal. The indications of leakage can be extracted by AE signal processing from the continuous data set.

As a traditional method to estimate the time delay of two signals, cross-correlation (CC) analysis is widely used to determine the leak location by using more than two AE sensors. Consider the case as shown in Fig. 1 that pipeline leak appears between two AE sensors. Suppose d_1=d_2, the signals ($x(n)$, $y(n)$) recorded by the two sensors in the same AE event should be identical. Otherwise, the two signals are high correlated by introducing the delayed samples τ regarding the different propagation distance. Define a cross-correlation function $R_{xy}(\tau)$ as

$$R_{xy}(\tau)=\sum_{n=0}^{\infty}x(n)y(n+\tau) \tag{1}$$

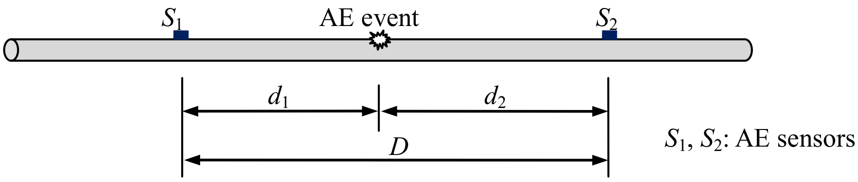


Fig. 1 Schematic diagram for AE event location

Note that the maximum similarity of $x(n)$ and $y(n+\Gamma)$ is expected since they are theoretically identical if Γ is the delayed samples corresponding to the time delay Δt between $x(n)$ and $y(n)$. Clearly, it holds

$$\Delta t = \frac{\Gamma}{f} \tag{2}$$

Here, f is the sampling rate. The location of AE source can be then obtained by

$$d^* = \frac{1}{2}(D - \Delta t \cdot c) \tag{3}$$

in which, d^* is the distance from the source to the acoustic sensor which corresponds to the AE event first; D is the distance of the two acoustic sensors, i.e., $D = d_1 + d_2$; c is the velocity of AE wave propagating in the pipeline.

3. Improved cross-correlation method for leak locating

In the direct cross-correlation method, an assumption is made that the propagating velocity of AE wave is a constant. The practical situation in pipeline leak, however, is that the velocity varies with the frequency band due to the characteristics of multi-mode and frequency dispersion of AE wave. Regarding this, an improved cross-correlation method based on wavelet transform is proposed in the study with due consideration to the frequency dispersion and the contribution of different mode.

3.1 Wavelet transform of the measured signals

By decomposing the measured signal into a coarse approximation and detail information at different levels, wavelet transform provides an effective way to analyze AE signals. Fig. 2 presents a typical two-level wavelet decomposition tree, where '$x(n)$' is the original signal; 'A' and 'D' represent the coarse approximation and the detail component, respectively; the subscript index stands for the level of decomposition.

In general, the original signal recorded with $2f_s$ sampling rate via j-level wavelet decomposition can be written as

$$x(n) = A_j + \sum_{i=1}^{j} D_i \tag{4}$$

Here, the frequency range of A_j is $[0 \quad f_s/2^j]$ and the frequency range of D_i is $[f_s/2^i \quad f_s/2^{i-1}],\ 1 \le i \le j$.

3.2 Time delay, propagation velocity and energy feature vectors

The signals corresponding to each decomposition level can be used to calculate the time delay according to Eqs. (1) and (2). For the reconstructed signal as shown in Eq. (4), a time delay vector is then written as

$$\mathbf{\Delta t} = [\Delta t_{j,A}\ \Delta t_{j,D}\ \Delta t_{j-1,D} \cdots \Delta t_{2,D}\ \Delta t_{1,D}] \tag{5}$$

