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Enhancing micro-seismic P-phase arrival picking: EMD-cosine function-based denoising with an application to the AIC picker

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A B S T R A C T

Micro-seismic P-phase arrival picking is an elementary step into seismic event location, source mechanism analysis, and seismic tomography. However, a micro-seismic signal is often mixed with high frequency noises and power frequency noises (50 Hz), which could considerably reduce P-phase picking accuracy. To solve this problem, an Empirical Mode Decomposition (EMD)-cosine function denoising-based Akaike Information Criterion (AIC) picker (ECD-AIC picker) is proposed for picking the P-phase arrival time. Unlike traditional low pass filters which are ineffective when seismic data and noise bandwidths overlap, the EMD adaptively separates the seismic data and the noise into different Intrinsic Mode Functions (IMFs). Furthermore, the EMD-cosine function-based denoising retains the P-phase arrival amplitude and phase spectrum more reliably than any traditional low pass filter. The ECD-AIC picker was tested on 1938 sets of micro-seismic waveforms randomly selected from the Institute of Mine Seismology (IMS) database of the Chinese Yongshaba mine. The results have shown that the EMD-cosine function denoising can effectively estimate high frequency and power frequency noises and can be easily adapted to perform on signals with different shapes and forms. Qualitative and quantitative comparisons show that the combined ECD-AIC picker provides better picking results than both the ED-AIC picker and the AIC picker, and the comparisons also show more reliable source localization results when the ECD-AIC picker is applied, thus showing the potential of this combined P-phase picking technique.

1. Introduction

The micro-seismic monitoring system, an effective tool to monitor regional seismic hazards such as fault slip and rock burst, has played an important role in engineering disaster control (Li et al., 2017b). The major technical issues of this tool are monitoring planning, data processing and micro-seismic event location (Ge, 2005). Accurate P-phase arrival picking is one of the key issues in data processing and the fundamental step in seismic event localization, source mechanism analysis and seismic tomography analysis (Ge, 2005; Gou et al., 2011; Alvarez et al., 2013; Yue et al., 2014). While the P-phase picking process can be conducted manually, the large number of seismic signals however, can make it cumbersome and time-consuming (Galiana-Merino et al., 2008; Karamzadeh et al., 2013; Hafez et al., 2013; Li et al., 2016a, 2017a). Motivated by this, many methods have been proposed for automatic seismic P-phase arrival picking. Some methods have shown good performances, such as the FilterPicker (FP, Lomax et al., 2012), the adaptive multi-band picking algorithm (AMPA, Alvarez et al., 2013), higher order statistics (HOS) and the Akaike Information Criterion (AIC) combined method (Küperkoch et al., 2010), and the damping energy-based method (Kalkan, 2016). Yet, micro-seismic signals are often mixed with high frequency noises and/or power frequency noises, which may reduce P-phase picking accuracy. Therefore, it is important to estimate these noises in order to enhance the performance of P-phase arrival pickers.

In this paper, we propose a micro-seismic P-phase arrival picking method based on the Empirical Mode Decomposition (EMD)-cosine function denoising and the commonly used Akaike Information Criterion (AIC) picker (Maeda, 1985). This picker capitalizes on both the EMD's ability to adaptively separate seismic data and high frequency noises and the ability of cosine function-based denoising to retain P-phase arrival amplitude and phase spectrum. The proposed method was tested with 1938 sets of micro-seismic waveforms obtained from the Chinese Yongshaba mine. The results show that the ECD-AIC picker performs better than both the EMD denoising-based AIC picker (ED-AIC picker) and the original signal based AIC picker (AIC picker). In addition, the EMD-cosine function-based denoising has good adaptability to signal-to-noise ratios (SNRs) and different shapes and forms of signals. Furthermore, the localization comparisons also show more reliable source

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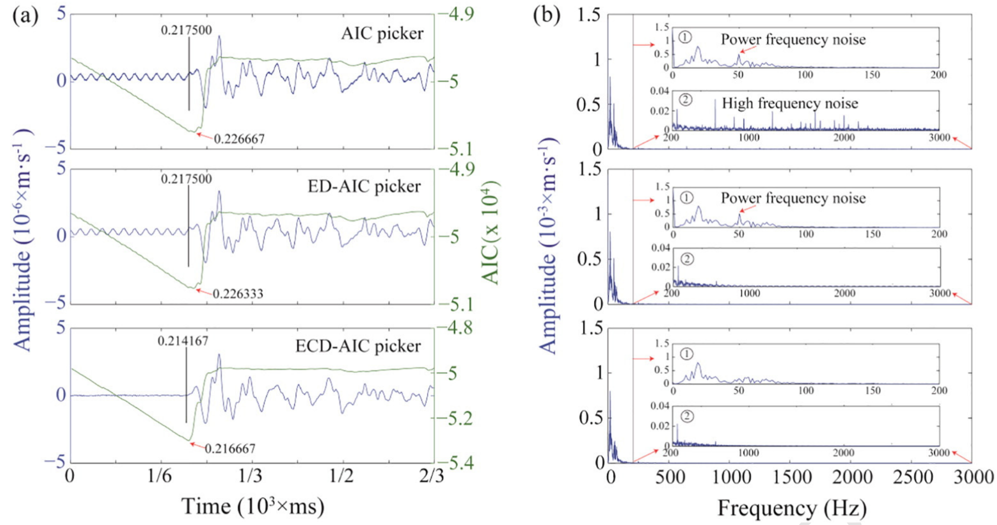

