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Study on Infrasonic Characteristics of Coal Samples in Failure Processunder Uniaxial Loading

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ABSTRACT
To study the precursory failure infrasonic characteristics of coal samples, coal rock stress loading system and infrasonic wave acquisition system were adopted, and infrasonic tests in uniaxial loading process were made for the coal samples in the studied area. Wavelet filtering, fast Fourier transform, and relative infrasonic energy methods were used to analyze the characteristics of the infrasonic waves in the loading process, including time domain characteristics, and relative energy. The analysis results demonstrated that the frequencies of the infrasonic signals in the loading process mainly distribute within 5–10 Hz, which are significantly different from noise signals. The changes of the infrasonic signals show clear peri- odic characters in time domain. Meanwhile, the relative energy changes of the infrasonic wave also show periodic characters, which are divided into two stages by the yield limit of coal samples, and are clear and easy to be recognized, so that they can be used as the precursory characteristics for recognizing coal sam- ple failures. Moreover, the infrasonic waves generated by coal samples have low frequency and low attenuation, which can be collected without coupling and transmitted in long distance. This study pro- vides an important support for the further in-situ prediction of coal rock failures.
Keywords: *Infrasound Relative energy Time-frequency analysis Failure prediction entification feature*

I. INTRODUCTION

Infrasonic waves mainly refer to the acoustic waves with fre- quency between 0.01 Hz and 20 Hz [1], which has the characteris- tics of low frequency and long wave length. Diffractions are easy to happen when they encounter obstacles in transmission. Therefore, the attenuation of them is low in transmission, and long distance transmission is easy to be realized [2]. Infrasonic waves often gen- erate in the brewing or occurring process of natural disasters, including earthquakes, volcanic eruptions, tsunamis, landslides, mud rock flows, sea storms, tornadoes, and so on [3–6]. To analyze the relation between infrasonic waves and geologic body failures, researchers have carried out studies from laboratory tests which are easy to be realized. Large numbers of failure tests have been made on granites, marbles, limestones, etc. It has been found that infrasonic signals generate in the stress process of rocks [7,8]. Then, infrasonic tests in uniaxial loading process have also been made for rock samples with different lithologies. The frequency, amplitude, energy characters, and the effect of lithology on the fre- quency characters of infrasonic waves were also analyzed [9,10]. Many experimental results have shown that the difference between the infrasonic characteristics of rock samples is the exter- nal representation of rock failure strength, failure time, etc., and monitoring research can be made for rock failure according to infrasonic characteristics.

With the constant and profound study on infrasonic waves, they have gradually achieved the favor of researchers in the field of nat- ural disaster prediction, since the attenuation and the loss of source message of them are both low in transmission process. According to the monitoring of the infrasonic signals in landslide process, the features and rules of infrasonic information in differ- ent deformation stages of landslide masses have been analyzed. It has been found that the sound waves caused by rock fracture and friction in the impending sliding stage of landslide masses mainly concentrate within infrasonic frequency (2–15 Hz) [11]. The abnormal pre-quake sound wave signals of 92 earthquakes stronger than 7.0 magnitude around the world during 2002–2008 were analyzed, and it was observed that the abnormal infrasonic signals were in good accordance with the occurrence of earth- quakes, with the frequency of abnormal infrasonic signals on The process of coal mine geological disasters is also the process of deformation and destruction of coal and rock bodies, which is very similar to the generation process of natural disasters, includ- ing earthquakes, landslides, and so on. To predict the geological disasters in coal mines, some researchers have carried out studies on the concomitant phenomena of geological disasters, and pre- dicted disasters according to the characteristics of such concomi- tant phenomena. Currently, most applied prediction technologies include acoustic emission monitoring, electromagnetic radiation, microseismic monitoring technique, and so on [18–20]. Such tech- niques are to some extent accurate in disaster prediction, but they have drawbacks, including coupled contact, large interference, fast attenuation, and so on. To overcome these drawbacks, some researchers have proposed infrasonic prediction technique for coal mine geological disasters, and demonstrated the feasibility of it [21], which reveals the good application prospect of infrasonic waves in predicting coal mine geological disasters. However, to predict coal mine geological disasters by monitoring infrasonic characteristics, the response characteristics of the infrasonic waves in the deformation and failure process of coal bodies should be understood at first. Currently, there have been few reports on the infrasonic response characteristics in the deformation and failure process of coal bodies, especially for the recognition features of the precursory failure infrasonic waves of coal samples. Therefore, in this study, tests and analysis were made for the infrasonic response characteristics of coal samples in uniaxial loading pro- cess. The relation between the deformation stage of coal samples and the infrasonic responses was established, and the recognition features of the precursory failure infrasonic waves were deter- mined, providing guidance for applying infrasonic technology in predicting coal mine geological disasters.

Infrasonic test experiment

Experimental principle and equipment

In the loading process, due to the existence of weak surfaces of coal samples, the internal force of coal sample is uneven, causing local deformation and air coupling effect, and generating sound waves with different frequencies. As the external representation, sound waves record the evolutionary process of the deformation and failures of coal samples. By monitoring and recording the infrasonic waves generated in the loading process through infra- sonic monitoring devices, the deformation process of coal samples can be indirectly recorded.

