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Time-varying multifractal of acoustic emission about coal samples subjected to uniaxial compression

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ABSTRACT

To explore the causes of acoustic emission (AE) mechanisms during different loading stages, the collected coal samples were subjected to uniaxial compression, and the AE counts signals were collected to analyze time-varying AE laws during loading process. Based on the time-varying multifractal theory, the multifractal characteristics with load and time were researched. The results showed that time-varying characteristics of AE corresponded well with load - time, which could reflect cracks evolution and loading process. And during different loading stages (from 20%σ_c to 80%σ_c), $\Delta\alpha$ narrowed gradually, which were related with the number and mode of fractures evolution. The time-varying multifractal characteristics revealed AE mechanisms and the proportion relation between strong and weak AE signals. $\Delta\alpha$ changes with time explained fractures compaction in different scales at the initial stage, cracks sliding and friction during the elastic deformation stage, and cracks expanding and linking at the fracture stage, while the other multifractal parameter (Δf) with time could reflect strong AE signals dominated at the initial and later stages, and the proportion of strong AE signals was almost equal to that of weak AE signals during the elastic deformation stage. The time-varying multifractal laws of AE counts about coal loading will provide significant guide to the early warning of coal deformation or fracture underground coal mines.

1. Introduction

Coal mining underground,coal seam gas and shale gas extraction will lead to the fracture of coal or rock, which will induce dynamic disaster eventually [1–6]. During the failure process, there is energy releasing, such as surface energy, elastic deformation energy [7], heat energy, acoustic emission (AE) energy [8–10], electromagnetic radiation (EMR) energy [11–12] and surface potential (SP) energy [13]. To forecast coal fracture and prevent dynamic disaster, AE, EMR and SP signals were collected to obtain the precursor signals of fracture or disaster [14]. Among AE, EMR and SP signals, the mechanism and change laws are different, but all the signals can correspond with coal deformation and fracture. How to explain the internal changes laws of geophysics signals is always the hot point in geophysical field.

Mandelbrot [15] put forward fractal theory in 1977, and Beck and Schlogl [16] introduced the chaotic systems in 1993, which created new idea for the geophysics responses. Xie [17] successfully combined damage mechanics and fractal geometry together in 1996, creating a new field about rock fractal field. Therefore, the fractal characteristics of AE, EMR and SP signals were widely researched. Yin et al. [18] researched the strength fractal features of AE in process of rock failure. Wang et al. [19] studied the fractal characteristics of b values with microseismic activity in deep mining, and Li et al. [20] studied the b-value and fractal dimension of AE during rock failure process in laboratory. In order to verify the universality of fractal characteristics about AE, Wu et al. [21] discussed the fractal dimension of AE serials of different rocks under uniaxial compression and obtained the similar results. About coal containing gas, Kong et al. [22] explored the relationship of AE fractal characteristics (correlation dimension) with time, and found the fractal dimension of AE developed from chaos to orderly state, which could be used as a precursory signal of coal sample fracture. Except for AE, The critical phenomena and fractal characteristics of EMR were observed before seismic or rock fracture [23–27].

The above researches are about the simple fractal of AE and EMR, but they can't explain the forming mechanisms of geophysics signals responses with time. Multifractal has attracted the scholars

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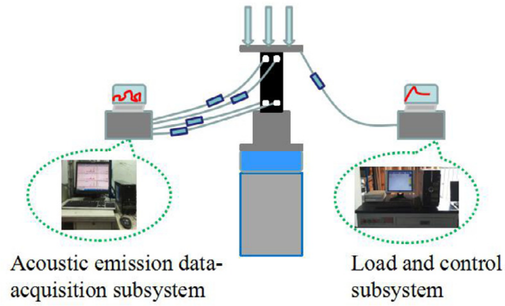

Fig. 1. Experimental system.

attention, because almost everything has multifractal characteristics [28–32]. Liu et al. [33] analyzed multifractal characteristics of SP of coal sample under uniaxial compression and researched the failure mechanism of coal under the load. Hu et al. [34] studied time-varying multifractal characteristics and formation mechanism of loaded coal EMR and concluded that dynamic multifractal spectrum was the objective response of EMR signals, which could be used to evaluate the coal deformation and fracture process. Kong et al. [35] discussed the multifractal laws of AE at the different stress level, and summarized that the mutltifractal of AE signals about sandstone under different temperature were of similar laws.

