Experimental Study of Shock Wave Spread Rule Monitoring with FBG Sensing for Lithologic Characteristics

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Abstract: To obtain the influence mechanism of lithologic characteristics when rock burst shock waves transmit through rock, the waves in different rock were monitored with fiber Bragg grating (FBG). The result shows that the wave will change the period $\Lambda$ and effective refractive index $n$ of FBG, and further affect the initial wavelength value. The amplitude, phase and frequency of shock wave are directly related to the wavelength drifts of FBG. The transmitting velocity of shock wave in rock is affected by lithologic characteristics. The Elastic modulus, density and Poisson's ratio of rock influence the initial wavelength value of FBG in the form of $\lambda = \sqrt{\frac{2E}{\rho(1+\nu)}}$, and are Cosine related to wavelength drifts. The experiments of shock waves monitoring were carried out in sandstone, limestone and marble respectively. The result shows that the lithologic parameters of rock were Cosine related to the initial wavelength value of FBG. This study provided a theoretical basis and practical application guidance for coal or rock burst monitoring with FBG sensing.

1. Introduction

With mining depth of China increasing gradually, the occurrence rate of rock burst also increases [1]-[2]. The study of mechanism and prevention of rock burst have always been the focus in the field of mining engineering [3]-[6]. Rock burst is often accompanied with strong mine earthquake [7]-[9], which transmits in coal and rock in the form of seismic waves with random energy. The energy level of shock waves is closely related to the occurrence of rock burst, and the higher the level of waves energy is, the greater the possibility of rock burst is. Thus, it becomes an important means to monitor earthquake waves for rock burst warning [10]-[12]. The following methods are often used: micro seismic, acoustic emission, electromagnetic radiation, etc. Jiang Fuxing et al. [13] developed the explosion-proof microseismic positioning monitoring system and carried it out in field application, which proved its feasibility in coal mine. Pan Yishan et al. [14] developed a monitoring and positioning system with kilometer-scale for breaking mine earthquake and analyzed the location of mine earthquake by picking up the vibration wave signals. The monitor was consistent with the earthquakes, which provided bases for mine disaster relief and loss reduction. Xie et al. [15] monitored the parameters of rock burst through acoustic emission, and obtained that the spatial distribution of microseismic events had fractal characteristics. Li Yuanhui et al. [16], studied the variation of AE b and fractal dimension of spatial distribution under different stress levels in the process of rock fracture by acoustic emission, which improved the stability of stress monitoring of rock. Wang Enyuan et al.
widely applied electromagnetic radiation technology in coal and rock dynamic disaster monitoring and early warning by studying electromagnetic radiation instrument. However, due to the underground complicated conditions, numerous large electrical equipment, serious electromagnetic interference and dynamic disturbance, and the influence of water, gas, that makes some of the mentioned monitor methods be invalid.

FBG is a kind of high-precision monitoring sensor sensing with wavelength drifts. Due to the merits of small size, anti-electromagnetic interference, corrosion resistance and so on, it has been widely used in many fields [19]-[21]. Relevant researches show that the transmission process of shock waves after earthquake can be monitored by FBG. Peng Baojin et al. [22], based on tilted grating filter demodulation, studied a FBG microstrain sensing system, and the accuracy reached 0.009 με. Wu Jianhui et al. [23], based on FBG sensing, set up a monitoring system of seismic wave with sensitivity of 0.54 pm/ms². Qiao Xueguang et al. [24], based FBG sensing, studied a seismic wave measurement system with sensitivity of 100 pm/g. Because both earthquake and rock burst origin from sudden release of energy under high compressive stress concentration in rock, the shock waves generated are similar, therefore, it is feasible to monitor rock burst of coal mine through FBG. Wang Jianda et al. [25] applied FBG sensing to underground coal mines, and developed early dynamic warning technology of rock burst as the early warning indexes of monitoring system of mining stress and stress gradient. Zhang Ningbo et al. [26] developed a multi-point stress and displacement monitoring system based on FBG sensing. Through experiments and engineering practice, the applicability of the system for rock burst in roadway was verified. Ginu Rajan et al. [27] adopted a high-frequency FBG testing system to monitor the high-frequency AE signals from stress-induced crack of rock samples with different shapes under compression load, and obtained the AE events consistent with the experiment, which revealed that high-frequency FBG can be used as a new technology for rock vibration monitoring. Gong H et al. [28] established a roof stability monitoring system in underground coal mine with FBG sensors, which verified the accuracy of FBG sensor in monitoring the strain of rock compression. Laudati et al. [29] designed a FBG triaxial acceleration sensor, and by measuring the axial deformation generated by dynamic acceleration of the fixture foundation, the lowest response frequency reached 0.1 Hz, providing a technical tool for underground microseismic monitoring.