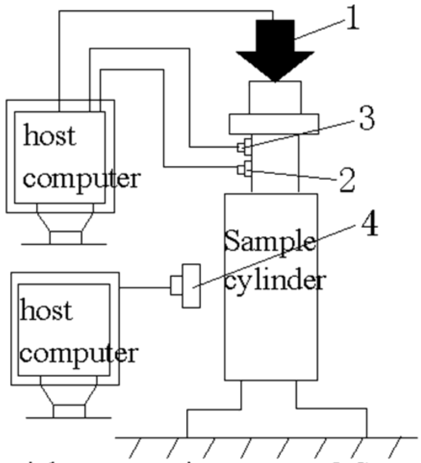
Coal rock creep seepage device, independently developed by Henan Polytechnic University, CASI-ISM-2013 high precision capacitive infrasound acquisition system, developed by Institute of Acoustics, Chinese Academy of Sciences were adopted for experimental device. The device mainly includes axial compression system, stress strain collection system, infrasound acquisition/ analysis system, as shown in Fig. 1.

(1) Stress loading system

The stress loading system is controlled by full digital computer program, which automatically save and display the collected data, with advantages of high resolution, high control accuracy, and low failure rate, guaranteeing the reliability of experimental data. The axial stress loading system can realize loading stress from 1 kN to 500 kN. Stress sensor mainly monitors the axial stress, with monitoring range of 0 kN–500 kN, and test force resolution is less than 2.5 N. Translation sensor mainly monitors axial translation, with monitoring range of 0–150 mm and translation resolution is less than 0.002 mm.

(2) Infrasound acquisition system

The infrasound collection system uses infrasound sensor to transform non-electric signals into electric signals. The signal is amplified by an amplifier and then transmitted to a digital network transmission acquisition device for storage. The working principle of the sensor is shown in Fig. 2. A metallic diaphragm acoustic compliance and a metal plate form a capacitor. The metallic dia- phragm vibrates under the effect of external infrasound, making the distance d between plates change, and reflecting the capacitor change. The capacitor change realizes the transform from non- electric signals to electric signals. The variation of capacitor reflects the information of infrasound.
According to the basic principle of capacitance, capacitance can be expressed as:



1.Axial compression system;2.Stress transducer; 3.strain transducer; 4.acquisition system of infrasonic wave.

Fig. 1. Schematic diagram of experimental apparatus.

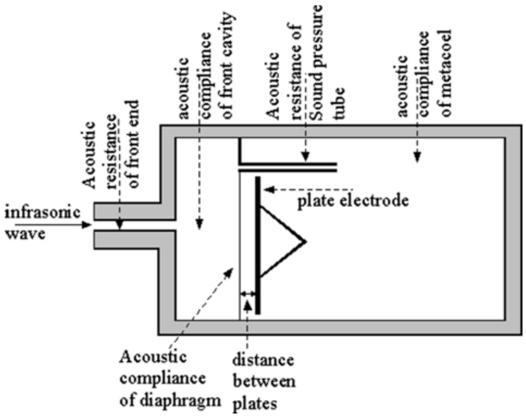


Fig. 2. Work principle diagram of CASI-ISM-2013 infrasound sensor.

$$C = \frac{\varepsilon S}{4\pi k d} \qquad (1)$$

where C-capacitance, F; e-constant of dielectric, F/m; S-area of par- allel plate, m^2; k-constant of electrostatic force; d-spacing of paral- lel plate, m; when the change of d is Dd, the change of capacitance isas follow:

$$\Delta C = \frac{\varepsilon S}{4\pi k(d - \Delta d)} - \frac{\varepsilon S}{4\pi k d} = C_0 \frac{\Delta d}{d - \Delta d} \qquad (2)$$

where C_0-the initial capacitance value, when the plate spacing is d.
The sensitivity of the sensor is 328 mv/Pa, with measuring fre- quency range of 0.001 Hz–100 Hz. Network transmitter uses 16 bit quantization, with arbitrary sampling frequency within 0.1 Hz– 250 kHz, and quantization error is less than 0.003%.

Coal sample making and experiment scheme

According to the requirements for coal sample collection and production in rock mechanics test experiments, the coal samples were collected from the fresh coal walls in study area, and then stored hermetically. In laboratory, liquid nitrogen cooling type cut-ting machine and drilling machine were used to make the coal samples into standard columnar samples of u50mm 100 mm, with the size and surface smoothness of coal samples satisfying the test requirements for rock mechanics. A total of 8 coal samples were made, two of which are spare samples.

