Research Article

Time-Frequency Characteristics and the Influence Mechanism of the EMR from Coal with Different Joint Angles

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It is vital to understand the electromagnetic radiation’s time-frequency characteristics in the process of coal and rock failure with different joint angles in order to reveal the generation mechanism of the electromagnetic radiation (EMR) and improve the accuracy of EMR early warning. We studied the time-frequency characteristics of EMR signals of coal samples with different joint angles. The study finds that, (1) with the increase of joint angle, the failure time and peak load of samples decrease first and increase later, and the postpeak failure time decreases gradually. The EMR counts’ peak value showed a slow rise, a sharp rise, and a slow rise in the three intervals of $\alpha = 0^\circ$ to $45^\circ$, $45^\circ$ to $60^\circ$, and $60^\circ$ to $90^\circ$, respectively. The accumulated EMR counts showed a steady upward trend. The duration of the EMR waveform, the dominant frequency of the EMR, and the peak number of the frequency spectrum of coal samples are on the rise. (2) As the joint angle increases, the samples’ failure mode changes from the stage fracture dominated by tension cracks to the rapid fracture with the coexistence of shear and tension cracks and finally to the burst fracture which produces a large number of fragments. This is also the main reason for the difference of the EMR generation mechanism and the signal of samples with different joint angles. (3) According to the experimental results, we established the modified formulas for calculating the EMR threshold value and deviation of coal and rock with joints under different stress environments and revealed that the longer the EMR waveform duration, the higher the dominant frequency, and the more the number of spectrum peaks, the greater the burst risk of coal and rock.

1. Introduction

Under the action of the earth’s internal and external forces, the strata and rock mass form folds, joints, faults, and other geological structures, resulting in complex and changeable geological and stress conditions of underground projects [1, 2]. In the complex geological and stress environment, the strength of coal rock mass rich in joints shows anisotropy, and the EMR and other geophysical signals generated in the failure process are also significantly different, which seriously affects the accuracy of the EMR in monitoring the instability of coal and rock mass with joints. It is urgent to study the fracture mechanical characteristics and EMR signal differences of coal and rock with joints and other defects under complex geological and stress conditions.

Scholars in the field have made fruitful achievements in the study of mechanical properties and geophysical signal characteristics of coal and rock with defects such as joints. In the study of the influence on mechanical properties, Nasseri et al. [3] studied the influence of joints on rock mass strength and stability through laboratory experiments, Cai et al. [4] proposed some theoretical and empirical methods to calculate the strength and deformation capacity of the jointed rock mass, and Yang et al. [5] studied the influence of joints on the strength of rocks and found that there were tensile failure, shear failure, and composite failure in the failure
process of rock samples with joints. In the study of the influence on geophysical signal characteristics, Cha et al. [6] performed research on the influence of joints on the propagation velocity and attenuation of the shear wave in the jointed rock mass. Song et al. [7] characterized the microstructure and anisotropy of coal samples with joints by CT imaging and tested the anisotropy characteristics of AE signals. Mu et al. [8] found that, with the change of joint angle, the impact tendency of coal samples shows a significant difference. Li et al. [9] carried out uniaxial compression experiments on briquettes with different angle macrocracks and considered that macrocracks have a significant influence on the variation law of AE signals. At present, EMR technology has been widely used in dynamic disaster early warning [10–12], earthquake monitoring [13, 14], structural stability of dams and tunnels, stress state detection, and other fields [15–17]. However, studies on the differences of EMR signal characteristics of coal and rock materials with defects such as joints are few.

The phenomenon of EMR is the process that cracks are produced in heterogeneous materials such as coal and rock, which lead to charge accumulation and release, and the released charged particles move at variable speed to generate EMR energy. EMR signal is closely related to the internal structure, composition, and failure mode of coal [18–21]. This is also an important reason that affects the accuracy of the EMR application and urges scholars to study in depth. Fukui et al. [22] tested the EMR of seven types of rocks under uniaxial compression and found that the EMR appeared with stress drop and was related to the damage and deformation of rocks. Li et al. [23] believed that both piezoelectric materials and nonpiezoelectric materials can produce EMR, and the coupling relationship between electromagnetic energy density and charge density was determined. Kong et al. [24] found that the change trend of the EMR signal in the process of sandstone deformation after different temperature treatments is different. Song et al. [25] carried out uniaxial compression tests on rocks with pre-fabricated cracks and found that the presence of precracks reduced the intensity and pulse number of EMR signals in the process of sample failure. The angle between the joint surface and the principal stress will affect the failure mode of samples and also has a significant impact on the EMR signal characteristics. Thus, it is vital to study the difference of EMR signals in the time domain and frequency domain of coal and rock with joints.