Fig. 1. Application of the AIC picker, the ED-AIC picker and the ECD-AIC picker (left) and their corresponding signal amplitude spectra (right). (a) The original micro-seismic signal (top), EMD denoised micro-seismic signal (center), and EMD-cosine function denoised signal (bottom) (blue lines) and their corresponding AIC time series (green lines). The vertical line and its above number mean the manual picking and the numbers indicated by an arrow correspond to the minimum AIC corresponding time; (b) Amplitude spectra of the original micro-seismic signal (top), EMD denoised micro-seismic signal (center), and EMD-cosine function denoised signal (bottom). The frequency bands [0,200] Hz and [200, 3000] Hz are drawn respectively for a better observation of the detail information. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

localization results when the ECD-AIC picker is applied, thus showing the potential and reliability of this combined P-phase picking technique to P-phase picking.

2. State of the art

Currently, the short- and long- term average (STA/LTA) ratio picker and the AIC picker are the two most widely used pickers for determining P-phase arrival. The STA/LTA ratio picker proposed by Allen (1978) has been improved by Baer and Kradolfer (1987), Earle and Shearer (1994), Gou et al. (2011), Hafez et al. (2009), Hafez and Kohda (2009), and Li et al. (2016a). Similarly, the autoregressive-AIC (AR-AIC) (Sleeman and van Eck, 1999) has been improved by Zhang et al. (2003), Sedlak et al. (2009, 2013), and Li et al. (2017a), whereas the EMD-based pickers are gaining popularity (Zhang and Zhang, 2015; Kirbas and Peker, 2016; Liu et al., 2017; Li et al., 2017a). The EMD is able to adaptively decompose seismic data and noise into different IMFs and sufficiently retain P-phase arrival information, but it may remove P-phase arrival features and not be able to estimate the effect of power frequency noise (Fig. 1b (center)). Other commonly used P-phase picking algorithms include

Table 1
Summary of the commonly used P-phase arrival picking methods.

Method	Brief introduction of the principle	Key references
STA/LTA picker	This algorithm, which utilizes the STA, is more sensitive to rapid fluctuations than the LTA and a P-phase is picked when the STA/LTA exceeds a specified threshold.	Allen, 1978, 1982; Baer and Kradolfer, 1987; Saari, 1991; Ruud and Husebye, 1992; Earle and Shearer, 1994; Withers et al., 1998; Trnkoczy, 2002; Hafez et al., 2009; Hafez and Kohda, 2009; Gou et al., 2011; Li et al., 2016a.
AIC picker	This assumes that the intervals before and after P-phase arrival are two different stationary processes and the AIC has a minimum value when a P-phase comes.	Maeda, 1985; Takanami and Kitagawa, 1988, 1991; Sleeman and van Eck, 1999; Zhang et al., 2003; Sedlak et al., 2009, 2013; Li et al., 2017a.
EMD-based picker	The EMD can decompose a signal adaptively and the P-phase onset is determined by the selected main IMFs that retain P-phase arrivals well.	Zhang and Zhang, 2015; Kirbas and Peker, 2016; Liu et al., 2017; Li et al., 2017a.
High order statistics	The high order statistics such as Skewness and Kurtosis are close to zero for noise (Gaussian signal) and increase when a P-phase comes (non-Gaussian signal).	Saragiotis et al., 1999, 2002, 2004; Lokajíček and Klíma, 2006; Galiana-Merino et al., 2008; Küperkoch et al., 2010; Nippress et al., 2010; Liu et al., 2014; Ross and Ben-Zion, 2014; Baillard et al., 2014; Li et al., 2016a.
Cross correlation technique	Seismic data and noise are generated by two different processes, therefore the cross correlation before and after the P-phase onset will change.	Vandecar and Crosson, 1990; Gibbons and Ringdal, 2006; Gibbons et al., 2012; Senkaya and Karslı, 2014; Ait Laasri et al., 2014.
Waveform fractal based algorithm	Waveform fractal dimension analysis depends on the property of self-similarity or self-affinity in multiple scaling objects.	Boschetti et al., 1996; Jiao and Moon, 2000; Gholamy et al., 2008; Liao et al., 2010.
AMPA algorithm	The adaptive multi-band picking algorithm (AMPA) applies a set of filters to multi-band components to mitigate background noise as well as to enhance the P-phase.	Alvarez et al., 2013; Romero et al., 2016; García et al., 2016.
Wavelet transform based algorithms	This decomposes a signal into different frequency bands: the P-phase arrival retains over several resolution scales, whereas noise decays quickly at lower resolutions.	Zhang et al., 2003; Galiana-Merino et al., 2008; Hafez et al., 2010, 2013; Ghamry et al., 2013; Karamzadeh et al., 2013; Gaci et al., 2014; Li et al., 2016a.
Neural networks based algorithms	This utilizes the absolute values of the seismograms and the associated values of the seismograms as a neutral network input vector to detect the P-phase arrival.	Wang and Teng, 1995; Mousset et al., 1996; Dai and MacBeth, 1995, 1997; Zhao and Takano, 1999; Gentili and Michelini, 2006.
Hybrid method	A single method may fail in picking the P-phase arrival, while the combined method, taking advantages of several pickers, can enhance the seismic P-phase arrival picking.	Tselentis et al., 2012; Akazawa, 2004; Diehl et al., 2009; Nippress et al., 2010.

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