During the loading process for infrasound test, due to the low frequency and attenuation of infrasound, and for analyzing the feasibility of non-coupling collection of infrasonic signals, non- coupling was adopted for sensors and coal samples, and sensors processing was made for the high frequency coefficients, and the processed coefficients were used for reconstruction.
were fixed with a distance of 40 cm away from coal samples.
The main test steps are as follow:

A. Number the coal samples; Test and record the size of coal samples;
B. Put the test coal samples into a sample jar, and connect the stress loading system and data acquisition system;
C. Fix the infrasonic sensor, and connect the infrasonic acquisi- tion system;
D. Set collection parameters for infrasonic waves with sam- pling frequency 100 Hz, and start environmental noise test; when the environmental noise test result is relatively stable, go to next step; when the environmental noise fluctuates dramatically, it is better to choose another time period to test;
E. Perform loading parameter test in force control mode, the loading speed 0.20 kN/s;
F. Set collection parameters for infrasonic waves with sam- pling frequency 100 Hz;
G. Synchronously start stress loading device and infrasonic wave collection device; collect the infrasonic signals in load- ing process until the sample completely fails, and automat- ically record and save the test data.

Test data processing method

Filtering and denoising

The purpose of filtering is to filter the test signals and preserve the sound signals in required frequency section. Butterworth filter was designed by setting passband/stopband frequency, and pass-band/stopband attenuation. Ideally, filtering is realized by setting the internal coefficient of the passband of this filter to 1, while the coefficient of the stopband to 0. The passband range of the filter was set to 0.01–20 Hz. By filtering the collected signals through this filter, the test signals outside the analyzed frequency section was removed.

The purpose of denoising is to remove the noise interference in the test result. Similarly, it was realized by using Matlab and self- coded wavelet denoising program. By comparing the decomposi- tion results with different layers, it was found that decomposing signals into 6 layers can not only remove noise, but also reduce sig- nal distortion as much as possible. Then, heuristic thresholding method was used to obtain the threshold. Finally, soft thresholding processing was made for the high frequency coefficients, and the processed coefficients were used for reconstruction.

Time-frequency analysis

In signal analysis, not only the features of the signals in time and frequency domain should be known, but also the change char- acters of frequency domain with respect to time should be under- stood, which is the basis of dynamic analysis. Therefore, the analysis in time domain should be combined with that in fre- quency domain, which is the time-frequency domain integrated analysis. To realize approximately dynamic analysis, time window function is introduced. By consecutively intercepting sections of signals through a time window, the signal within a limited time period (delimited by the same time window) is considered to be stable. Then Fourier transform is used for analysis, and this is short time Fourier transform. The short time Fourier transform for the filtered and denoised signals is expressed as follows.

$$X(f;t) = \int_{-\infty}^{\infty} f(\tau)\, w(\tau - t)\, e^{-2\pi i f \tau}\, d\tau \qquad (3)$$

where $X(f;t)$-time-frequency function after transformation; f-fre- quency, Hz; t-time, s; $f(\tau)$- filtered signal; $w(\tau - t)$-analysis win- dow; τ-limited time, s.

Relative energy

In infrasound parameter test process, the main tested parame- ter was the variation parameter of amplitude with respect to time. However, amplitude represents the vibration extent of signals, which can somewhat reflect the energy degree of signals. There- fore, previous studies on energy calculation were combined. The relative energy can be expressed as:

$$E = \int |f(t)|^2 dt \tag{4}$$

where E-relative energy, 1; $f(t)$-amplitude function of sound waves; t-time, s.

The infrasound sensor records a discrete time series, so its cumulative relative energy can be expressed as:

$$E_0 = \sum_{M}^{N} |f(t_i)|^2 \frac{1}{F} \tag{5}$$

where E_0-the accumulated relative energy from M/F time to N/F time, 1; $f(t_i)$-Amplitude of sound waves at the i-th sampling point; n-Total number of samples, 1; M,N-number of samples; F-sampling frequency, Hz.

According to formula (5), in a certain period of time, the relative energy in the other frequency band can be expressed as:

$$E_1 = \sum_{M}^{N} |g(t_i)|^2 \frac{1}{F} \tag{6}$$

where E_1-the relative energy in the other frequency band in a certain period of time, 1; $g(t_i)$-The amplitude of the acoustic wave corresponding to the i-th sampling point after band-pass filtering of $f(t_i)$

In a certain period of time, The ratio of the infrasound relative energy in the other frequency band to the accumulated relative energy can be expressed as:

$$d = \frac{E_1}{E_0} \tag{7}$$

where d-the ratio of the infrasound relative energy in the other frequency band to the accumulated relative energy

Results and discussions

According to the experimental scheme and requirements, infrasonic tests under uniaxial loading were performed for coal samples, and the above data processing method was used to process the data. It was found by analysis that the change characteristics of the infrasonic waves of the 6 coal samples are the same, with the same change mechanism. Therefore, to avoid repetition, the first 2 coal samples are detailedly demonstrated.

Environment noise analysis

To reduce the interference of abnormal signals in environmental noise to the tests, the real infrasonic signals in coal rocks were obtained as much as possible. The environmental noise was tested before experiment, with the test result shown in Fig. 3. Short time Fourier transform was used for time-frequency analysis of test result, with analysis result shown in Fig. 4.