Depending on the angle between the drill hole and the joint surface, seven groups of coal samples were drilled and processed, including 0°, 15°, 30°, 45°, 60°, 75°, and 90°. We studied the time-frequency characteristics of EMR signals of samples with different joint angles under uniaxial compression, and the differences are discussed from the perspective of the crack propagation mode and EMR generation mechanism. The guiding significance of the research results to the determination of the critical value of the EMR early warning index is analyzed, and the feasibility of using the EMR frequency-domain signal to evaluate the burst risk of coal and rock is discussed. The study is crucial to deeply reveal the generation mechanism and precursory law of the coal and rock EMR signal and improve the accuracy of EMR early warning of engineering geological damage.

2. Experimental Design and Method

2.1. Sample Preparation. The raw coal used in this experiment is taken from a coal seam with impact tendency. To reduce the effect of the internal structure difference of the sample on the experiment, all samples are drilled in one coal body. As shown in Figure 1(a), the coal samples are made into 7 groups depending on the angle between the coal seam joint surface and the horizontal plane (α), including 0°, 15°, 30°, 45°, 60°, 75°, and 90°. The standard cylinder samples with a length of 100 mm and a diameter of 50 mm are prepared by coring, cutting, and grinding. The joint surface angle of each group of samples is shown in Figure 1(b). Each group contains three samples, as shown in Figure 1(c).

2.2. Experimental System. The experimental system includes the loading control system, EMR monitoring system, electromagnetic shielding system, and data acquisition system, as shown in Figure 2.

The loading control system adopts the YAW-600 electrohydraulic servo pressure testing machine, which has three control modes of test force, displacement, and deformation. The rigidity of the main engine of the testing machine is more than 5000 kN/mm, the maximum test force is 600 kN, the load resolution is 3 N, and the displacement resolution is 0.3 μm. It can display the test state in real time and meanwhile draw the curves of stress-strain and stress-time.

The EMR monitoring system adopts the SAS-560 ring electromagnetic antenna with the response frequency range of 20 Hz–2 MHz. It has two channels of 10 kHz–10 MHz and two DCs~10 MHz. The impedance is 50. The amplifier amplifies the signal (80 dB) in advance, and then it connects six gears (30, 16, 8, 4, 2, and 0 dB) for the adjustable attenuation output.

To ensure the accuracy of the data collected in the experiment process and eliminate the interference of the environmental electromagnetic field on the experimental signal, before the experiment, we first determined the EMR threshold based on the EMR signal collected in the no-load state. All experiments are conducted in the EMR shielding room. Adopting the GP1A electromagnetic shielding room, the comprehensive shielding efficiency is above 75 dB.

The data acquisition system has 12 data acquisition channels, the highest sampling frequency is 10 MHz, and the A/D conversion accuracy is 16 bits. The system can simultaneously collect EMR, load, and other signals in a full-waveform, real-time, and synchronous manner.

2.3. Experimental Scheme. Firstly, 7 groups of coal samples are numbered, and the diameter, height, and other parameters of samples are measured, as shown in Table 1. Then, connect the experimental system, debug and test, and make it run normally. The coal sample and ring electromagnetic antenna shall be arranged so that the antenna is placed vertically against the coal sample, with a distance of 7 cm. Adjust the
press, set the preload to 500 N, and load by the displacement control, and the loading rate is 55 \( \mu \text{m s}^{-1} \). After debugging, close the EMR shielding room door. Before the experiment, the high-speed EMR data acquisition system was opened to display the monitoring data in real time. After the coal sample is destroyed, the experimental data are saved, and the image information during the experiment is recorded. After the experiment, the next group of experiments was carried out.

3. Experimental Results and Analysis

3.1. Mechanical Characteristics of Samples with Different \( \alpha \).
The size and mechanical data are shown in Table 1. In view of the similarity of mechanical characteristics of three samples in each group, we analyzed the time-load curve of the first sample in each group, as shown in Figure 3. There are a lot of load fluctuations in the time-load curve of samples with...
α = 0° and 15°, which indicate that the fracture is accompanied by the whole loading process of samples; a small amount of load drop occurred in the loading process of samples with α = 30° and 45°, which indicates that the coal samples had less fracture during the loading process; the time-load curve of samples with α = 60°, 75°, and 90° is relatively smooth, and there is no fluctuation before and after the peak load, which indicates that the sample is destroyed at the moment of reaching the peak load.