As mentioned above, the velocity of AE wave propagating in the pipeline at each decomposition level is different, a similar vector of the propagation velocity holds

$$\mathbf{c} = [c_{j,A}\ c_{j,D}\ c_{j-1,D} \cdots c_{2,D}\ c_{1,D}] \tag{6}$$

On the other hand, the energy feature of the reconstructed signals corresponding to the i-th decomposition level can be calculated by

$$E_{i,D} = \sum_{n=0}^{N} D_i^2(n) \tag{7}$$

$$E_{i,A} = \sum_{n=0}^{N} A_i^2(n) \tag{8}$$

Regarding the energy conservation property of wavelet transform, the total energy feature of the observed signal $x(n)$ is given by

$$E_{tot} = \sum_{i=1}^{j} E_{i,D} + E_{j,A} = \sum_{i=1}^{j}\sum_{n=0}^{N} D_i^2(n) + \sum_{n=0}^{N} A_j^2(n) \tag{9}$$

Define the ratio of the j-level energy feature and the total energy feature as

$$p_{j,D} = E_{j,D} / E_{tot} \tag{10}$$

$$p_{j,A} = E_{j,A} / E_{tot} \tag{11}$$

An energy feature vector can be constructed by assembling all the ratios

$$\mathbf{P} = [p_{j,A}\ p_{j,D}\ p_{j-1,D} \cdots p_{2,D}\ p_{1,D}] \tag{12}$$

3.3 Flow chart: leak location

Based on the above wavelet transform and the construction of time delay and energy feature vector, the flow chart of the proposed method is illustrated in Fig. 3, which consists of the following steps. (1) Frequency spectrum signatures of the measured AE signals are first investigated to determine the dominant frequency range. (2) Wavelet transform of the original signals are then carried out, based on which the time delay vector and the energy feature vector are constructed according to Eq. (5) and Eq. (12). (3) The decomposition levels covering the dominant frequency (peak frequencies in the spectrum) are selected. The components of the time delay vector and the energy feature vector corresponding to the selected levels are extracted. (4) The preliminary tests are conducted to calibrate the velocity of AE wave propagating in the pipeline at the selected frequency range. Based on the selected components of the time delay and propagation velocity, a set of identified results for leak location can be determined according to Eq. (3). (5) Use the energy feature components as weighting coefficients. The dot product of the sets of leak location and energy feature leads to the ultimate estimation of the leak location.

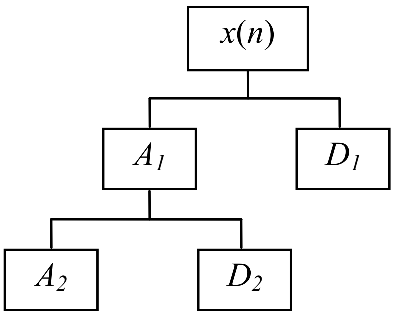


Fig. 2 Wavelet decomposition tree

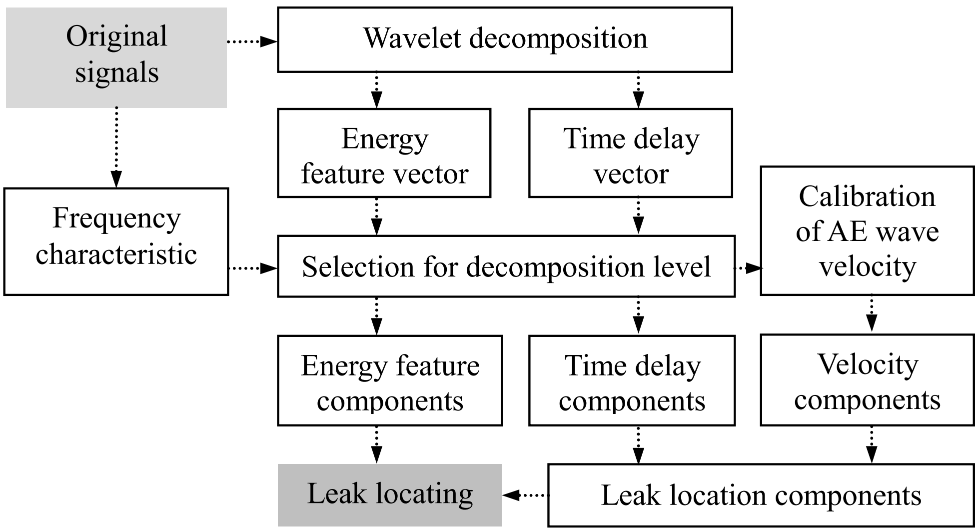


Fig. 3 Flow chart of the improved cross-correlation method

4. Laboratory experiments

4.1 Apparatus

A device for gas leak simulation is designed and set up, consisting of a steel pipe, an air compressor and the other pipe components. As shown in Fig. 4, the steel pipe is 2 m long with the nominal diameter of 200 mm and the wall thickness of 8 mm. A hole of 10 mm diameter are artificially introduced to the pipe, where an electric ball valve is fixed to precisely control the diameter of the leakage hole changing from 0mm to10 mm. The gas is pumped into the pipe via the air compressor and the inside pressure is measured by a pressure gauge.