It is clear from results of the noise signal test that the environmental noise signals were relatively stable with few abnormal signals and small changes in frequency and amplitude with respect to time. Moreover, the frequency of the environmental infrasonic noise mainly distributed below 5 Hz. In such test environment, the interference of noise signals to test signals was little, which was conducive to the post-processing of signals and obtaining test signals with high signal-to-noise ratio.

Stress-strain test results

According to the experimental scheme, stress-strain-time tests under uniaxial loading were made for coal samples. To the convenience of analyzing the relationship between infrasonic waves and coal sample deformation, the stress strain time curve of coal samples is drawn and shown in Fig. 5.

According to the stress strain time curve of coal samples, it is clear that the stress-strain of the coal samples in the loading process shows periodic characteristics, which can be divided into compaction, elastic deformation, plastic deformation, and post peak failure stages. In this study, the main task is to analyze and predict coal sample failure. Therefore, we focus on analyzing the infrasonic characteristics of coal samples before and after reaching yield limit. When the coal samples reached yield limit, the corresponding stress, strain, and time are shown in Fig. 5.

For (a) coal sample, when loading was performed to 175 s, the stress became 17.5Mpa, reaching yield limit, and the coal sample deformation changed from elastic deformation into plastic deformation.

For (b) coal sample, when loading was performed to 230, the stress became 20.5Mpa, reaching yield limit, and the coal sample deformation changed from elastic deformation into plastic deformation.

Time-frequency characteristics of infrasonic waves

According to the test results, short time Fourier transform was adopted to process the test results. The time-frequency diagram of the transformed infrasonic signals is shown in Fig. 6.

It is clear from the figure that in the loading process, the changes of infrasonic waves showed periodic charactersitics. Combined with the stress strain time test results of coal samples, the change characters of the coal samples in different deformation

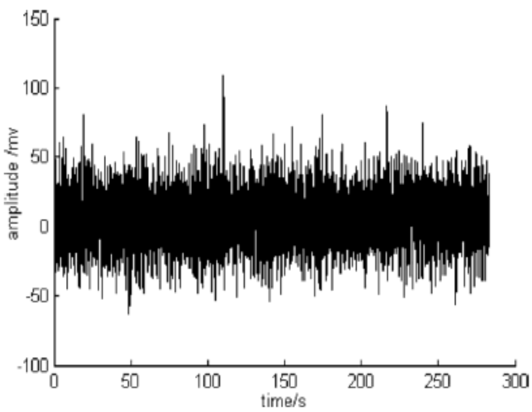


Fig. 3. The tested results of environmental noise signal.

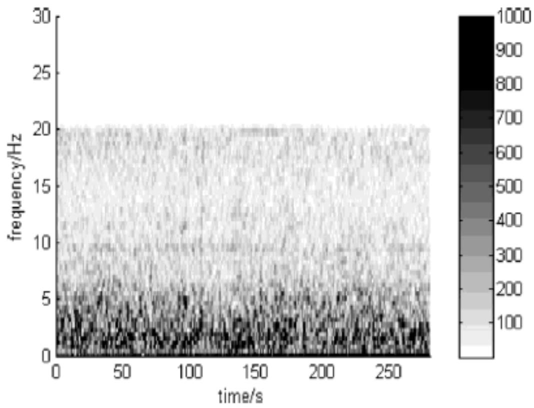
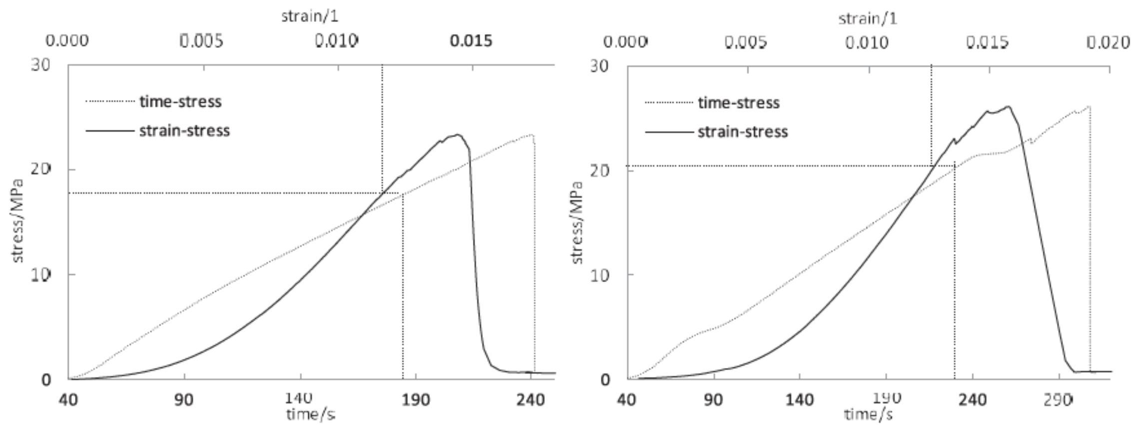


Fig. 4. Time-frequency diagram of environmental noise signal (Grayscale represents the size of the intensity).



(a) (b)

Fig. 5. Results of strain-stress-time of coal samples.