In general, the study of rock burst monitoring with FBG sensing is still in development, and it is only achieved to receive the dynamic signal of rock burst. However, the research on mechanism of FBG sensing for rock burst, especially the transmission characteristics and influencing factors of shock waves in different rock are not involved.

In this paper, based on the transmission characteristics of shock waves and the sensing principle of FBG, the influence of lithologic characteristics on the monitoring process was analyzed.

2. Mechanism of Lithologic Characteristics For Shock Wave Monitoring of Rock Burst With Fbg Sensing

The sensing principle of FBG was analyzed and deduced based on coupled mode theory. By solving the wave equation with Maxwell’s theory, the expression of wavelength of FBG was [30]:

\[ \lambda_p = 2\left(n_{\text{eff}} + \Delta n_{\text{eff}}\right)\Lambda \]  

(1)

Where \( \lambda_p \) is the FBG reflected center wavelength, \( n_{\text{eff}} \) and \( \Lambda \) are the effective refractive index and grating period of the fiber core, respectively.

According to Newton's law and Hooke's law, the rock generates volume and shape deformation under external forces. Two deformation spread in coal and rock by P and S wave. The movement direction of the P-wave is the same to the spreading direction, while the S-wave is perpendicular to the spreading direction.

The velocities \( V_p \) of P-wave and \( V_s \) of S-wave can be respectively expressed as following [31]:

\[ V_p = \sqrt{\frac{\mu + 2\mu}{\rho}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \]  

(2)
\[ V_i = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{2 \rho (1 + \nu)}} \] (3)

Where \( \lambda \) and \( \mu \) are Lamé Constants, \( E \) is the Elastic modulus, and \( \nu \) is Poisson’s ratio. 
\[
\lambda = \frac{E \nu}{2(1+\nu)(1-2\nu)}, \quad \mu = \frac{E}{2(1+\nu)}. 
\]

R. H. Scanlan and K. Sachs proposed to use Fourier series to simulate ground motion time history [31]:
\[
\alpha(t) = \sum_{k=1}^{N(t)} A_k \cos(\omega_k t - \phi_k) \quad (4)
\]

Where \( A_k \) is the amplitude spectrum value of the vibration time history; \( \phi_k \) is the phase spectrum value of the vibration time history; \( \omega_k \) is the frequency.

When the vibration wave spreads, the relation between wavelength and wave velocity is expressed as following:
\[
V_i = \lambda_k \omega_k \quad (5)
\]

Where \( V_i \) is wave speed, and \( \lambda_k \) is wavelength.

Put the equation (3) (4) and (5) into (1), it can be gotten as following:
\[
\lambda_i = 2 n_i \gamma \Lambda \left[ 1 + \gamma \Lambda \cos \left( \frac{2E}{\rho (1 + \nu)} \cdot \frac{t}{2\lambda} \right) \right] \quad (6)
\]

According to Equation (6), when shock waves are monitored by FBG, the Elastic modulus, density, Poisson’s ratio and other parameters of rock will affect its initial wavelength. That also means that when shock waves with same parameters spreads in different rock, the wavelength drifts are different, and the influence is in the form of cosine.

