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Source identification of microseismic events in underground mines with interferometric imaging and cross wavelet transform

Linqi Huang[a,b], Hong Hao[b,1], Xibing Li[a], Jun Li[b,*]

[a] School of Resources and Safety Engineering, Central South University, Changsha, Hunan 410083, China
[b] Centre for Infrastructural Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia

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ABSTRACT

Interference based source locating is a newly developed algorithm, which could be used to locate the microseismic event source while not requiring the exact arrival time or picking up the difference of arrival time instants in measured different sensor waveforms. The cross-correlation calculation, which is a key component in the interferometric based source locating algorithm, has some defects, namely, its accuracy is sensitive to the noise effect in sensor measurements and the peak of the cross-correlation function is not obvious with strong oscillations. Therefore the method has a high possibility to output false identifications. All of those shortcomings may result in considerable source locating errors. To solve these problems, while considering the non-stationary, strong randomness and noise effect of signals in the microseismic and blasting vibration monitoring, a new microseismic event locating approach based on interferometric imaging and cross wavelet transform is proposed. The cross wavelet power function is used to replace the cross-correlation function in the traditional interferometric based approach. The effects of main factors affecting the accuracy and robustness of the proposed approach, i.e. the number of placed sensors and the error in the estimation of wave propagation velocity, are investigated. The results demonstrate that the proposed approach gives a more reliable and robust source location accuracy than the traditional approach.

1. Introduction

With the increasing depth in underground projects, an increasing stress environment and a greater uncertainty regarding the mechanical behaviour of the underground rockmass are observed, which may result in an increased safety and economic risk. To address these challenges, over the past decades, there have been numerous studies focusing on disaster protection in underground space. Based on deep mining experience (Zhao et al., 2017; Zheng et al., 2016), microseismic monitoring has become state of the art practice for in-situ brittle failure monitoring. Microseismic source event locating is vital for predicting and avoiding the traditional mine disasters such as rock burst, roof caving, and water inrush and slope landslide (Chen et al., 2015; Cao et al., 2016; Li, 2006). The accuracy in source locating depends on several key factors (Ma et al., 2015), such as the velocity model of wave propagation, the array of sensors, the efficiency in picking up the absolute time of the first arrival wave from sensor measurements and the robustness of algorithms (Feng et al., 2017).

To investigate the influence of the wave propagation velocity model on the microseismic source locating, Thurber (1985) proposed a nonlinear Newton method and added the second order partial derivative into the calculation to improve the stability of the traditional linear methods in locating the earthquake source (Crosson, 1976), however, the computational demand increased significantly. Prugger and Gendzwill (1988) proposed a nonlinear approach based on a simplex stepping algorithm for microseismic source locating, in which the intensive computational task on solving the partial derivative and inverse matrix was avoided. Since then various global nonlinear optimization algorithms, such as simulated annealing method and genetic algorithms, have been used in microseismic source locating in underground space (Billings et al., 1994; Xie et al., 1996). Recently, Dong and Li (2013) proposed a source locating approach in underground mines, where the information of pre-measured wave propagation velocity was not needed. The performance of using it for locating the microseismic sources with different sensor placement configurations and site conditions was investigated. Since the requirement of the wave propagation

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[*] Corresponding author at: Centre for Infrastructural Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Kent Street, Bentley, WA 6102, Australia.

E-mail addresses: hong.hao@curtin.edu.au (H. Hao), junli@curtin.edu.au, LI.Jun@connect.polyu.hk (J. Li).

[1] Principle corresponding author. Centre for Infrastructural Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Kent Street, Bentley, WA 6102, Australia.

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velocity was removed in the abovementioned method in identifying the seismic source location, it effectively decreased the identification error (Li and Dong, 2011). Feng et al. (2015) proposed a sectional velocity model to locate the microseismic source in tunnel engineering. Results from a tunnel simulation showed that the velocities obtained using the sectional velocity model were close to the actual ones and the average location error was reduced by 78.3%. Ma et al. (2016) proposed a method which integrates numerical simulation and microseismic monitoring for evaluation of cavern stability, in which the microseismic monitoring system provides real-time data of microseismic events and pre-warns the possible threats to the stability of the underground storage caverns.

Regarding the influence of sensor placement and number, it has been investigated in locating the earthquake sources. Peters and Crosson (1972) and Uhrhammer (1980) used different sensor deployment strategies, such as the regular hexagonal, asymmetric hexagonal, triangle and the quadrangle distributions, and compared the advantages and disadvantages of different placements for locating the seismic sources in earthquake. In underground space engineering, Hardy et al. (1981) introduced a transducer array for detecting the locations of AE/MS activities associated with an underground gas storage. Li et al. (2014) studied the mechanism of the location effect of two-dimensional station layout, and suggested the general principle for sensor placement for microseismic monitoring in deep coal mine.