We analyzed the average values of the peak load, failure time, and postpeak failure time of samples with different α statistically. Because there is gangue in the second sample with α = 30°, its peak load is much greater than the other two samples, so it will be discarded in statistical analysis. It is shown in Figure 4 that, with the increases of α, both peak load and failure time decrease first and increase later. The maximum and minimum values of peak load appear in α = 75° and α = 30°. The longest and the shortest failure time also appear in α = 75° and α = 30°. As α changes from 45° to 60°, the peak load and failure time hugely increase; as α changes from 0° to 30°, the postpeak failure time declines hugely and then remains at a low level after 30°. From the above rules, it is found that the mechanical characteristics of the seven groups of samples show significant differences with 30° and 75° as the dividing points.

3.2. Time-Domain Characteristics of the EMR from Samples with Different α.

Figure 5 shows the variation law of the EMR count with time in the failure process of coal samples with different α. It is found that the time sequence characteristics of the EMR are quite different due to the influence of joint angle.

The time-load curves of coal samples with α = 0° and 15° fluctuate greatly before and after the peak, and there are obvious postpeak stages. The load drop is usually accompanied by a large EMR count, and the EMR counts are less in the stage without load drop. In the postpeak stage, the accumulated EMR counts increase significantly with the larger load drop, and there is a good correlation between the EMR counts and the load drop; for α = 30° and 45° coal samples, there is a small amount of load drop before the peak load, and the EMR counts in the stage without load drop are more than those of α = 0° and 15° coal samples. When the main failure occurs, the EMR counts increase suddenly and reach the maximum value; for α = 60°, 75°, and 90° coal samples, the load intensity of coal samples is higher, the time-load

| α (°) | Samples | Diameter (mm) | Height (mm) | Peak load (kN) | Failure time (s) | Postpeak failure time (s) |
|------|---------|---------------|-------------|----------------|-----------------|--------------------------|
| 0    | C-0-1   | 49.64         | 100.28      | 41.20          | 250             | 62.981                   |
|      | C-0-2   | 49.72         | 100.08      | 48.28          | 280             | 43.333                   |
|      | C-0-3   | 49.74         | 100.26      | 46.59          | 255             | 56.766                   |
| 15   | C-15-1  | 49.74         | 100.16      | 23.24          | 255             | 30.435                   |
|      | C-15-2  | 49.76         | 100.20      | 27.24          | 190             | 18.118                   |
|      | C-15-3  | 49.76         | 100.29      | 27.15          | 210             | 25.176                   |
| 30   | C-30-1  | 49.86         | 100.20      | 27.18          | 155             | 7.052                    |
|      | C-30-2  | 49.76         | 100.28      | 41.57          | 185             | 6.265                    |
|      | C-30-3  | 49.78         | 100.32      | 27.45          | 125             | 4.561                    |
| 45   | C-45-1  | 49.82         | 100.16      | 39.34          | 180             | 2.220                    |
|      | C-45-2  | 49.72         | 100.40      | 41.96          | 190             | 4.493                    |
|      | C-45-3  | 49.72         | 100.26      | 39.24          | 185             | 3.316                    |
| 60   | C-60-1  | 49.74         | 100.48      | 70.00          | 325             | 0.060                    |
|      | C-60-2  | 49.72         | 100.18      | 73.45          | 360             | 0.085                    |
|      | C-60-3  | 49.8          | 100.20      | 70.73          | 295             | 0.116                    |
| 75   | C-75-1  | 49.78         | 100.12      | 64.58          | 400             | 0.104                    |
|      | C-75-2  | 49.74         | 100.20      | 81.30          | 440             | 0.090                    |
|      | C-75-3  | 49.78         | 100.16      | 73.51          | 440             | 0.088                    |
| 90   | C-90-1  | 49.78         | 100.18      | 68.00          | 355             | 2.064                    |
|      | C-90-2  | 49.74         | 100.24      | 67.16          | 360             | 3.041                    |
|      | C-90-3  | 49.78         | 100.14      | 81.18          | 380             | 3.820                    |

Figure 3: Load-time curves of coal samples with different α.