The AE testing system employed in this experiment consists of two PAC R15α sensors, two PXPAIV pre-amplifiers, an 8-channel PXI-5105 data acquisition card with the maximum sampling rate of 50 MS/s, and a PC (personal computer). In the experiment, three cases of in-pipe pressure (p) are considered: 0.25 MPa, 0.5 MPa, 0.75 MPa. For a given pressure, the diameter of the leakage hole (DL) is set to be 2.5 mm, 3 mm, 4 mm and 5 mm, respectively. AE data is recorded with the sampling rate of 1.0 MHz for all the cases. As for the AE sensor location, d_1 is fixed to be 0.3m and d_2 changes from 0.4 m to1.0m

4.2 Frequency spectrum signatures of AE leak signals

As the environmental noise mainly comes from low-frequency vibration and machine operation, the signals are first processed by 10 kHz high-pass filtering before further analysis is carried out. Fig. 5 presents the waveform and the spectrum of the leak signal in the case of DL=3 mm and p=0.5 MPa as well as the environmental noise after high-pass filtering. This indicates that the dominant frequency components of all the AE signals induced by the pipeline leakage mainly range from 0 to70 KHz and the influence of the noise can be successfully removed.

In the following work, each AE signal is decomposed using db6 wavelet into five frequency bands: a4 (0~31.25 kHz), d4 (31.25~62.5 kHz), d3 (62.5~125 kHz), d2 (125~250 kHz), d1 (250~500 kHz). In view of the aforementioned fact that the dominant frequency components corresponding to the peak frequencies of the leakage events are within 0~70 KHz, a4 and d4 decomposition levels are selected for signal reconstruction, based on which the time delay is estimated for the further leakage source locating.

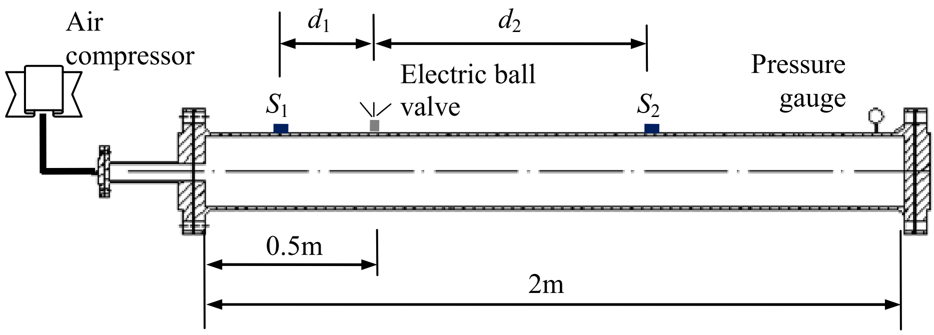
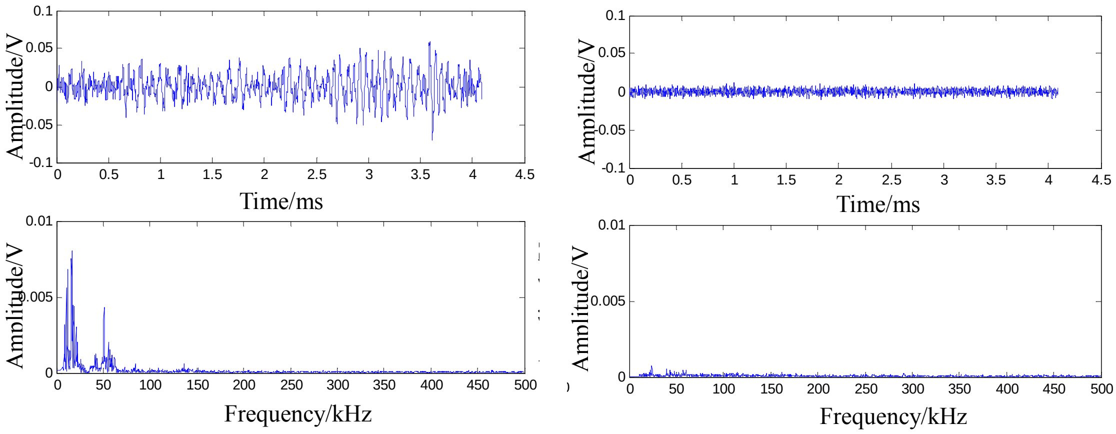


