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Research paper

Cross-correlation analysis and time delay estimation of a homologous micro-seismic signal based on the Hilbert–Huang transform

Hong-Mei Sun [a], Rui-Sheng Jia [a,b,*], Qian-Qian Du [a], You Fu [a]

[a] College of Information Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China
[b] Shandong Province Key Laboratory of Wisdom Mine Information Technology, Shandong University of Science and Technology, Qingdao 266590, China

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ABSTRACT

A micro-seismic signal's transient features are non-stationary. The traditional weighted generalized cross-correlation (GCC) algorithm is based on the cross-power spectrum density. This algorithm diminishes the performance of the time delay estimation for homologous micro-seismic signals. This paper analyzed the influence of calculation error on the cross-power spectrum density of a non-stationary signal and proposed a new cross-correlation analysis and time delay estimation method for homologous micro-seismic signals based on the Hilbert–Huang transform (HHT). First, the original signals are decomposed into intrinsic mode function (IMF) components using empirical mode decomposition (EMD) for de-noising. Subsequently, the IMF components and the original signals are analyzed using a cross-correlation analysis. The IMF components are subsequently remodeled at different scales using the Hilbert transform. The marginal spectrum density is obtained via a time integration of the remodeled components. The cross-marginal spectrum density of the two signals can also be obtained. Finally, the cross-marginal spectrum density is used in the weighted GCC algorithm for time delay estimation instead of the cross-power spectrum density. The time delay estimation is determined by searching for the weighted GCC function peak. The experiments demonstrated the superior time delay estimation performance of the new method for non-stationary transient signals. Therefore, a new time delay estimation method for non-stationary random signals is presented in this paper.

1. Introduction

The localization of original seismic activity is an essential micro-seismic monitoring technique. Accurate localization can explain the focal mechanisms of the seismic activity or evaluate disasters, such as rock burst. The time difference of arrival method is commonly used for micro-seismic source localization. In this method, the time difference immediately impacts the localization accuracy.

The arrival time difference of the signals acquired by different vibrational sensors is called the time delay. Typical time delay estimation methods include the generalized cross-correlation (GCC) method (Knapp and Carter, 1976; Souden et al., 2010), least mean square (LMS) method (Youn et al., 1982; Salvati and Canazza, 2013; Gedalyahu and Eldar, 2010), acoustic transfer function (ATF) method (Dvorkind and Gannot, 2003; Cornelis et al., 2010) and time–frequency energy method (Juliana, 2011). The GCC method is the most common. The method calculates the cross-correlation function between two homologous micro-seismic signals and later searches for the maximum peak. Accurate time delay estimations can be obtained for cases characterized by weak Gaussian noise. However, the performance declines in the case of low-SNR signals (Lee et al., 2014). Therefore, various improved techniques have been proposed, such as the ROTH filter (ROTH), smoothed coherence transform (SCOT), maximum likelihood (ML), ECKART filter (ECKART), Wiener filter (WP), phase transform (PHAT) and Hassab Boucher (HB) methods. Among these methods, the ML, ECKART, WP and HB methods can reach the Cramer-Rao low bound (CRLB) (Knapp and Carter, 1976; Davide et al.,2013), reducing the time delay estimation noise influence to a certain extent.

These methods are based on the second-order statistics theory and technology that comply with the Gaussian noise distribution characteristics. However, seismic signals and noise are non-stationary and non-Gaussian (Yue et al., 2012). Therefore, these methods significantly reduce the time delay estimation performance. This paper proposes a time delay estimation method based on the HHT to address the non-stationary characteristics of micro-seismic signals with noise. This method decomposes the micro-

* Corresponding author at: College of Information Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China.
E-mail address: jrs716@163.com (R.-S. Jia).

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seismic signals using empirical mode decomposition (EMD) and sets reconstruction rules for the intrinsic mode function (IMF) to filter the high frequency noise. The marginal spectrum densities of the micro-seismic signals are then obtained via the Hilbert transform. The cross-marginal spectrum density is used in the weighted GCC algorithm instead of the cross-power spectrum density to estimate the time delay, thereby improving the time delay estimation performance.

2. Influence of non-stationary seismic signals on the GCC algorithm

2.1. Generalized cross-correlation time delay estimation algorithm

The seismic geophone acquisition of vibration signals is affected by external noise during the micro-seismic monitoring process, as shown in Fig. 1.

The $x_1(t)$ and $x_2(t)$ signals are received by the seismic geophones m_1 and m_2 and expressed as:

$$x_1(t) = s(t) + b_1(t) \tag{1}$$

$$x_2(t) = s(t - D) + b_2(t), \tag{2}$$

where $s(t)$ represents the original signal, D is the time difference between the two seismic geophones (m_1 and m_2) and $b_1(t)$ and $b_2(t)$ represent the external noise. In addition, $s(t)$, $b_1(t)$ and $b_2(t)$ are uncorrelated. The cross-correlation function between the micro-seismic signals $x_1(t)$ and $x_2(t)$ is subsequently represented as

$$R_{x_1x_2}(\tau) = E\left[x_1(t)x_2(t+\tau)\right] = R_{ss}(\tau - D) + R_{sb_1}(\tau - D) + R_{sb_2}(\tau) + R_{b_1b_2}(\tau) \tag{3}$$

