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Use of ultra-low-frequency electromagnetic emission to monitor stress and failure in coal mines

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ABSTRACT

Using an established acoustoelectric signal testing system, we conducted a series of experiments on coal rock samples of lower strength under uniaxial compression and shear loading to study the characteristics of ultralow frequency (ULF) electromagnetic radiation (EMR) signals emitted during their damage and failure, compared them with signals of very low frequency (VLF) (5 kHz), middle frequency (MF) (300 kHz) and acoustic emission (AE) (42.3 kHz), and explored the generation mechanism of this ULF EMR. Using our self-developed ULF signal acquisition instruments, we monitored the ULF EMR signals at the mining face, and studied the space and time distribution laws of ULF EMR in the front of the mining face. The results showed that the coal rock materials subject to uniaxial compression and shear loading can produce ULF EMR signals, which are well correlated with stress, and AE signals. The ULF signals emitted from the two processes are caused firstly by the changes in the induction field due to charges moving and secondly by the piezomagnetic effect resulting from some metal minerals in the coal rock materials after applying stress. Under rock pressure in mines, the coal mass ahead of the face during its deformation and failure emits strong ULF EMR with a strong ability to resist interference. The time and space distributions of these EMR are well correlated with stress in coal mass in the front of the mining face.

1. Introduction

Marble, granite and other hard rocks are capable of generating magnetoelectric radiation (EMR), which has been confirmed by many studies on earthquakes. When these hard rocks are loaded to a certain load level, they emit EMR in some radio bands [1–7]. For some coal rock masses of lower strength, most researchers focused mainly on a radio frequency band above 3 kHz and found that coal rock deformation and failure can generate EMR signals from very low frequency (VLF) to middle frequency (MF) (3 kHz–3 MHz), and the emission law and the generation mechanism of different band EMR signals were different [8–12]. Rabinovitch [13] experimentally explored the stagewise characteristics of EMR signals and presented his model of LF–MF EMR generated by oscillating dipoles formed at the tips of cracks [14]. Frid et al. [15,16] investigated the characteristics of coal rock EMR and the relationships between EMR and loading to which coal rock is subject, the drilling bits, and the like, and used these to forecast coal gas outbursts and rockbursts, as well as to monitor changes in stress in rock mass. He and Wang et al. [17–21] systemically explored the effects of coal rock EMR (above the VLF band, mainly in the range of 3 kHz–3 MHz), its time-domain variations, spectral characteristics, memory effects, correlations to loading, non-linear characteristic and generation mechanism. They proposed the mechanism of EM emission generated by the stress-induced polarization of coal rock mass, i.e., the inhomogeneous, variable deformation caused by coal rock subject to stress resulting in the generation of electric dipole groups, as well as the mechanism of EMR generation by non-uniformly moving charged particles. They further developed EMR forecasting and early-warning technologies and devices (including portable and on-line equipment) and successfully applied them to forecast coal and gas outbursts, rockbursts, and the goaf roof stability, and to assess the stress distribution state in coal rock mass, and thus realized continuous monitoring and forecasting of coal rock dynamic disasters in some small areas (less than 22 m).

Based on the requirements of forecasting dynamic disasters in the vicinity of the working face or coal wall, currently developed EMR

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monitoring technologies and equipment are orientated to EMR in the range of 3 kHz–500 kHz and a monitoring area within about 7–22 m generally. Thus, it was impossible to measure dynamic disasters over a longer distance and on a larger scale with these technologies and equipment. Although they were originally less interfered by mining, transportation machinery, and working cables beyond about 2 m, with the level of integrated mechanized mining significantly increasing in recent years, their interfering range increased to greater than 10 m, especially in large or extra large coal mines in which high-powered mining, transportation, and communication machineries are operating. In some cases electricity has to be shutoff, resulting in discontinuous testing. For impacts or roof disasters induced by long distance roof movement or mining activities, especially top caving of thick coal seams (>8 m), it is impossible to observe obvious EMR responses.

Compared with the most studied coal rock EMR bands, the EMR signal of ULF band (300 Hz–3 kHz) has fewer interfering factors and a longer propagation distance, which make it significant for forecasting coal rock dynamic disasters. However, studies on whether coal rock material of lower strength could emit ULF signals during its damage and failure, and if so how the signal changes, have not yet been reported. In this study we first discussed the characteristics of ULF signals generated by coal rock samples subject to uniaxial compression and shearing, then compared them with those of VLF (5 kHz), MF (300 kHz) and AE (42.3 kHz) signals, and further explored the generation mechanism. Based on the results, we developed a ULF EMR signal acquisition system, used it for real-time mining face monitoring, and further studied the time and space distributions of ULF EMR signals in the front of the mining faces. This study is of importance to complete the coal rock EMR theory, develop coal rock EMR technology research, and further reveal the mechanism of coal rock dynamic disasters.