3.2. Time-Domain Characteristics of the EMR from Samples with Different α. Figure 5 shows the variation law of the EMR count with time in the failure process of coal samples with different α. It is found that the time sequence characteristics of the EMR are quite different due to the influence of joint angle.

The time-load curves of coal samples with α = 0° and 15° fluctuate greatly before and after the peak, and there are obvious postpeak stages. The load drop is usually accompanied by a large EMR count, and the EMR counts are less in the stage without load drop. In the postpeak stage, the accumulated EMR counts increase significantly with the larger load drop, and there is a good correlation between the EMR counts and the load drop; for α = 30° and 45° coal samples, there is a small amount of load drop before the peak load, and the EMR counts in the stage without load drop are more than those of α = 0° and 15° coal samples. When the main failure occurs, the EMR counts increase suddenly and reach the maximum value; for α = 60°, 75°, and 90° coal samples, the load intensity of coal samples is higher, the time-load
Figure 4: Peak load and failure time curves of coal samples with different $\alpha$.

Figure 5: Continued.
curve fluctuation is small, and there is only one load peak point, which has strong impact tendency. The common characteristics of coal sample signals from all angles are that the EMR counts’ peak value appears in the main failure position of coal samples.

In order to quantitatively analyze the influence of joint angle on EMR time-domain signal characteristics, the variation rules of the EMR counts’ peak value and accumulated EMR counts with the joint angle of coal samples are counted, as shown in Figure 6. As \( \alpha \) increases, the EMR counts’ peak value is on the rise as a whole, but there are significant differences in different stages. From 0° to 30°, the EMR counts’ peak value increased slowly. From 45° to 60°, the EMR counts’ peak value increased sharply. When \( \alpha \) exceeds 60°, the rising trend of the EMR count becomes slow. Different from the EMR counts’ peak value, the accumulated EMR counts increase steadily with the increase of \( \alpha \).

### 3.3. Waveform and Spectrum Characteristics of the EMR from Different \( \alpha \)

Figure 7 shows the EMR waveform of samples with different \( \alpha \) at the moment of main failure. The moment of main failure is defined as the moment when the load curve drops instantaneously and drops to zero, the EMR counts suddenly increase, and the coal sample loses stability [26]. When the joint angle is small, such as \( \alpha = 0° \) and 15°, the EMR waveform oscillation is relatively sparse, which indicates that there are obvious low-frequency components in the EMR signal. When \( \alpha \) is large, such as \( \alpha = 75° \) and 90°, the EMR waveform changes more intensively, which indicates that there are obvious high-frequency components in the EMR signal.

The EMR waveform duration is the time from the trigger of the EMR waveform to the waveform attenuation to a stable value. The duration and maximum amplitude of the EMR waveform are important characteristics of the EMR waveform, and their change trend with angle is shown in Figure 8. The duration of the EMR waveform of the coal sample with \( \alpha = 0° \) is the smallest, which is 22.8 ms. The duration of the EMR waveform of coal samples with \( \alpha = 15°, 30°, \) and 45° is 22.1–27.5 ms. The duration of the EMR waveform of coal samples with \( \alpha = 60° \) and 75° is 33.1–34.5 ms. The maximum duration of the electromagnetic radiation waveform is 42.1 ms, and the maximum
amplitude is 3.029 V. With the increase of α, the waveform duration and maximum amplitude of the EMR show an obvious upward trend.

The frequency-domain characteristics of the EMR contain rich damage and failure information of coal samples. To further analyze the effect of joint angle on the frequency-domain characteristics of the EMR caused by coal sample failure, after wavelet filtering, the frequency spectrum of the EMR frequency distribution within 0–50 kHz is obtained by using fast Fourier transform (FFT), as shown in Figure 9.

It can be seen from Figure 9 that compared with high-frequency signals, low-frequency EMR signals carry more EMR characteristics, and the EMR energy is concentrated in 0–20 kHz. The change trend of the dominant frequency and the number of spectrum peaks of the EMR with angle is shown in Figure 10. We can see that the dominant frequency and the number of spectrum peaks of the EMR increase with the increase of α. According to the angle between the joint plane and loading principal stress, seven groups of coal samples are divided into coal samples with nearly parallel angle (α = 0°–15°), coal samples with inclined angle (α = 30°–60°), and coal samples with nearly vertical angle (α = 75°–90°). The dominant frequency and the number of spectrum peaks of the EMR among different types of coal samples are quite different. The dominant frequency of the EMR of coal samples with nearly parallel angle is relatively low, mainly distributed in 1-2 kHz, and the number of spectrum peaks is about 2-3; for coal samples with inclined angle, the dominant frequency of the EMR is about 1.7–5 kHz, and the number of spectrum peaks is about 6; for coal samples with nearly vertical angle, the dominant frequency of the EMR is relatively high at 5–9 kHz, and the number of spectrum peaks is about 11.