Fig. 4 Experimental setup for gas leak simulation



(a) Leak signal (*DL*=3 mm, *p*=0.5 MPa) (b) Environmental noise

Fig. 5 Waveform and spectrum of leak signals

4.3 Calibration of AE wave propagation velocity

To calibrate the propagation velocity of AE wave in the concerned frequency range, a preliminary test is conducted by using pencil lead break as an AE event. The specimen, the sensor placement and the AE source location are exactly same as the situation shown in Fig. 4.

The AE signals are recorded at the sampling rate of 1.0 MHz. Wavelet transform of the original signals are then carried out, based on which the time delay vector is calculated in terms of Eq. (2) and Eq. (5). Meanwhile, frequency spectrum signatures of the measured signals are investigated and the decomposition levels corresponding to the dominant frequency range are selected. For each selected level, the velocity can be estimated according to Eq. (3) by using the calculated time delay component and the given location of pencil lead break. Considering the repeatability of mode velocity measurement, totally 50 tests are conducted by setting different distances (d_1, d_2). The average propagation velocity of a4 and d4 are determined as 2400 m/s and 2800 m/s, respectively.

4.4 Leak locating

Following the steps as mentioned in Section 3.3, the identified results of the leak location in the case of different inside pressure are listed in Tables 1-3. Note that the estimation d_l^* for each case is the average result using 20 sets of AE data sample, which is recorded with the same duration (4096 points, 1 MHz) when the internal pressure of the pipe is kept stable. A parameter is defined here to evaluate the accuracy of the leak location identification as

$$\alpha = 1 - \frac{\left| d_1^* - d_1 \right|}{D} \tag{13}$$

It can be seen that the identified accuracy is better than 80% when the diameter of the leak hole is larger than 2.5 mm. The inside pressure has little influence on the identified accuracy, whereas the difference ($\Delta d = |d_1 - d_2|$) matters a lot. The identified accuracy gets worse with the increase of Δd, which may be due to the reason that the energy feature vector is calculated by using one signal regardless of its difference between the two signals.

4.5 Comparison of different leak locating methods

Taking the case of DL=3 mm and p=0.75 MPa for example, different methods for leak locating are compared, including the cross-correlation methods by using (1) the original signals (CC), (2) the a4 level signals (a4-CC), (3) the d4 level signals (d4-CC) and (4) the proposed method (WT-CC). The comparison of the identified results is listed in Table 4.

Table 1 Identified leak location in the case of 0.75 MPa

Sensor location \ DL		5 mm		4 mm		3 mm		2.5 mm	
d_1 (m)	d_2 (m)	d_1^* (m)	α (%)	d_1^* (m)	α (%)	d_1^* (m)	α (%)	d_1^* (m)	α (%)
0.3	0.4	0.311	98.4	0.314	98.0	0.308	98.9	0.324	96.6
	0.5	0.332	96.0	0.352	93.5	0.357	92.9	0.373	90.9
	0.6	0.379	91.2	0.361	93.2	0.39	90.0	0.419	86.8
	0.7	0.417	88.3	0.425	87.5	0.342	95.8	0.431	86.9
	0.8	0.453	86.1	0.45	86.4	0.362	94.4	0.457	85.7
	0.9	0.541	79.9	0.475	85.4	0.509	82.6	0.507	82.8
	1.0	0.535	81.9	0.529	82.4	0.518	83.2	0.638	74.0