Although there are different source location approaches, the most popular one is the arrival time difference approach which has been used almost exclusively in geotechnical studies (Ge and Hardy, 1988). Identifying the Time Difference of Arrival (TDOA) in measured waves for microseismic monitoring is challenging because of the complex local geological conditions and noise effect in the sensor signals induced by mining activities (Li et al., 2013). The absolute method was developed first for picking up the arrival time instants and calculating the TDOA between two P-waves from two sensors. The first arrival waves (commonly assumed as P waves) of two signals are determined respectively, and those two absolute time instants are subtracted to obtain TDOA. The error associated with picking up the time instant of the first arrival wave might be significant, especially when the signal-to-noise ratio is low, and P wave may be mixed with S wave or even S wave arrives first. The commonly used absolute methods include long time average/short time average method (LTA/STA), fractal dimension method, digital image processing method and neural networks (Tian and Chen, 2002; Mahdevari and Torabi, 2012). These methods have also been combined with different filtering techniques, such as Fourier analysis and wavelet transform to improve the accuracy in picking up the time instant of the first arrival wave. In order to improve the signal-to-noise ratio, Knapp and Carter (1976) proposed the relative method by using the correlation of two signals measured under the same vibration source to calculate TDOA. Waldhauser and Ellsworth (2000) improved this method by introducing two concepts, namely, event pairs and double difference, into the event station, and evaluated a set of events respectively at the current location by the spatial partial derivatives. The developed method can be directly applied to existing earthquake catalogs and/or digital waveform data as provided by any seismic sensor network. The widely used relative methods are the double-difference algorithm (DDA) and multi-correlation method.

Besides the methods based on TDOA as mentioned above, the imaging-based approaches have also been explored in recent years for microseismic source locating. The theoretical background of those methods is based on time-reversal invariance theory of wave field (McMechan, 1982; McMechan et al., 1985) and diffraction stack (Kao and Shan, 2004; Kao and Shan, 2007). The process of the traditional method based on the travel time inversion determines the seismic source location from the recorded waveform travelling in the monitoring space. On the other hand the locating method based on the interference imaging uses the recorded energy (or amplitude) at the spatial grid points and the source image. Schuster et al. (2004) developed the source locating method based on the seismic interference image with the correlation calculation of data. The main procedure of this method is presented as follows: (a) Calculating the travel time from all grid points in the target area to every sensor's location by tracing the ray or solving Eikonal equation based on the given velocity model; (b) Performing the cross-correlation calculation of the received seismic records within the selected observation window and collecting the cross-correlation results, which include the difference of arrival time information; (c) Carrying out the cross-correlation migration by multiplying the cross-correlation results and the migration kernel function; (d) Obtaining the stack migration profiles and the final imaging profiles for locating the seismic source. Grandi and Oates (2009) detected the microseismic source location by using the Cross-Correlation and Migration (CCM) for the permanent reservoir monitoring in a layered medium. The feasibility of using the interferometric imaging in the microseismic source locating was verified. The interferometric imaging based approach offers many advantages compared with the traditional methods, for example, (1) It can be applied to any array of sensors; (2) Picking up the phase information is not necessary; (3) A flexible velocity model can be used (such as homogenous model, layer model, and cube model); and (4) The use of cross-correlation calculation provides a more precise estimation of TDOA.

When evaluating the correlation of signals involved in the interferometric imaging method, the cross correlation is usually used. However, the cross-correlation function to measure the similarity of signals is sensitive to noise effect, especially when the measured wave from the microseismic events is weak with a low signal-to-noise ratio (Huang et al., 2016). In this paper, a microseismic event source identification approach in underground mines with interferometric imaging and cross wavelet transform is proposed. The cross wavelet transform is applied to calculate the correlation between sensor signals to improve the accuracy when signals with low signal-to-noise ratios are used. The background theory of the proposed approach will be presented in Section 2. The microseismic source locating will be conducted and compared with the existing methods with the in-field testing data from a real underground mine. The performance and robustness of the proposed approach are discussed, and the effects of two main factors, namely, the estimation of wave propagation velocity and the array of sensors, are investigated.

2. Theoretical background and development

This section will present the theoretical background and development of the proposed approach for microseismic source locating based on the interferometric imaging and cross wavelet transform. The basic theory of the interferometric imaging, cross wavelet transform, cross wavelet power correlation function and the main procedure of the proposed approach are presented.

2.1. Interferometric imaging based microseismic source locating

The interferometric imaging based microseismic source locating approach is divided into two parts: the cross-correlation calculation and the source location searching. The main principle of this approach is shown in Fig. 1. Assuming that the measured signals of two placed sensors A and B under a microseismic event are $a(i)$ and $b(i)$ respectively, which are transmitted from the randomly assumed microseismic source location S' to the sensor locations with the assumed velocity model. If the real TDOA of these two signals from sensors A and B is τ, the cross-correlation function $f_{A,B}(k)$ will reach the maximum value theoretically when $t = \tau$. Therefore the function value of $f_{A,B}(k)$ ($k = (S'B\text{-}S'A)/v$) between $a(i + k)$ and $b(i)$ shows the possibility that S' is the actual event source corresponding to the measured signals of sensors A and B.

The cross-correlation function $f_{A,B}(*)$ between sensor signals $a(i)$ and $b(i)$ is calculated as