Hindawi Publishing Corporation
Shock and Vibration
Volume 2015, Article ID 121053, 8 pages
http://dx.doi.org/10.1155/2015/121053

Research Article

In Situ Test Study of Characteristics of Coal Mining Dynamic Load

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Received 5 November 2014; Revised 22 January 2015; Accepted 27 January 2015

Academic Editor: Mickaël Lallart

Combination of coal mining dynamic load and high static stress can easily induce such dynamic disasters as rock burst, coal and gas outburst, roof fall, and water inrush. In order to obtain the characteristic parameters of mining dynamic load and dynamic mechanism of coal and rock, the stress wave theory is applied to derive the relation of mining dynamic load strain rate and stress wave parameters. The in situ test was applied to study the stress wave propagation law of coal mine dynamic load by using the SOS microseismic monitoring system. An evaluation method for mining dynamic load strain rate was proposed, and the statistical evaluation was carried out for the range of strain rate. The research results show that the loading strain rate of mining dynamic load is in direct proportion to the seismic frequency of coal-rock mass and particle peak vibration velocity and is in inverse proportion to wave velocity. The high-frequency component damps faster than the low-frequency component in the shockwave propagating process; and the peak particle vibration velocity has a power functional relationship with the transmitting distance. The loading strain rate of mining dynamic load is generally less than class 10^{-1}/s.

1. Introduction

Coal mining can cause dynamic loading phenomena such as roof downfalls, fault slipping, and coal pillar stability loss, which can induce mining earthquake. The elastic stress wave caused by mining earthquakes transmitted to coal and rock mass will generate fluctuating load changing with time in the coal-rock medium, and this load is known as mining dynamic load. In the coal mining process, there is a limited transition zone of the plastic and elastic zones due to the stress redistribution by the caving space. While the coal and rock mass in the transition zone is located in the critical intensity state, the increase of stress can cause which fracturing in the transition and its neighboring zones. The stress wave generated by mining earthquakes will change the coal and rock stress state instantly and lead the coal and rock mass damaged and destroyed instantly, so that it causes such dynamic disasters as rock burst [1–3], coal and gas outburst [4], roof fall [5], water inrush [6], and even the damage to underground and surface buildings [7, 8].

The coal mining dynamic load has become a research hotspot of mine disaster prevention owing to the numerous disasters caused by it. Gad et al. [9] studied the peak particle vibration velocity and residential building destruction caused by underground blasting in the mining area by observation and established a simple destruction evaluation method based on peak particle vibration velocity. Singh et al. [10] studied room and pillar mining process, overlying strata movement, and changing features of mining dynamic load and emphasized the importance of field measurement to acquisition of mining data.

Presently, the studies on coal mining dynamic load mainly go by laboratory test and numerical simulation. The former is mainly performed by the Split Hopkinson pressure bar with a dynamic load strain rate range of 10^2~10^4 s^{-1} generally, while the numerical simulation refers to the study

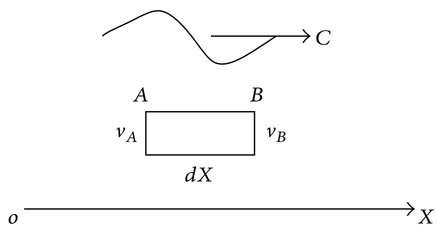


FIGURE 1: Strain rate analysis of stress wave transmission medium.

of dynamic load on coal and rock by man-made parameters of dynamic shockwave [11–13]. These research methods are not involved in the characteristics of mining dynamic load, so that the reliability and effectiveness for study results are unauthentic.

Key parameters of dynamic load characteristics including magnitude, loading rate, and loading period are significant to study loading effect of mining dynamic load. The coal mechanical property indicates strong correlation with loading rate, and what the loading strain rate represents is the loading rate; that is, the loading strain rate of the mining dynamic load has a great impact on coal-rock damage and destruction. The mining dynamic load is very important for disaster risk assessment of coal-rock mass under a mining dynamic load action, so it is necessary to give a further study on it. This paper studied the mining dynamic load strain rate characteristics by in situ monitoring test to get further knowledge of the mining dynamic load. The studied result can provide a better choice of dynamic load parameters for the study of loading effect of it.