3. Monitoring Experiment of Shock Waves Spreading with FBG

3.1. Experimental System

In order to analyze the influence of rock characteristics for shock waves monitoring with FBG sensing, three kind of rock boards were selected for the experiment, covering sandstone, limestone and marble slabs with sizes of 60 cm x 60 cm x 2 cm, as shown in Figure 1. The mechanical parameters of the three samples were obtained through mechanics experiments, as shown in Table 1.

![Figure 1. Rock sample.](image)
Table 1. Lithologic characteristic parameters.

| Rock sample | Sandstone | Limestone | Marble |
|-------------|-----------|-----------|--------|
| Elastic modulus (MPa) | 4.3105×10⁴ | 3.1274×10⁴ | 7.3914×10⁴ |
| Density (g/m³) | 2.1 | 2.6 | 2.7 |
| Poisson's ratio | 0.12 | 0.18 | 0.15 |

The SA-JZ electric vibrator was used to provide shock signals with frequency of 0-15 kHz, and the SA-SG030 signal generator was used to simulate the shock. The Os7100 FBG acceleration sensors and SM130-700 dynamic FBG demodulators manufactured by Micron Optics (USA) were applied to acquire shock signals. In order to compare with the FBG sensor, the electric sensors were also used. The system was shown in Figure 2.

3.2. Experimental Scheme

Control variable method was used in the experiment, which meant that, for the three rock boards, two parameters were constant, including the position of the sensors, and the output frequency of the signal generator and the lithologic characteristics was the only variable factor in the process of experiment. The output sine wave was selected with frequency of 100 Hz. Three FBG acceleration sensors were pasted on the surface of the rock board at A, B and C point respectively, and the distance of OA was 10 cm, OB 20 cm and OC 30 cm. The initial wavelength of the FBG was 1532 nm, 1540 nm and 1544 nm, respectively. In order to compare the test results, the electric sensors were placed at the same position. The diagrams of the experiment were shown in Figure 3 and 4.

![Electric vibrator and Signal generator](image1)

(a) Shock generator

![Display and FBG demodulation instrument](image2)

(b) Signal acquisition equipment

Figure 2. Experimental facilities.

![Diagram of experimental setup](image3)

Figure 3. Sensor layout.
4. Results Analysis
To analyze the influence of rock characteristics, the point A was taken as an example. Amplitude-frequency characteristic curves in different rock were shown in Figure 5, and the characteristics of sandstone was shown in Figure 5(a). The peak occurred at 100 Hz and 200 Hz, and the average value of the peak value was about 6 μm. The curve of limestone was shown in Figure 5(b). The peak occurred at 100 Hz and its frequency multiplication at 200 Hz with an average peak value of about 9.5 μm. The curve of marble was shown in Figure 5(c). The peak occurred at 100 Hz and its frequency multiplication at 200 Hz with an average value of the peak about 10 μm. The peaks of the three curves all occurred at 100 Hz and 200 Hz, which was consistent with the set frequency of the signal generator.

![Figure 4. Experimental process and monitoring system.](image)

(a) Sandstone

(b) Limestone
Figure 5. Amplitude-frequency characteristic curves in different rock.

The curves of FBG wavelength drifts of point A were shown in Figure 6. The wavelength variation of sandstone was shown in Figure 6(a). The maximum peak of the wave was 1540.216 nm, and the minimum peak was 1540.210 nm. The maximum variation of the wavelength was 6 pm. The variation of wavelength of limestone was shown in Figure 6(b). The maximum wave was 1529.632 nm, and the minimum was 1529.620 nm. The variation of wavelength was 12 pm. The variation of wavelength of marble was shown in Figure 6(c). The maximum wave was 1540.214 nm, and the minimum was 1540.200 nm. The variation of the wavelength was 14 pm.
Wavelength drifts in different rock monitored by FBG acceleration sensors were shown in Figure 7. It can be gotten from the figure that, the wavelength drifts of sandstone were within 0 pm~6 pm, the limestone within 0 pm~12 pm, and the marble within 0 pm~14 pm. The average variation was 3.11 pm, 7.45 pm and 9.89 pm respectively. Overall, the wavelength drifts of marble and limestone were obviously greater than sandstone, and the drifts of marble and limestone were close to each other.