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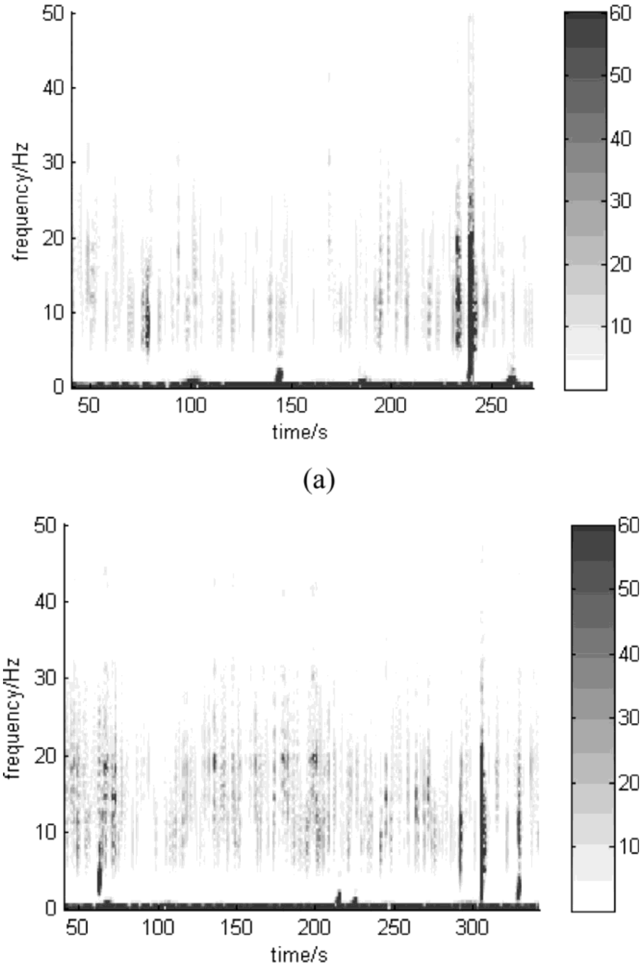


(a)

(b)

Fig. 6. The time-frequency diagrams of infrasonic wave (Grayscale represents the size of the intensity).

stages of coal sample are analyzed, and the detailed changes of infrasonic waves in different stages are as follows.

For (a) coal sample, in early loading stage (40–110 s), a certain number of infrasonic waves generated. This loading stage corre- sponds to the compaction stage of coal sample deformation. The deformation of coal samples in this stage is mainly dominated by the closure of cracks between particles. Due to the closure of cracks between coal particles, some angular contact surfaces or crack ends on crack surfaces fail, causing some infrasonic events. In mid- dle loading stage (110 s–180 s), the strength of infrasonic waves was generally small. This loading stage corresponds to the elastic deformation stage of coal sample deformation. The deformation of coal samples in this stage is mainly dominated by the elastic deformation of coal particles, and there are few failure regions in this stage, with sporadic infrasonic events generated in regions where local stress concentrates. In late loading stage (after 180 s), the strength of infrasonic waves rapidly grew, and maintained at a high value. This loading stage corresponds to the plastic failure stage of coal sample deformation. The deformation of coal samples is mainly dominated by plastic failure. With the increase of stress, local regional failures occur when the stress reaches the local load limit of coal samples, and infrasonic events generate. Moreover, with the increase of local failure regions, the overall bearing capac- ity gradually lowers, and the overall failure occurs when the bear- ing capacity is insufficient. Therefore, the strength of infrasonic waves in this stage was the largest.

For (b) coal sample, in early loading stage (40–146 s), some infrasonic waves were generated. This loading stage corresponds to the compaction stage of coal sample deformation. The deforma- tion of coal samples in this stage is mainly dominated by the clo- sure of cracks between particles. In the process of crack closure, since a part of angular contact surfaces and local weak surfaces on fracture surface failed, a certain number of infrasonic events happened. In middle loading stage (146–235 s), the strength of infrasonic waves was generally small. This loading stage corre- sponds to the elastic deformation stage of coal sample deforma- tion. The deformation of coal samples in this stage is mainly dominated by the elastic deformation of coal particles, and there are few failure regions in this stage. Therefore, the strength of infrasonic wave is weak. The late loading stage (after 235 s) corre- sponds to the plastic failure stage and post peak failure stage of coal sample deformation. The deformation of coal samples in this stage is mainly dominated by plastic failure, and large number of infrasonic waves generate in the internal failure process of coal samples with relatively high strength.

By analyzing the infrasonic characteristics in the deformation process of coal samples, it can be concluded that the variation of infrasonic waves in loading process shows periodic characteristics, which can be divided into three stages, namely initial stage with certain number of infrasonic events, middle stage with few infra- sonic events, and late stage with rapid growing speed of infrasonic events and high number. Such periodic variation characteristics are dominated by the internal deformation character of coal samples, and are the external representation of internal deformation. It is clear from the period analysis that the division of stages is in accor- dance with the deformation stages of coal samples, especially for the period entering from the elastic deformation into plastic defor- mation of coal samples, and the period entering from the middle stage where infrasonic events are few to the late stage where infra- sonic events grow rapidly and maintain at a high level. The charac- teristics of these two stages are clear and easy to be recognized, which can be used for predicting coal sample failure.