3.4. Time-Frequency Response Mechanism of EMR Signals with Different α. There are great differences in the characteristics of the EMR signal of coal samples with different joint angles, and regular changes are shown with the increase of α. We analyzed the difference from the angle of the crack propagation mode and EMR generation mechanism.

According to the previous research results, under uniaxial compression, the propagation modes at the crack tip of coal and rock are mainly divided into wing cracks, antiwing cracks, and secondary cracks [27, 28]. Among them, wing-type cracks and antiwing cracks are generally tension cracks (T), and secondary cracks are generally shear cracks (S). As shown in Figure 11, when α ≤ 15°, the loading direction is nearly parallel to the joint surface, and the tensile failure along the joint surface is more likely to occur in the coal sample. The cracks are mainly tension cracks, and there are fewer shear cracks. When 30° ≤ α ≤ 60°, the load component of the coal sample subjected to the vertical joint surface increases gradually, and the shear cracks caused by the load component of the vertical joint surface also increase. As the load increases, the shear crack and tensile crack gradually connect, and the joint action causes the sample failure. When 75° ≤ α ≤ 90°, the loading direction is nearly vertical to the joint surface, and the load component of the parallel joint plane is small and only plays the role of crack, which makes the coal sample not easy to produce sliding failure along the joint surface. The coal sample easily accumulates a lot of elastic energy before the loading failure, and it is prone to burst failure at the moment of loading limit, and the failure is mainly a large number of small fractures (F) along joints and vertical joints.

At present, there are mainly theories about the mechanism of EMR signal generation in coal and rock, such as crack propagation effect [29], piezoelectric effect [30, 31], friction effect [32], electrodynamics effect [33], and thermionic emission effect [34]. Through the analysis of the crack propagation mode and mechanical properties of coal samples with different α, we believe that the crack propagation effect is the main factor affecting the difference of the EMR signal of samples with different α. The propagation mode of cracks leads to the difference of free charge generation and separation, which leads to the difference of EMR signal characteristics.

In the process of crack propagation, the EMR signal is mainly caused by charge oscillation. Cracks propagate unstably under load, and positive and negative charges are generated and accumulated on the crack wall. With the opening and closing of the crack and the vibration of the crack wall, the positive and negative charges continue to separate and radiate energy in the form of electromagnetic waves, which results in EMR [34, 35]. As shown in Figures 11 and 12, the failure of samples with different α has different crack propagation modes and causes different EMR signal generation mechanisms. When α ≤ 15°, the failure mode of the coal sample is mainly tensile failure, and a small number of tensile cracks can cause sample damage, so the accumulated EMR counts are small. Figure 12(a) shows that, under the action of tensile cracks, the distance between two sides of cracks increases gradually; that is, the crack width increases gradually, and the frequency of charge oscillation gradually decreases. Moreover, the postpeak failure time of the samples is longer, the crack propagation and the intensity of oscillation are relatively low, so the dominant

![Figure 6: Variation of EMR signals in the time domain with different α.](image-url)
frequency of the EMR is low, and the peak value of the spectrum is less. When $30^\circ \leq \alpha \leq 60^\circ$, under the combined action of the shear crack and tensile crack, the number of cracks and EMR-accumulated count of coal samples increase gradually. Figure 12(b) shows that the failure mode of the sample is mainly shear failure, and the positive and negative charges slip along the shear surface of the crack, charge and discharge continuously, and release energy to the outside in
the form of electromagnetic waves. Moreover, the postpeak failure time of the samples decreases sharply, and the crack expansion and oscillation intensity increase. Therefore, the dominant frequency of the EMR increases, and the number of spectrum peaks also increases gradually. When \(75^\circ \leq \alpha \leq 90^\circ\), because the loading direction is nearly perpendicular to the joint surface, the coal sample will burst and produce a large number of cracks and small fractures, so the accumulated EMR counts’ value also increases to the maximum. Guo and Liu [29] and Sun et al. [30] also observed that a large number of fragments were splashed out when the rock broke and proposed that the surface of the debris was charged, and electrons escaped from the surface of the debris and emitted outward, causing the EMR signal. Figure 12(c) shows that because of the irregular size and shape of fragments after coal sample failure, the surface charge distribution is also more complex. According to Frid et al. [13], the relationship between EMR frequency and crack width is \(f = V_R/2b\), where \(f\) is the EMR frequency, \(b\) is the crack width, and \(V_R\) is the Rayleigh wave velocity. When the crack width is small, the dominant frequency of the EMR is higher, and the peak value of the EMR spectrum is more complex due to the complexity of damage debris.