From the analysis of Figure 5, 6, the wavelength drifts and amplitude variations of three rock were shown in Figure 8. It can be obtained that the wavelength variation of marble and limestone were obviously greater than sandstone, and the variation of marble and limestone were close to each other. This was mainly due to the influence of \( l = \frac{2E}{\rho (1+v)} \), and the corresponding wavelength drifts were also different.

(c) Marble

**Figure 6.** Wavelength drifts curves of FBG in different rock.

**Figure 7.** Wavelength drifts in different rock.
The $I$ of sandstone, limestone and marble were 6102, 4914 and 6900, and the single peak relationship between lithologic parameter $I$ and wavelength drifts were shown in Figure 9. The figure showed that the wavelength variation in different rock caused by same shock waves was different. The parameter $I$ was nonlinearly related to the wavelength drifts. Considering that the difference of $I$ had an approximate periodicity, it could be fitted to the curve equation shown in the figure. Without considering the impact of shock wave reflection, refraction and scattering on the wavefront diffusion, $I$ had a cosine correlation with the wavelength variation of FBG, which was consistent with the result of theoretical analysis.

5. Conclusion
When shock waves with the same parameters in different rocks are monitored by FBG, the wavelength will be affected by the lithological characteristic parameter $I$, and has a cosine correlation with it. Therefore, as long as the rock mechanics parameters are obtained, the degree of influence of the lithological characteristics on the FBG monitoring can be obtained.

The experiment shows that the lithologic characteristic parameter $I$ is cosine related to the wavelength variation of FBG, which is consistent with the result of theoretical analysis. This provides an important theoretical basis for coal or rock burst monitoring with FBG sensing, and can promote the application of optical test method for coal mine dynamic disaster.

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7. References

[1] Kang Hong-pu, Wu Yong-zheng, He Jie, et al. Rock bolting performance and field practice in deep roadway with rock burst 2015 Journal of China Coal Society. 10, 2225-33.

[2] PAN Yi-shan, LI Zhong-hua, ZHANG Meng-tao. Distribution, type, mechanism and prevention of rockburst in china 2003 Chinese Journal of Rock Mechanics and Engineering. 11, 1844-51.

[3] DOU Lin-ming, LU Cai-ping, MOU Zong-long, et al. Intensity weakening theory for rockburst and its application 2005 Journal of China Coal Society. 6, 690-4.

[4] PAN Yi-shan. Disturbance response instability theory of rock burst in coal mine 2018 Journal of China Coal Society. 5, 1607-13.

[5] QI Qing-xin, PAN Yi-shan, LI Hai-tao, et al. Theoretical basis and key technology of prevention and control of coal-rock dynamic disasters in deep coal mining 2020 Journal of China Coal Society. 5, 1567-84.

[6] LIANG Jin, WANG En, CAO An. Study on rockburst monitoring and prediction methods in China 2014 Coal Science and Technology. 10, 1-5.

[7] XIA Yong-xue, KANG Li-jun, QI Qing-xin, et al. Five indexes of microseismic and their application in rock burst forecasting 2010 Journal of China Coal Society. 12, 2011-16.

[8] JIANG Fu-xing, YAO Shun-li, WEI Quan-de, et al. Study of site forewarning mechanism of rockburst induced by shock bump and its application 2015 Chinese Journal of Rock Mechanics and Engineering. 34, 3372-79.

[9] JIANG Fu-xing, YANG Shun-hua, ZHAO Shan-kun, et al. A study on microseismic monitoring of rock burst in coal mine 2006 Chinese Journal of Geophysics. 49, 1511-1516.

[10] PAN Yi-shan, ZHAO Yang-feng, GUAN Fu-hai, et al. Study on rockburst monitoring and orientation system and its application 2007 Chinese Journal of Rock Mechanics and Engineering. 26, 1002-1011.

[11] ZHANG Meng-hui, LIU Jian, ZHAO Xin-dong, et al. Study on b-value and fractal dimension of acoustic emission during rock failure process 2009 Rock and Soil Mechanics. 30, 2559-2563+2574.