Table 2 Identified leak location in the case of 0.5 MPa

Sensor location \ DL		5 mm		4 mm		3 mm		2.5 mm	
d_1 (m)	d_2 (m)	d_1^* (m)	α (%)	d_1^* (m)	α (%)	d_1^* (m)	α (%)	d_1^* (m)	α (%)
0.3	0.4	0.325	96.4	0.282	97.4	0.288	98.3	0.361	91.2
	0.5	0.356	93.0	0.359	92.6	0.372	91.0	0.391	88.6
	0.6	0.409	87.9	0.363	93.0	0.339	95.7	0.439	84.6
	0.7	0.404	89.6	0.469	83.1	0.372	92.8	0.479	82.1
	0.8	0.481	83.5	0.484	83.3	0. 392	90.8	0.524	79.6
	0.9	0.477	85.3	0.453	87.3	0.387	92.8	0.555	78.8
	1.0	0.546	81.1	0.49	85.4	0.465	87.3	0.585	78.0

Table 3 Identified leak location in the case of 0.25 MPa

Sensor location \ *DL*		5 mm		4 mm		3 mm		2.5 mm	
d_1 (m)	d_2 (m)	d_1^* (m)	α (%)	d_1^* (m)	α (%)	d_1^* (m)	α (%)	d_1^* (m)	α (%)
0.3	0.4	0.317	97.6	0.303	99.6	0.298	99.3	0.342	94.0
	0.5	0.332	96.0	0.322	97.3	0.328	96.5	0.377	90.4
	0.6	0.333	96.3	0.335	96.1	0.348	94.7	0.411	87.7
	0.7	0.416	88.4	0.352	94.8	0.369	93.1	0.488	81.2
	0.8	0.431	88.1	0.386	92.2	0.414	88.6	0.531	79.0
	0.9	0.466	86.2	0.414	90.5	0.478	85.2	0.582	76.5
	1.0	0.474	86.6	0.53	82.3	0.54	81.5	0.62	75.4

Table 4 Comparison of the identified leak location (*DL*=3 mm, *p*=0.75 MPa)

Sensor location		CC		a4-CC		d4-CC		WT-CC	
d_1 (m)	d_2 (m)	d_1^* (m)	α (%)	d_1^* (m)	α (%)	d_1^* (m)	α (%)	d_1^* (m)	α (%)
0.3	0.4	0.388	87.5	0.314	98.0	0.309	98.7	0.308	98.9
	0.5	0.362	92.2	0.36	92.5	0.36	92.9	0.357	92.9
	0.6	0.403	88.5	0.4	88.8	0.4	88.9	0.39	90.0
	0.7	0.522	77.8	0.427	87.3	0.423	88.7	0.342	95.8
	0.8	0.55	77.3	0.461	85.3	0.515	80.5	0.362	94.4
	0.9	0.6	75.0	0.54	80.0	0.495	83.8	0.509	82.6
	1.0	0.65	73.1	0.58	78.4	0.548	80.9	0.518	83.2

Clearly, the direct cross-correlation method presents relatively large estimation errors. By using the a4 or d4 level signals, the identified accuracy is greatly improved. The best results are achieved based on the improved cross-correlation method proposed in this study. Most of the identified accuracy is above 90%.

5. Conclusions

The traditional direct cross-correlation methods for pipeline leak locating are based on the assumption that the propagation velocity of multi-mode AE wave is a constant, which is inconsistent with the fact that the propagation velocity varies with the mode frequency. Regarding this, an improved cross-correlation method based on wavelet transform is proposed in the study with due consideration to the frequency dispersion characteristics of AE wave and the contribution of different mode. The laboratory experiments on the simulation of pipeline gas leakage verify: (1) the identified accuracy is better than 80% when the diameter of the leak hole is larger than 2.5 mm; (2) the inside pressure has little influence on the identified accuracy; (3) with the increasing difference between the distances of the two AE sensors away from the leak location, the identified accuracy decreases probably due to the reason that the energy feature vector is calculated by using one signal regardless of its difference between the two signals; (4) compared with the traditional methods for pipeline leak locating, the proposed method present higher accuracy and reliability.

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CC