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Precursory waves and eigenfrequencies identified from acoustic emission data based on Singular Spectrum Analysis and laboratory rock-burst experiments

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ABSTRACT

Important task for acoustic emission (AE) monitoring involves detecting frequency shift phenomenon and intense periodic components. In the present research, we investigate time dynamics embedded in AE signal acquired in the laboratory rock burst experiment on limestone sample. By applying the Singular Spectrum Analysis (SSA)-based algorithm developed in this research, we reconstruct the decomposed components and then select the main component with a decision-making process based on the criterion that it should be significant both in the eigenvector space and spectral domain, termed eigenfrequency. The frequency shift phenomenon is represented by the eigenfrequencies of the first main component consistently. Precursory waves of the first main component represents time dynamics of the rock burst process by elastic wave over the low-level loading phase, high-frequency wave with self-oscillating envelopes at unloading, low-frequency quasi-shock waves during the rheological delay phase and low-frequency shock wave at complete rock burst failure.

1. Introduction

Rock burst is typically a complicated dynamical process and essentially a conversion process of the accumulated potential energy into the kinetic energy in a violent manner.[1] They contain a large quantity of seismic events taking place in time sequence and can be observed by micro-seismicity (MS) or acoustic emission (AE) monitoring as time series.[2] AE signals, as transient stress wave, carries considerable information regarding the seismic location, failure mechanisms and the constitutive behavior of the materials by its mode and amplitude, providing a window into grain-scale motion, crack initiation and propagation till macroscopic failure. Thus time-series analysis has played an important role in the rock burst studies.

AE signal can be analyzed for extracting frequency-spectrum precursors which are recognized robust for its physical and mathematical consistencies.[3] If signal has a significant sinusoidal component with frequency ω_O, then the spectrum will exhibit a peak centered at that frequency. Whereas, if the time series is a purely random process with zero means, then the spectrum is uniform appearing flat for any frequency bands.[4] Extensive investigations revealed that the main periodicity as argued by the highest peak in the spectra, known as main frequency, moves from high-spectral band to low band as the rock was brought to failure, e.g., the coal and gas outburst,[5,6] in- situ rock bursts and laboratory simulated rock bursts,[1,3,7–10] and earthquake ground motion.[11,12]

Due to uncertainty and variability in rock mass strength and boundary conditions in the lithosphere, the frequency shift phenomenon does not always hold in the above-reviewed traditional spectral analyses. For example, in the laboratory experiments on water saturated basalt samples, the spectral precursors are hybrid containing distinctive high and low frequencies at onset of the failure whose proportion depend on pore fluid being present in the rock under straining.[13] In the field cases, the AE events are also hybrid close to the monitored outbursts and the low frequency components are only the necessary condition other than the sufficient condition for indicating the incoming seismic events due to the "site effects".[14–16]

Although the underground seismicity represents a very complex phenomenon to study in all its various aspects,[17] periodicities could be the first type of time fluctuations that need to be revealed and analyzed.[18] The periodical components of intense seismicity is usually interspersed with those of low seismicity and contaminated by noises of different types. The spectra, therefore, usually have severe frequency dispersions along the spectral axis and could produce misleading results.[19] In order to explore the intrinsic features of time dynamics

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and locate accurately the main spectral components of AE sequence, the state-of-the-art approaches of statistical mechanics should be employed.

Singular spectrum analysis (SSA) is a novel technique for the time series analysis developed in recent decades.[17,18] It is usually used for extracting the dominant periodical components existed in natural or artificial observations. In the present research, a SSA-based algorithm is developed specially for analyzing long AE time series captured in the laboratory rock burst experiment on limestone sample #2. Results of the rock burst experiment and spectral analysis for the limestone sample was reported previously.[1] However, main frequencies were not identified accurately and features of time dynamics were not analyzed because of the frequency dispersion and complexity of the AE signal.

In this work, main portion of the original AE waveforms are reconstructed with the significant components decomposed and selected by using the SSA-based algorithm. Frequencies of the components corresponding to the significant part of eigenvalue spectrum are accurately identified, which are termed eigenfrequency (EF), and then employed in characterizing the frequency shift phenomenon. Analyses of the time-domain waveforms of the significant periodic components are also performed to capture features of time dynamics of the original AE waveforms. The aim of this work is to extract the intrinsic dynamical rock burst precursors in temporal and spectral spaces.

2. Physical background

2.1. Rock sample and testing machine

The AE data are from the rock burst experiment on limestone sample #2 by using laboratory rock burst testing machine, i.e. the modified true-triaxial apparatus.[1] The sample was cored from Jiahe Coal Mine of Xuzhou coal mining group in eastern China, at a depth of 1040 m and is referred to as Shuicang limestone, which resides in a layer of Paleozoic Carboniferous Permian. The average density, uniaxial compression strength, and elastic modulus of the rock are 2.65 g/cm3, 78.4 MPa, and 36.7 GPa, respectively. XRD analysis of the sample showed that the major minerals of the rock are calcite (96.3%) with some quartz (3.7%), and traces of chlorite and illite.

