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Adaptive noise cancellation based on EMD in water-supply pipeline leak detection

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ABSTRACT

In water-supply pipeline leak detection and location, both the leak signals and blurred noises are closely related to the pipeline states and surroundings and most of the conventional noise-cancellation methods have to depend on the empirical parameters of either signals or noises. EMD (Empirical Mode Decomposition) is an adaptive signal decomposition method and is exclusive of base functions. A signal is decomposed into several IMFs (Intrinsic Mode Functions) in EMD, then the noise in a signal can be cancelled through removing uncorrelated IMFs. The existing EMD noise cancellation methods need to know the characteristics of either the wanted signal or the noise for rebuilding the noise-removed signal. However the characteristics of leak signals and noises are not fixed in various pipeline conditions, so the existing EMD noise cancellation methods can't be directly applied in water-supply pipeline leak detection. This paper proposes an adaptive noise cancellation method based on EMD, in which the IMFs that don't or less contain the components related to the leak can be removed through the cross-correlation between the IMFs and another signal collected at the either side of a suspect leak. In simulation analysis, the adaptive noise cancellation method can increase the SNRs (Signal to Noise Ratios) of leak signals as high as 16 dB. In processing practical pipeline vibro-acoustic signals, with the proposed method the peak of adaptive time delay estimate of leak signals, which determines the location of a leakage, becomes more distinguished, and thus the error of leakage location is improved.

1. Introduction

In water-supply pipeline leak detection and location, the cross-correlation of collected signals at either sides of a suspect leak can be used to judge whether there is a leak, and the time delay between the leak signals contained in the two collected signals can be used to locate the leakage. The SNRs of leak signals in collected signals directly influence the cross-correlation and the error of time delay estimate. The improvement of SNRs through suppressing the noises in collected signals is essential to ensure the reliability of leak detection and reduce the error of leak location.

The SNRs of leak signals can be improved by pre-filtering in which the frequency bands of leak signals are extracted [1]. But it is difficult to determine the bands of leak signals in various pipeline states (pipeline sizes, pressures, materials, leakage apertures, etc.) and surroundings (embedding pipeline media, ambient temperature, etc.). The features of leak signals and noises change with the pipeline states and surroundings, if the pass-bands of pre-filters are different from that of actual leak signals, the components of leak signals will be eliminated, and the reconstructed signals from pre-filtering cannot be used to detect leaks and locate leakages.

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The adaptive time delay estimation based on the minimum mean square error can be free of the choice of frequency bands of leak signals [2]. In this method, the mean square error between the estimated value and the actual value can converge to the minimum by iterative calculation. When the algorithm converges, the time delay of two leak signals in the collected signals will be achieved. However the time delay estimate is a biased estimate, and the Cramer-Rao Bound indicates that the minimum mean squared error between the estimated and the true value is inversely proportional to the SNR of a signal [3,4]. The lower the SNR is, the greater the deviation of estimation will be. In order to get more accurate judgment of the presence or absence of leak and obtain more accurate location of leakage, the SNRs of leak signals in collected signals need to be increased.

Wavelet denoising can suppress the burst interferences (such as traffic noises) in the collected signals [5], because of the singularity of the burst interferences and the relative stationarity of leak signals, the burst interferences can be suppressed by setting appropriate thresholds in the wavelet coefficients. However the thresholds are related to the selection of appropriate segment lengths of collected signals. In order to achieve good denoising effect, the segment length of collected signals is chosen usually on an empirical basis according to the features of burst interferences. Different segment lengths of collected signals can result in distinct denoising effects. The method based on the length of self-correlation of signals can remove fixed interference noises (such as the sound of drill, etc.) [6], but the method needs to set the lengths of self-correlation of different signals still from empirical data. Because the features of leak signals and noises change with the pipeline states and surroundings, it is impossible to predict the frequency bands and the self-correlation length of a leak signal and noises. When the selected self-correlation lengths of leak signals and noises deviate from the actual ones, it is also impossible to keep the leak signals and remove the unwanted noises. The above noise cancellation methods rely on empirical parameters which are readily varied with pipeline states and surroundings. In order to obtain good noise cancellation effect independent of empirical parameters, it is necessary to find a noise cancellation method which can adapt to the different pipeline states and surroundings. EMD is a kind of adaptive signal decomposition method which is independent of base functions [7].

A signal can be decomposed into several IMFs which have different time scale in EMD. By selecting specific parameters, such as the frequency features in signals or noises, different filters can be made by filtering IMFs in EMD [8,9]. In the existing EMD noise cancellation methods, the low-frequency signal is usually set to be the wanted signal and the noise is supposed white. The SNR of a signal can be increased by removing some parts of high-frequency IMFs [10–12]. However if the characteristics of a wanted signal or a noise are unknown, it will be hard to judge which IMFs contain the components of the wanted signal and which IMFs primarily contain the noise. In the pipeline leak detection, the characteristics of leak signals and noises are difficult to predict in different pipeline states and surroundings, the SNRs of leak signals cannot be increased by directly using the existing EMD noise cancellation methods.

This paper proposes an adaptive noise cancellation method in which there is no necessary to know the characteristics of leak signals or noises in advance. The collected signal at one side of a suspect leak is used as the detection signal and the other one collected at another side of the suspect leak is used as a reference signal. When a leak exists, the reference signal and the detection signal both contain leak signal. Only the IMFs containing leak signal is related to the reference signal in the cross-correlation between the IMFs and the reference signal. Therefore, the IMFs that are unrelated to the reference signal can be removed and the IMFs that are related to the reference signal can be reserved. The reconstructed signal can be achieved by the superposition of the reserved IMFs.

2. The principle of adaptive noise cancellation

2.1. EMD

EMD is a data-driven technique, so there are no base functions, it can decompose a signal into different IMFs. Through eliminating the envelope of a detection signal, the high-frequency component of the detection signal can be obtained, if the high-frequency component does not meet the criteria of an IMF, the elimination will go on until the high-frequency component meets the criteria of an IMF and the high-frequency component is retained as IMF. Then the detection signal subtracts the IMF, the low-frequency component of the original signal will be left. The low-frequency component is used as an alternative detection signal, then the low-frequency component is decomposed by eliminating its envelope, and the IMF whose time scale is larger can be retained. With loop operation, when the low-frequency component meets the termination condition, all of the IMFs can be ontained [13,14].

Suppose the detection signal is $x(t)$, in EMD $x(t)$ is represented as expression (1), $c_i(t)$ is the IMF, the number of IMFs is m, $r_0(t)$ is the trend function whose frequency is the lowest [15].

Recognition criteria of IMF is referred to as expression (2) [16], SD is the threshold of recognition criteria of IMF, when $SD < 0.2, T$ is the length of $x(t)$, $h_k(t)$ is the kth order IMF.

$$x(t) = \sum_{i=1}^{i=m} c_i(t) + r_0(t) \tag{1}$$

$$SD = \sum_{t=0}^{T} \left[\frac{|(h_{(k-1)}(t) - h_k(t))|^2}{h^2_{(k-1)}(t)} \right] \tag{2}$$

2.2. Noise cancellation

A signal can be adaptively decomposed into several IMFs. If it can be determined that which IMFs contain the components of a wanted signal or which IMFs contain noise, it is ready to keep the signal-dominant IMFs and remove the noise-blurred IMFs.