where $E[\cdot]$ represents the mathematical expectation, R_{ss} is the auto-correlation function of the original signal and $R_{b_1b_2}$ is the cross-correlation function of additive noise from the two seismic geophones m_1 and m_2. It is assumed that $s(t)$, $b_1(t)$ and $b_2(t)$ are unrelated and completely orthonormal, yielding

$$R_{sb_1}(\tau - D) = R_{sb_2}(\tau) = R_{b_1b_2}(\tau) = 0 \tag{4}$$

Formula (3) can be rewritten as

$$R_{x_1x_2}(\tau) = R_{ss}(\tau - D) \tag{5}$$

The auto-correlation function is governed by $|R_{ss}(\tau - D)| \le R_{ss}(0)$. Thus, R_{ss} is maximized when $\tau - D = 0$. The time delay estimation between the two seismic geophones can now be expressed as

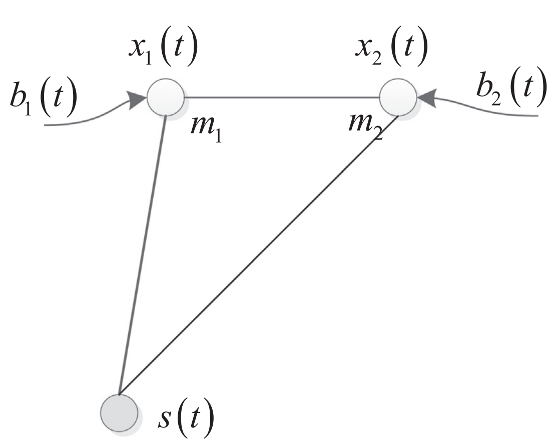

Fig. 1. Seismic geophone detects micro-seismic signals with noise.

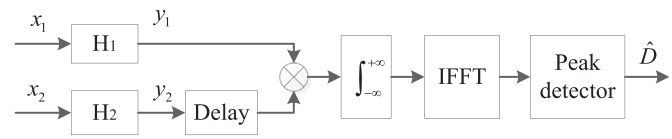

Fig. 2. Schematic diagram of the GCC method.

$$\hat{D} = \arg\max_{\tau}\left[R_{x_1x_2}(\tau - D)\right] \tag{6}$$

When the SNR is sufficiently large, the cross-correlation method can estimate the time delay by detecting the peak position of the cross-correlation function. However, the cross-correlation function does not work if background noise exists. The GCC method pre-filters the signals using the weighted function in the frequency domain before passing the signals to the correlator. This step whitens the signals and noise, accentuates the original signal and suppresses the noise power to improve the time delay estimation. The principle of the GCC algorithm is shown in Fig. 2.

As shown in Fig. 2, a generalized cross-correlation function can be defined as the Fourier inverse transformation of the weighted power spectrum density function.

$$R^{(g)}_{x_1x_2}(\tau) = F^{-1}\left[G_{x_1x_2}(f)\right] \tag{7}$$

$G_{x_1x_2}(f)$ can be expressed as

$$G_{x_1x_2}(f) = H_1(f)H_2^*(f)G_{x_1x_2}(f) \tag{8}$$

where * represents the complex conjugate and $G_{x_1x_2}(f)$ represents the cross-power spectrum density function of $x_1(t)$ and $x_2(t)$. The cross-correlation function of $x_1(t)$ and $x_2(t)$ can then be expressed as

$$R^{(g)}_{x_1x_2}(\tau) = \int_{-\infty}^{+\infty} H(f)G_{x_1x_2}(f)e^{j2\pi f\tau}df \tag{9}$$

where:

$$H(f) = H_1(f)H_2^*(f) \tag{10}$$

$H(f)$ is the generalized weighted function. Common generalized weighted functions include the SCOT, PHAT, ECKART and HB functions (Knapp and Carter, 1976; Joseph and Ronald, 1979; Wittlinger et al., 2007).

2.2. Error influence when calculating the power spectrum density of the time delay estimation algorithm

The GCC and improved-GCC algorithms are based on the phase difference of the power spectrum. The power spectrum density function is defined as

$$P_{xx}(\omega) = \frac{1}{N}\left|\sum_{n=0}^{N-1} x(n)e^{-j\omega n}\right|^2 = \frac{1}{N}|X_N(\omega)|^2 \tag{11}$$

where $P_{xx}(\omega)$ represents the power spectrum density and $X_N(\omega)$ is the Fourier transform for finite sequences $X_N(n)(n = 0, 1, 2, \ldots, N-1)$. In theory, the Fourier transformation can only be applied to stationary random signals, while micro-seismic signals are non-stationary and non-Gaussian. Therefore, a relatively large error will accrue during the power spectrum estimation process, which affects the precision of the time delay estimation. Modern power spectrum estimation techniques, such as the Welch, AR modeling, maximum entropy and Burg recursive methods, have improved the time delay estimation precision. However, these methods are all based on the Fourier transform. Fig. 3 shows the time delay estimation results for two micro-seismic signals utilizing the PHAT-GCC and SCOT-GCC algorithms,