Energy characteristics of infrasonic waves

Energy characteristics of infrasonic waves with different frequency

The generation process of infrasonic waves is the process of releasing accumulated internal energy of coal samples. To analyze the loading process and the frequency characteristics of infrasonic waves, the energy representation method of infrasonic waves in loading process was proposed. According to the above mentioned energy representation method, the ratios of the relative energy of infrasonic waves in different frequency sections, with an interval of 5 s, (0.01–5 Hz, 5–10 Hz, 10–15 Hz, 15–20 Hz) in loading process were calculated, as listed in Table 1.

It is clear from Table 1 that the infrasonic waves generated in loading process mainly concentrate in 0.01-5Hz, with a ratio of 80.3%; a part distributes in 5–10 Hz, and a very small part dis- tributes in 10–20 Hz. The infrasonic waves generated by coal sam- ple failures are significantly different from the infrasonic waves generated by environmental noise, and the available signals can be distinguished by frequency characteristics. Meanwhile, in load- ing process, the frequency of a part of infrasonic events distributes in a range of 10–20 Hz, where very few noise signals exist. There- fore, the characteristics of the infrasonic signals in this frequency section can be used for analyzing and predicting the deformation and failures of coal samples.

Cumulative relative energy characteristics of infrasonic waves in low frequency section

According to the relative energy representation method for infrasonic waves, 5 s was set as an interval, and the cumulative rel- ative energy of the infrasonic waves in 0.01–20 Hz within an inter- val was calculated, resulting in the variation rule of the cumulative relative energy of infrasonic waves with respect to time, as shown in Fig. 7.

It is clear in Fig.7 that the variation of infrasonic waves in the loading process exhibits periodic characteristics, and the detailed variation relative energy of the infrasonic waves in each stage of different coal samples is as follows.

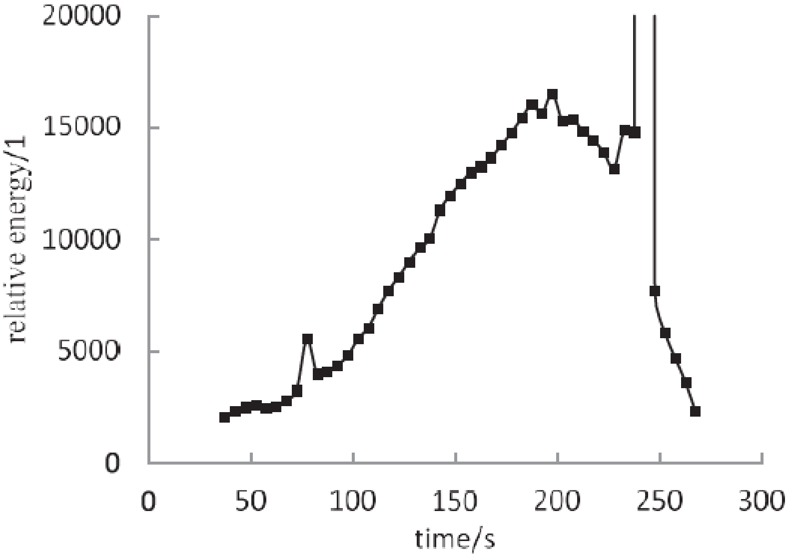
For (a) coal sample, in early loading stage (40–180 s), the rela- tive energy variation showed a linear increasing trend. This loading stage corresponds to the compaction and elastic deformation stages of coal samples. The macro deformation of coal samples in this stage is dominated by compression deformation, which causes

Table 1
The proportion of relative energy in different frequency bands.

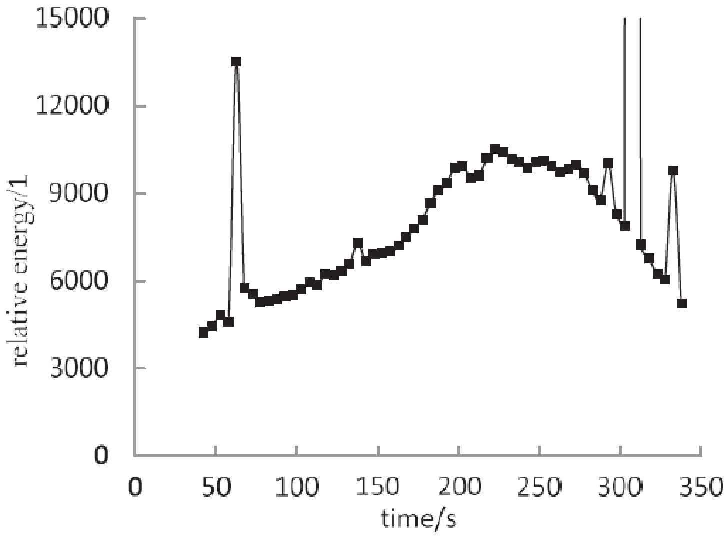
Sample No.	Proportion/1			
	0.01–5	5–10	10–15	15–20
a	0.073	0.555	0.157	0.215
b	0.090	0.533	0.159	0.219
c	0.089	0.547	0.144	0.220
d	0.070	0.384	0.401	0.146
e	0.072	0.576	0.155	0.198
f	0.057	0.694	0.108	0.141
Average value	0.075	0.548	0.187	0.190
Noise	0.803	0.132	0.029	0.036