Due to lack of AE mechanism research, it is not clear about AE signals changes with time. And it is urgent to reveal the mechanism of AE signals formed during coal or rock fracture. In this paper, the coal samples were subjected to uniaxial compression, and the AE counts signals were collected to analyze time-varying AE laws during loading process. Based on the time-varying multifractal theory, the multifractal characteristics with load and time were researched. This research is helpful for us to understand the cracks evolution and the causes of AE signals responses, which provides significant guide to the early warning of coal deformation or fracture underground coal mines.

2. Experiments

2.1. Experimental system

As shown in Fig. 1, the experimental system consists of an axial loading subsystem (YAW4306), which is an electrohydraulic servo pressure-testing machine controlled by a microcomputer, and an acoustic emission data-acquisition subsystem (AEwin Test for Express-8.0). The experimental parameters were as follows: the loading rate was 20 N/s, the sampling frequency was 500 kHz and the threshold value was 45 dB.

2.2. Coal samples preparation

Coal bulks were collected from DaAnshan mine of Beijing, China. Then the samples of 50 × 50 × 100 mm size were made from the raw coal bulk. Among the various samples prepared, we chose 6 samples. The nonparallelism of two ends about the selected coal samples were less than 0.05 mm.

3. Time-varying characteristics of acoustic emission

During loading process, AE data were collected in real time. Fig. 2 showed AE responses during the whole loading process. The AE responses curves of each specimen was almost similar, and according to the curve of accumulative counts, it could be divided into 4 stages, such as quiet phase, linear increase stage, rapid increase stage and saturation period. Therefore, the AE accumulative counts curve could also characterize the loading and deformation failure process of the specimen.

(1) *Quiet phase:* During initial loading stage, the fissures contained in the sample were compacted, so there were a few AE events. Accordingly, the accumulative AE counts curve was close to 0, which was defined quirt phase.
(2) *Linear increase stage:* When coal loading entered into elastic deformation stage, AE events counts maintained a steady value. Therefore, the accumulative AE counts curve showed in linear increase. The elastic deformation was reversible, which could recover to original state. However, it was inevitable to be formed micro-damage with fewer AE events.
(3) *Rapid increase stage:* Approaching the peak load, AE counts suddenly started to increase. In the vicinity of the peak load, AE counts reached the maximum. When the load exceeded the uniaxial compressive strength of the specimens, the specimens were fractured. Cracks expanding and linking or sample fracture would lead to much more AE responses. Compared with the previous stages, fracture size was larger, so AE counts increased rapidly and the accumulative counts curve was of slope within larger value.
(4) *Saturation period:* After sample fracture, the corresponding load experienced a sudden drop. The loading entered the residual deformation phase, the cumulative counts curve of AE tended to be in stationary phase, indicating that after the failure of the sample, cracks evolution gradually stopped.

4. Time-varying multifractal of AE

4.1. Multifractal theory

The concept of fractal was introduced by Mandelbrot to describe and evaluate irregular, complex existent forms in nature [16]. In the following, multifractal theory was proposed to describe unstable phase and disordered media [28–32]. Many scholars have applied this theory to study AE characteristics in failure process of coal or rock [22,35].

AE counts can reflect the deformation and failure process of coal or rock and reveal their spatiotemporal dynamic characteristics. Assuming that an AE time series $\{x_i\}$ can be divided into N subsets of length ε, the probability distribution of each subset is calculated as $\{P_i(\varepsilon)\}$. If the time series meet multifractal characteristics, the probability distribution function $\{P_i(\varepsilon)\}$ and divided scale ε as $\varepsilon \to 0$ obey the following equation:

$$\{ P_i(\varepsilon)\} \propto \varepsilon^{\alpha} \tag{1}$$

where i is a sign of the AE data changing over time, which reflect the amount of AE data. α is a constant known as the singularity exponent, which controls the singularity of the probability function $\{P_i(\varepsilon)\}$, and reflects the various divided scale ε of the time series.

If the number of units with the same probability in the subsets marked by α is denoted as $N_\alpha(\varepsilon)$, the smaller the divided scale ε, the more the number of subsets obtained. Therefore, $N_\alpha(\varepsilon)$ decreases with ε and meets the following relationship:

$$N_\alpha(\varepsilon) \propto \varepsilon^{-f(\alpha)} \tag{2}$$

where $f(\alpha)$ is the frequency of the subset represented by α in the whole subset collection, which is also called the fractal dimension of α subset.

Using this definition, however, it is difficult to calculate fractal dimension. Thus, the statistical physics method is generally applied to compute multifractal spectra. Partition function is defined as follows:

$$X_q(\varepsilon) \equiv \sum P_i(\varepsilon)^q \sim \varepsilon^{\tau(q)} \tag{3}$$