4. Application and Discussion

4.1. Case Analysis of the Influence of Geological Conditions

Due to the influence of folds (syncline and anticline), faults, and other geological structures, the direction of the main stress of jointed coal in slope, hydraulic engineering, tunnel, and other underground engineering is uncertain. Through the above study, it can be concluded that there are great differences in EMR monitoring and early warning signals under different principal stresses and joint plane angles. Taking Xinzhou Yao mine as an example, this paper discusses the influence of the geological structure and engineering construction factors on the EMR signal produced by instability and failure of geological engineering with joints.

As shown in Figure 13, Xinzhou Yao mine is located in the northeast end of Datong coalfield syncline. Because Xinzhou Yao mine is a shallow buried coal mine, the vertical stress is small. Therefore, the horizontal stress caused by the syncline structure is the main stress of the Xinzhou Yao mine coal seam. The coal seam of Xinzhou Yao mine is nearly horizontal, and the joint surface inside the coal seam is also near horizontal, so in most cases, the direction of the main stress of the coal seam is roughly parallel to the joint surface.

Figure 14(a) shows the numerical simulation model established according to the actual situation of Xinzhou Yao mine. A large number of coal pillars will be left in the mining process of the panel. The stress concentration of the overlying coal pillars will be generated and transmitted to the lower coal seam, resulting in the vertical stress concentration on the district pillars in the lower coal seam section. Because the two sides of the district pillars of the lower coal seam are goaf and roadway, the horizontal tectonic stress of the district pillars is greatly reduced, and the main stress of the district pillars becomes the vertical stress of the vertical coal seam and joint surface. In Figure 14(a), section I-I is intercepted from the numerical simulation results. The district pillar at section I-I is subjected to vertical stress to produce plastic failure, as shown in Figure 14(b). In actual engineering, both sides of the roadway will be damaged, and the field failure is shown in Figure 14(c).

We can see from Figures 13 and 14 that, for the same engineering project, the main stress of jointed coal and rock will change by 90° due to the influence of tectonic stress and engineering construction factors. At the same time, the generation mechanism and signal characteristics of the electromagnetic radiation signal in the process of coal rock failure also change obviously, and the critical value of the electromagnetic radiation warning index needs to be corrected in time.

4.2. Significance to Determining the Early Warning Index of the EMR

Practice shows that EMR can reflect the stress state of coal-rock, and the intensity of the EMR is closely related to stress. The EMR signal is obvious in the high-stress area or in the area of serious deformation and fracture. The burst risk of coal and rock can be evaluated and predicted by using the EMR [33, 36]. At present, the EMR early warning mostly uses the critical value method and the deviation method, and these early warning indicators have great differences in the field application [19, 37–39]. Scholars mainly study the reasons of these differences through laboratory experiments and think that the main reasons for these differences are the physical and mechanical properties of coal and rock and the field stress situation. For example, Frid and Vozoff [32] pointed out in the experiment that the EMR energy generated by coal with different strengths has great difference. The greater the uniaxial compressive strength is, the greater the peak intensity of the EMR generated in the failure process is. The experimental results in this paper (Figure 15) also show that the uniaxial compressive strength of coal...
Figure 9: EMR spectrum of samples with different $\alpha$. 
Figure 10: Number of spectrum peaks and dominant frequency of samples with different $\alpha$.

Figure 11: Failure modes of samples with different $\alpha$.