the coupling of coal samples’ internal deformation and air to gen- erate infrasonic waves. With the increase of compression degree, the relative energy of infrasonic waves shows gradual increasing trend. In late loading stage (after 180 s), the variation of the rela- tive energy showed a slow descending characteristic. This stage corresponding to the plastic deformation stage of coal samples, where the internal deformation of coal samples changes from com- paction dominated deformation to expansion, macroscopically represented as volume increase. According to the expansion theory of seismic wave causes, when the deformation of coal samples changes from compression deformation to expansion, the strength of the generated infrasonic waves significantly decreases, causing the relative energy of infrasonic waves to gradually decrease.

For (b) coal sample, in early loading stage (40–230 s), the relative energy showed a gradual increasing characteristic. This stage corresponds to the compaction and elastic deformation stages of coal samples, where the internal deformation of coal samples is dominated by compression deformation. With the increase of com- pression degree, the relative energy of infrasonic waves shows a gradual increasing trend. In late loading stage (230 s), the variation of the relative energy showed gradual a decreasing characteristic. This stage corresponds to the plastic deformation stage of coal samples, where the internal deformation of coal samples is dominated by expansion, and the strength of infrasonic wave decreases, causing the relative energy of infrasonic waves to grad- ual decrease.



(a)



(b)

Fig. 7. The change of relative energy over time.

In loading process, the relative energy variation of infrasonic waves shows periodic characteristics. According to the differences of variation characteristics, they can be divided into two stages, namely early stage with linear increase, and late stage with gradual decrease. The early stage mainly corresponds to the compaction stage and elastic deformation stage of coal samples, while the late stage mainly corresponds to the plastic deformation stage of coal samples. When the deformation of coal samples changes from elas- tic deformation stage into plastic deformation stage, the variation trend of the relative energy of infrasonic waves changes from lin- ear increase into gradual decrease. The variation characteristics of the relative energy of infrasonic waves is in good accordance with the deformation characteristics of coal samples, and the peri- odic characteristics of the two stages are significant and easy to be recognized, making it possible to use the variation characteristics of the relative energy of infrasonic waves to analyze the deforma- tion stages of coal samples and predict the failures of them.

II. DISCUSSIONS

By analyzing the time-frequency characteristics of the infrasonic waves generated in the loading process, it was found that the vari- ation of infrasonic waves in loading process showed periodic char- acteristics, which can be divided into 3 stages. The division is consistent with the division of the deformation stages of coal sam- ples. By analyzing the variation characteristics of infrasonic waves, the deformation characteristics of coal samples can be inverted and predicted. There have been similar studies, but they mainly focused on the frequency and amplitude of infrasonic waves, while there have been few reports on the relation between the time- frequency characteristics and deformation stages of coal samples.

Using the relative energy representation method of infrasonic waves to analyze the relative energy variation of infrasonic waves in loading process, we found that the relative energy variation of infrasonic waves can be divided into two stages, which have signif- icant periodic characteristics and are easy to be recognized. These characteristics can be used to effectively distinguish the elastic and plastic deformation stages of coal samples. In particular, the change of the relative energy of infrasonic waves from linear increasing trend into gradual decreasing or stable trend indicates the deformation of coal samples enters plastic deformation stage, and failures are about to happen. Previous studies also focused on the precursory failure infrasonic characteristics of coal samples, but only some general variation characteristics were found. This study is the first to propose the precursory failure infrasonic char- acteristics of coal samples and the corresponding relationship between the characteristics and coal sample deformation.

By collecting the environmental noise signals and the infrasonic

signals in loading process, and adopting signal processing methods including wavelet denoising, short time Fourier transform, the recognition characteristics of precursory failure infrasonic waves were determined. Not only were the feasibility of non-coupling collection of infrasonic waves and the reliability of data process method demonstrated, but also the failure prediction method for coal samples is established based on time-frequency characteris- tics and relative energy characteristics of infrasonic waves. Previ- ous studies on failure prediction methods for coal samples were mainly exploratory studies, without establishing concrete predic- tion methods, and particularly, the study on precursory failure recognition characteristics was insufficient.

III. CONCLUSIONS

By analyzing the infrasonic characteristics in loading process of coal samples, the following conclusions are drawn.

(1) Clear infrasonic signals generate in the loading process of coal samples, and they can be collected by non-coupling methods. Moreover, the variation of the infrasonic signals shows significant periodic characteristics in time- frequency domain, which are consistent with the deforma- tion of coal samples, and can be used to predict and invert the deformation of coal samples.