2. Experiments

2.1. Sample preparation and experimental program

2.1.1. Samples

Coal samples were mined from Tongjialiang Mine, Datong, Shanxi Province, China, and Sanhejian Mine, Xuzhou, Jiangsu Province, China, while rock samples were taken from Sanhejian Mine, Xuzhou, Jiangsu Province, China.

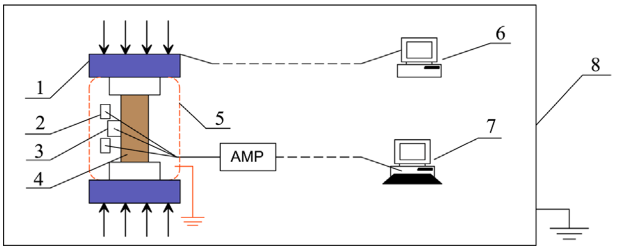

Fig. 1. Coal and rock acoustoelectric signal test system. (1) Press machine, (2) ferrite antennae, (3) AE sensor, (4) sample, (5) electromagnetic shield, (6) load control system, (7) AE and EMR acquisition system, and (8) electromagnetic shielding room.

According to the size standards of the International Society for Rock Mechanics (ISRM), we prepared coal rock samples at the Strata Control Experimental Center of State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology. Parts of the coal and rock samples, after being cored, were prepared as cylindrical samples of 50 mm diameter and 100 mm length; the remaining parts were prepared as cubic samples of 50 mm × 50 mm × 50 mm and as cuboidal samples of 50 mm × 50 mm × 30 mm.

All of the samples were given label numbers and put in an airtight glass container sealed with vaseline to keep their original states.

2.1.2. Experimental system

The acoustoelectric signal test system is the core part of the experimental arrangement (Fig. 1). It was mainly composed of the loading system, data acquisition system, and electromagnetic shielding system. The performances and physical parameters of the test system are given as follows:

(1) The loading system is a YAW4306 computer-controlled electrohydraulic test machine with maximum load capacity of 3.0×10^3 kN, test force resolution of 1/300,000 full-scale with relative error of 1%, and loading speed of 600–60,000 N/s with accuracy of ±1%. YAW4306 has two control modes, the displacement and the force load, and can be used for uniaxial compression and tension, cyclic loading and creep tests.

(2) The data acquisition system is a PCI-2 AE system manufactured by PAC (Physical Acoustic Corporation). It has a board with 18-bit A/D conversion scheme, eight digital I/O, and two complete high-speed channels of real time data acquisition. It has such important functions as the real time feature extraction, waveform processing and transfer. Its range of frequency response is from 3 kHz to 3 MHz (at -3 dB points)

(3) The EM shielding system is an EM shielding room GP6.

(4) The AE signal sensor is an AE sensor of 42.3 kHz resonant frequency, and ferrite antennae of 1 kHz (ULF), 5 kHz (VLF) and 300 kHz (MF) resonant frequencies were incorporated for measurement. In the experiment, the ferrite antennae were set around the sample at less than 10 cm distance, while the AE sensor was positioned with glue tape on the walls of the coal rock samples with its bottom surface coupled with a vaseline coupling agent to ensure that it can well receive the elastic waves generated by coal rock deformation and failure.

2.1.3. Experimental program

We carried out a series of experiments with uniaxial compression and shear loading on the coal and rock samples, respectively, and investigated the characteristic changes in EM and AE signals generated from the coal and rock samples as well as in stress in the coal rock mass during sample failure. The detailed experimental programs are listed in Table 1.

Table 1
Experiments of low-frequency EM signals from loaded coal rock samples during their destruction

Sample type	Method	Loading mode	Loading path	Sample size
Raw coal from Sanhejian Mine	Uniaxial compression	Force control	1000 N/s	$\varnothing 50\times100$ mm^2
Raw coal from Tongjialiang Mine	Shearing	Displacement control	0.5 mm/s	$50\times50\times50$ mm^3
Roof sandstone from Sanhejian Mine	Uniaxial compression	Displacement control	1 mm/s	$\varnothing 50\times100$ mm^2
Roof sandstone from Sanhejian Mine	Shearing	Displacement control	1 mm/s	$50\times50\times30$ mm^3