Figure 12: Schematic diagram of the EMR generated by different joint angles. (a) Tension crack. (b) Shear crack. (c) Shear and tension cracks.
samples, the EMR counts’ peak value, and accumulated EMR counts produced in the failure process of the same coal sample under different loading principal stresses and angles of the joint surface are quite different. As the joint angle increases, the EMR counts’ peak value and accumulated EMR counts increase gradually. The maximum EMR counts’ peak value (1181) and maximum accumulated EMR counts (2171) are observed when $\alpha = 90^\circ$, and the minimum values were 68 and 381, respectively, when $\alpha = 0^\circ$; the maximum values were 17.37 and 5.70 times of the minimum values, respectively. The experimental results show that the existence of joints has a great effect on the determination of the early warning critical value of EMR monitoring. Therefore, according to the experimental results of different joint surface angles, we propose to modify the EMR warning threshold under different field stress environments.

The critical value method is based on the average value of the characteristic parameters of the EMR monitored $n$ times under the normal condition that there is no danger of rock burst, and $k$ times of the average value are taken as the warning critical value. When the monitoring data are greater than the warning critical value, it is predicted that the burst risk of coal and rock will increase [40]. The critical value $E_i$ prediction formula is as follows:

$$E_i = kE,$$

\( (1) \)
Overlying coal pillars
District pillars
II
II
Roadway
Goaf
11-2 Roof
11-2 Coal seam
14-3 Roof
14-3 Coal seam
Floor

(a)

(b)

Figure 14: Continued.
where $E$ is the average value of EMR amplitude (or pulse number) monitored $n$ times; $n$ and $k$ values are selected according to coal seam conditions; generally, $n > 10$ and $k = 1.4–1.5$.

The deviation method is to predict the degree of the burst risk of coal and rock by analyzing the deviation between the monitoring data $E_i$ and the average data under normal conditions [40]. The prediction formula of deviation $A_i$ is as follows:

$$A_i = \frac{(E_i - E)}{E}. \quad (2)$$

As shown in Figure 15, for the same coal, under different loading principal stresses and joint plane angles, the maximum and minimum values of the EMR counts’ peak value were observed at $\alpha = 90^\circ$ and $\alpha = 0^\circ$, and the maximum values were 5.7 times of the minimum values. The maximum and minimum values of accumulated EMR counts were observed at $\alpha = 90^\circ$ and $\alpha = 0^\circ$, and the maximum values were 17.37 times of the minimum values. This difference is beyond the range of $k = 1.4–1.5$. In this case, the coefficient $k$ and the average value $E$ of EMR monitored $n$ times cannot effectively calculate the critical value of early warning. In this paper, the angle between the loading principal stress direction and the joint surface is taken as the main variable, and the value of $\lambda$ is introduced to modify $E$ of the EMR critical value method and deviation.

$$\bar{E} = \lambda E = \frac{e_i}{e_n} E. \quad (3)$$

where $\lambda$ is the average correction coefficient of the EMR based on the angle between the loading principal stress and

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**Figure 14:** Analysis of the main stress change of the district pillar caused by mining factors in Xinzhou Yao mine. (a) Numerical simulation model of Xinzhou Yao mine. (b) The district pillar at section I-I is subjected to vertical stress to produce plastic failure. (c) Roadway failure diagram.

**Figure 15:** Statistical comparison of force and EMR time-domain signals of coal samples with different $\alpha$. 
joint surface as the main variable under experimental conditions; $e_i$ is the EMR signal value measured by experiments with reference to the stress and joint surface conditions of the monitoring target position; $e_n$ is the electromagnetic radiation signal value measured by experiments with reference to the position stress and joint surface condition of $N$ times electromagnetic radiation monitoring.

Then, the early warning calculation formulas of the modified EMR critical value method and deviation method are as follows:

$$E_i = kE = k\frac{e_i}{e_n}$$

$$A_i = \frac{(E_i - E)}{(E - (e_i/e_n)E))/((e_i/e_n)E)$$

4.3. Discussion on the Evaluation of Burst Risk by the EMR Frequency-Domain Signal. As mentioned above, the intensity, amplitude, count, and other time series indexes of the EMR are generally used in the prediction of coal and rock dynamic disasters, and the waveform and frequency spectrum characteristics of the EMR are rarely used to warn or evaluate the burst risk of coal and rock. Song et al. [41] deduced the calculation formula of the EMR signal frequency range in the process of coal and rock deformation and failure and revealed the relationship between the EMR signal frequency of loaded coal and rock and its physical parameters. According to the research conducted by Qian et al. [42] and Guo and Liu [29], the EMR frequency of coal and rock is closely related to physical and mechanical parameters such as elastic modulus, Poisson’s ratio, density, and crack size. Qiu et al. [35] considered that the burst and dispersion of the low-frequency EMR (1 kHz) signal are very sensitive to rock burst and analyzed the feasibility of low-frequency EMR signal warning of the rock burst. Based on these studies, it can be considered that the frequency-domain signal is of potential significance for early warning or evaluation of the burst risk of coal and rock.