[12] ZHAO Zheng. Application progress of fiber grating sensing technology in coal mining technology 2020 Journal of China Coal Society. 6, 642-5.

[13] LI Yu-hui, LIU Jian-pao, ZHAO Xin-dong, et al. Study on b-value and fractal dimension of acoustic emission during rock failure process 2009 Rock and Soil Mechanics. 30, 2559-2563+2574.

[14] ZHANG Meng-hui, LIU Xiao-fei, LI Zhong-hui, et al. Application of electromagnetic radiation technology in monitoring and warning on coal and rock dynamic disasters 2012 Journal of Liaoning Technical University (Natural Science). 5, 642-5.

[15] HE Xue-qiu, NEI Bai-sheng, WANG En-yuan, et al. Electromagnetic emission forecasting technology of coal or rock dynamic disasters in mine 2007 Journal of China Coal Society. 1, 56-9.

[16] WANG En-yuan, LIU Xiao-fei, LI Zhong-hui, et al. Application of electromagnetic radiation technology in monitoring and warning on coal and rock dynamic disasters 2012 Journal of Liaoning Technical University (Natural Science). 5, 642-5.

[17] ZHAO Zheng. Application progress of fiber grating sensing technology in coal mining technology 2020 Journal of China Coal Society. 6, 642-5.

[18] ZHAO Zheng. Application progress of fiber grating sensing technology in coal mining technology 2020 Journal of China Coal Society. 6, 642-5.
[22] B. J. Peng, Y. Q. Shen, C. F. Ying, et al. (2009) Novel detection system for micro-strain signal based on Advanced Optical Manufacturing and Testing Technologies: Optical Test and Measurement Technology and Equipment, 7283, 1-5.

[23] J. H. Wu, K.T. Yang, Q. L. Xiang, et al. Nuclear explosion seismic wave detection based on the Fiber Bragg Grating geophone 2008 Photonics and Optoelectronics Meetings, 7278, 1-7.

[24] Y. Y. Weng, X. G. Qiao, T. Guo, en al. (2011) A robust and compact Fiber Bragg Grating vibration sensor for seismic measurement. IEEE Sensors Journal, 4, 800-803.

[25] WANG Jian-da, QIN Kai, DENG Zhi-gang, et al. Study on early warning technology of rock burst based on mining stress monitoring by fiber grating 2019 Coal Science and Technology. 6, 126-132.

[26] ZHANG Ning-bo, WANG Jian-da, QIN Kai, et al. The evaluation technology of coal bump risk in excavation roadway based on multi-point stress and displacement monitoring system 2020 Journal of China Coal Society. 1-11. https://doi.org/10.13225/j.cnki.jccs.2019.0952.

[27] Ginu Rajan, Shivakumar Karekal. 2017 High Frequency Fiber Bragg Grating Interrogator for Monitoring Rock Cracking Events for Mining Applications. In 2017 2nd International Conference for Fibre-optic and Photonic Sensors for Industrial and Safety Applications, 45-51

[28] Gong H, Kizil M S, Chen Z, et al. (2017) Validation of Bare FBG Sensors in Monitoring Compressive Rock Mass Deformation. In 2017 2nd International Conference for Fibre-optic and Photonic Sensors for Industrial and Safety Applications, 85-90.

[29] Laudati A, Mennella F, Esposito M. A Fiber Optic Grating Seismic Sensor 2008 IEEE Photonics Technology Letters, 24, 1991-1993.

[30] WEI Shi-ming. (2008) Study on Theory and Method of Fiber Bragg Grating Sensing in Rock Deformation Test. Ph.D. Dissertation, Xi’an University of Science and technology.

[31] Gibowicz S J, Kijko A. (1994) An introduction to mining seismology. Academic Press, San Diego.

[32] Scanlan. R. Sachs, H. K. (1974) Earthquake Time Histories and Response Spectra. J. of Engineering Mechanics Division, ASCE. 4, 635-655.