(2) With the proceeding of loading process, the variation of the relative energy of infrasonic waves shows periodic charac- teristics, which can effectively distinguish the elastic and plastic deformation of coal samples. The characteristics are significant and easy to be recognized, which can be used as the precursory failure recognition characteristics of coal samples for predicting coal sample failures;

(3) The precursory failure infrasonic characteristics for coal samples easy to be recognized are determined, a new predic- tion method for coal sample deformation and failures based on the variation characteristics of infrasonic waves is established.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.rinp.2017.11.018.

REFERENCES

[1]. Matozaa RS, Pichona AL, Vergoza J, Herrya P, Lalandea JM, Leeb H, Cheb IY, Rybinc A. Infrasonic observations of the June 2009 Sarychev peak eruption, Kuril Islands: implications for infrasonic monitoring of remote explosive volcanism. J Volcanol Geoth Res 2010;200:35–48.

[2]. Negraru PT, Herrin ET, Golden P. Travel time and signal characteristics of infrasonic arrivals at regional distances. Agu Fall Meeting Abstracts, 2010.
[3]. Marsden O, Bogey C, Bailly C. A study of infrasound propagation based on high- order finite difference solutions of the Navier-Stokes equation. J Acoust Soc Am 2014;135:1083–95.
[4]. Johnsona JB, Asterb RC, Ruizc MC, Malonea SD, McChesneya PJ, Leesd JM, Kyleb PR. Interpretation and utility of infrasonic records from erupting volcanoes. J Agr Food Chem 2009;55:1832–8.
[5]. Feng HS, Tuo XG, Yin F, Yu XP. Software design of monitoring & warning system for infrasonic wave just before landslide sliding. J Southwest Univ National 2010;36:832–5.
[6]. Chen WS, Li JZ, Xia YQ, Liu CY, Chen HQ. Early prediction of great earthquake and Tsunami in Japan and impending signals. J Beijing Univ Technol 2013;39:1206–9.
[7]. Tang LB, Li SY, Su F. Experimental study on precursory low-frequency waves of earth-quakes. Earthq Res China 2003;19:48–57.
[8]. Qin F, Zhang F, Li JZ. Mechanism model of infrasonic wave abnormality before strong earthquakes. J Beijing University Technol 2007;33:104–7.
[9]. Xu H, Zhou TQ. Energy characteristics of infrasound abnormality during rock deformation and failure of rock. Chinese J Geotec Eng 2016;38:1044–50.
[10]. Zhu X, Xu Q, Zhou J, Tang M. Experimental study of infrasonic signal generation during rock fracture under uniaxial compression. Int J Rock Mech Min 2013;60:37–46.
[11]. Zhang N, Yao LH, Wang Q. Study of non-contacted warning methods of the initiation of debris flows. Int Symp Geomat Int Water Resour Manage 2012;23:322–6.
[12]. Liu CY, Liu JY, Chen WS, Li JZ, Xia YQ. An integrated study of anomalies observed before four major earthquakes: 2004 Sumatra M9.3, 2006 Pingtung M7.0, 2007 Chuetsu Oki M6.8, and 2008 Wenchuan M8.0.. J Asian Earth Sci 2011;41:401–9.
[13]. Xia Y, Liu JYT, Cui X, Li J, Chen W. Abnormal infrasound signals before 92M=
[14]. 7.0 worldwide earthquakes during 2002–2008. J Asian Earth Sci 2011;41:434–41.
[15]. Takashi M, Hiroyuki S. Infrasonic sounds excited by seismic waves of the 2011 Tohoku-oki earthquake as visualized in ionograms. J Geophys Res Space Phys 2014;119:4094–108.
[16]. Morrissey M, Garces M, Ishihara K, Iguchi M. Analysis of infrasonic and seismic events related to the 1998 Vulcanian eruption at Sakurajima. J Volcanol Geoth Res 2008;175:315–24.
[17]. Lane Stephen J, James Mike R, Corder Steven B. Volcano infrasonic signals and magma degassing: first-order experimental insights and application to Stromboli. Earth Planet Sci Lett 2013;377–378:169–79.
[18]. Thüring Thomas, Schoch Marcel, van Herwijnen Alec, Schweizer Jürg. Robust snow avalanche detection using supervised machine learning with infrasonic sensor arrays. Cold Reg Sci Technol 2015;111:60–6.
[19]. Jiang XF, Xun L. Application of microseismic monitoring technology of strata fracturing in underground coal mine. Chinese J Geotec Eng 2002;24:147–9.
[20]. Wen GC, Li JG, Zou YH. Preliminary study on the application conditions of acoustic emission monitoring dynamic disasters in coal and rock. J China Coal Soc 2011;36:278–82.
[21]. He XQ, Nie BS, Wang EY. Electromagnetic emission forecasting technology of coal or rock dynamic disasters in mine. J China Coal Soc 2007;32:56–9.
[22]. Wei JP, Liang SJ, Wang YG. Feasibility study on infrasonic wave monitoring dynamic disasters in coal and rock. Prog Geophys 2016;31:0814–20.