Seven groups of coal samples are divided into three groups: coal samples with nearly parallel angle ($\alpha = 0^\circ$–$15^\circ$), coal samples with inclined angle ($\alpha = 30^\circ$–$60^\circ$), and coal samples with nearly vertical angle ($\alpha = 75^\circ$–$90^\circ$). As the joint angle changes, the EMR signal waveform and frequency spectrum characteristics have a significant regularity. As the joint angle increases, the duration of the EMR waveform, the dominant frequency, and the number of spectrum peaks increase. For the coal samples with nearly parallel angle, the dominant frequency of the EMR is significantly lower, mainly distributed in 1-2 kHz, and the number of spectrum peaks is about 2-3; for coal samples with inclined angle, the dominant frequency of the EMR is about 1.7–5 kHz, and the number of spectrum peaks is about 6; for coal samples with nearly vertical angle, the dominant frequency of the EMR is about 8-9 kHz, and the number of spectrum peaks is about 11. The duration of the waveform is bounded by $45^\circ$ with the duration of $0^\circ \leq \alpha < 45^\circ$ ranging from 22.8 to 29.6 ms and that of $45^\circ < \alpha \leq 90^\circ$ waveform ranging from 27.5 to 45.2 ms.

A large number of experimental research studies on the burst risk of coal and rock show that the greater the uniaxial compressive strength and the shorter the postpeak failure time, the greater the burst risk of coal and rock mass [43, 44]. The theoretical basis of the drilling cutting method to evaluate the burst risk shows that, in the same coal seam, the greater the stress is, the more pulverized coal is drilled and the greater the burst risk is [45]. Figures 4, 15, and 16 show that, with the increase of loading principal stress and joint plane angle, the uniaxial compressive strength of coal becomes greater, the postpeak failure time becomes shorter, and the fragment size becomes smaller. Therefore, for the same kind of coal, the loading principal stress and the angle $\alpha$ of the joint plane are positively correlated with the burst risk of coal and rock.

Since the frequency-domain signal of the EMR has a positive correlation with the angle $\alpha$, we can establish the
relationship between EMR frequency-domain characteristics and the burst risk of coal and rock assessment: when the EMR waveform duration is longer, the dominant frequency is higher, and the number of spectrum peaks is more, the burst risk of coal and rock is greater. Therefore, it is feasible to use the waveform and frequency spectrum characteristics of the EMR to evaluate the burst risk of coal and rock, and it is vital to fully consider the defects such as the angle between the joint surface and principal stress when using the waveform and frequency spectrum characteristics of the EMR to evaluate the burst risk of coal and rock.

5. Conclusion

We tested the mechanical properties and EMR response law of coal samples with different joint angles and studied the time-frequency characteristics of EMR signals of coal samples with different joint angles. From the perspective of the crack propagation mode and EMR generation mechanism, the regularity difference is discussed, and the guiding significance of EMR monitoring and evaluation of the burst risk of coal and rock is analyzed. The conclusions are as follows:

(1) The EMR time-domain characteristics of coal samples with different joint angles are significantly different. The EMR counts’ peak value showed a slow rise, a sharp rise, and a slow rise in the three intervals of $0°–45°$, $45°–60°$, and $60°–90°$, respectively, while the accumulated EMR counts showed a steady upward trend as a whole.

(2) With the increase of joint angle, the duration of the EMR waveform of the coal sample increases from 22.8 ms to 45.2 ms. The dominant frequency of the EMR increases from 1 kHz to 9 kHz, and the number of spectrum peaks increases from 2 to 11.

(3) With the increase of joint angle, the generation of the EMR is also gradually transformed from the tension and shear slip of the crack to the burst failure. This is the main reason for the difference of EMR signals of coal samples with different joint angles.

(4) The existence of joints has a great influence on the determination of the early warning critical value of EMR monitoring. The longer the duration of the EMR waveform and the higher the dominant frequency and the number of spectrum peaks, the greater the burst risk of coal and rock. The research results are of great significance for multimeans evaluation of the coal seam burst risk and improving the accuracy of EMR monitoring of the burst risk of coal and rock.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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