Fig. 1a shows the six faces of the limestone specimen #2. it is seen that the rock has a dense texture and showed a grayish white color. Several vertical vines and one sub-horizontal fracture could be observed by the naked eye. Lines about the orientation of these layering on the specimen faces 1, 2, 3 and 4 are given relative to the major principal stress, σ_1, direction (see Fig. 1a). The testing machine (schematically shown in Fig. 1b) can exert load on the six faces of a cubical specimen in three perpendicular directions. Novelty of the testing machine lies in the single-face unloading along the minimum principal stress direction by sudden drop of the detachable loading shaft, creating a rock burst stress condition found at or near the excavation boundaries. The periphery data acquisition systems include the forces, high-speed digital imaging and acoustic emission monitoring.

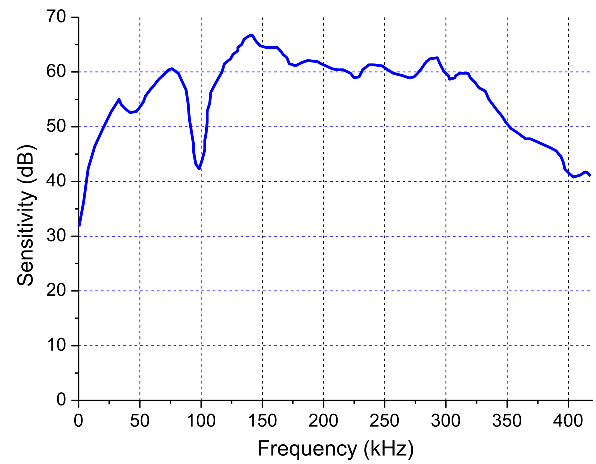

Fig. 2. Calibration curve for AE sensor used in the previously reported rock burst experiments in Reference.[1].

2.2. AE monitoring system

PXWAE AE monitoring system, manufactured by Beijing Pengxiang Science and Technology Ltd., was employed. Two resonance type AE transducers were mounted on the steel loading plates. Fig. 2 shows the sensitivity response of the transducer. It has a fairly flat response over the range 0–400 kHz and a resonance frequency of about 150 kHz. The pre-amplification is 40 dB and gain amplification is 10. The maximum sampling rate is 20 MHz/s with a resolution of 12 bits. During the test, the data acquisition rate was set to 1 MHz and AE events over a waveband of 0–512 kHz were recorded at 8 ms interval with 8192 points which is the observational time series under investigation. A band-pass filter between 30 and 400 kHz was used to eliminate noise in the low frequency range (machine shaking noise) and AE signals beyond the effective upper range of the transducer. A threshold voltage was set at 2.5 V to screen out the background noise.

2.3. 3. Experimental results

Fig. 3a shows the monitored complete stress path and 3b is the enlarged segment a short while before unloading and the process during the complete rock burst failure. Different loading state (σ_1, σ_2, σ_3) are denoted by A–G marked on the stress path from the initial

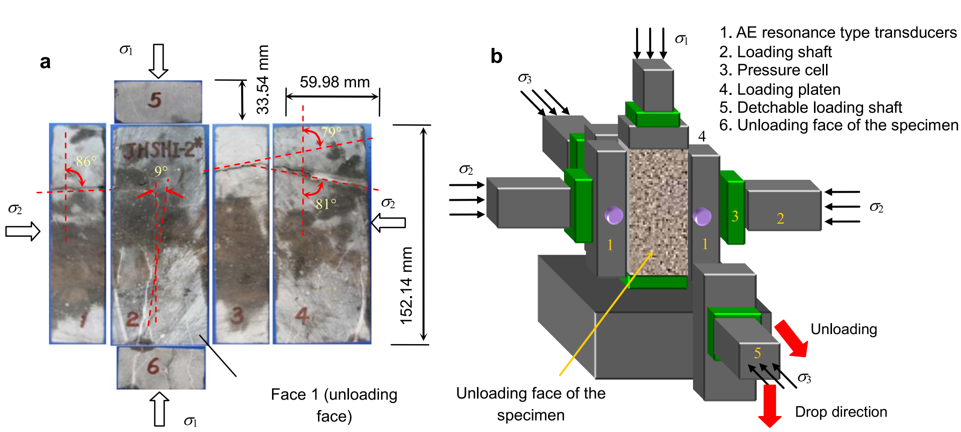

Fig. 1. Rock sample and testing machine: (a) photographs showing six faces of the lime stone sample #2, and (b) schematic of the testing machine, i.e. the modified true-triaxial apparatus; the maximum loading capacity is 450 kN.