2. Relation of Strain Rate and Stress Wave Parameters

Assume the seismic source of mining dynamic load is located at the origin O and the shockwave propagates outward at a velocity of C; take a length as an infinitesimal of dX for analysis as shown in Figure 1. The vibration velocities of the particles at infinitesimal end faces A and B at t are v_A and v_B, respectively; then, after the time dt, the additional strain caused by the shockwave is

$$\varepsilon = \frac{\left(\int v_B\,dt + \int v_B' t\,dt\right) - \left(\int v_A\,dt + \int v_A' t\,dt\right)}{dX}. \quad (1)$$

Then, the average change rate of the strain within dt can be

$$\overline{\varepsilon_t} = \frac{\varepsilon}{dt} = \frac{(v_A - v_B) + (1/2)\left(v_B' - v_A'\right)dt}{dX}. \quad (2)$$

The change rate of the infinitesimal dX at t when $dt \to 0$ is

$$\dot{\varepsilon} = \frac{v_B - v_A}{dX}. \quad (3)$$

The space change rate on the shockwave transmission line is the strain rate of particle.

According to the elastic stress wave theory, any stress wave can be composed of several sine waves. Hence, the sine wave is the basic form of the stress wave. For the sine stress wave propagated along the X direction, the particle vibration velocity can be written as

$$v(X,t) = v_0 \sin\left[2\pi f\left(t - \frac{X}{C}\right)\right], \quad (4)$$

where v_0 is particle peak vibration velocity and f is stress wave frequency. The strain rate function based on (3) and (4) can be written as

$$\dot{\varepsilon}(X,t) = \frac{\partial[v(X,t)]}{\partial X} = -\frac{2\pi f v_0}{C}\cos\left[2\pi f\left(t - \frac{X}{C}\right)\right]. \quad (5)$$

Then, the maximum strain rate is

$$\dot{\varepsilon}_{\max} = \frac{2\pi f v_0}{C}. \quad (6)$$

It is clear that the maximum strain rate generated in propagating medium by mining earthquake is correlated with the shockwave frequency f, particle peak vibration velocity v_0, and the wave transmitting velocity C. As the wave transmitting velocity is relatively stable, the change rate of dynamic load caused by shockwave is mainly related to the shockwave frequency and particle peak vibration velocity. When the particle peak vibration is at a certain velocity, the bigger the frequency is, the shorter the vibration period is and the shorter the time is from 0 to the particle peak vibration velocity, and then the bigger the accelerated velocity is, the bigger the instant stress for the particle is. Hence, Expression (6) has a universal meaning.

3. In Situ Test for Coal Mining Dynamic Load Characteristics

3.1. Testing Program. According to Expression (6), the parameters such as the particle peak vibration velocity, shockwave frequency, and wave transmitting velocity should be determined for evaluation of the range of mining dynamic load strain rate. The parameters should be determined by monitoring. As the mining earthquake occurs in time and location randomly, the sensors applied to monitor shockwave are only mounted in several decided positions, and the data monitored by the sensors changes in a certain range, the sensors have to be located at several positions. According to the propagation law of shockwave, the value ranges of shockwave parameters at the seismic source can be inverted based on the vibration parameters monitored by the several monitoring sensors.

The test in the literature [14] indicates that the peak particle vibration velocity has a power function relation with transmitting distance, but the underground shockwave propagation law has not been studied. In order to determine the shockwave propagation law to further decide the range of mining dynamic load strain rate, the SOS microseismic monitoring system, developed by the Central Mining Institute (GIG) of Poland, was applied in the in situ test in

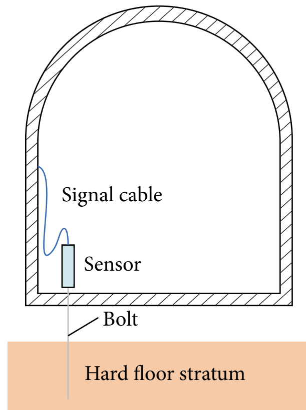


FIGURE 2: Installation of sensors.

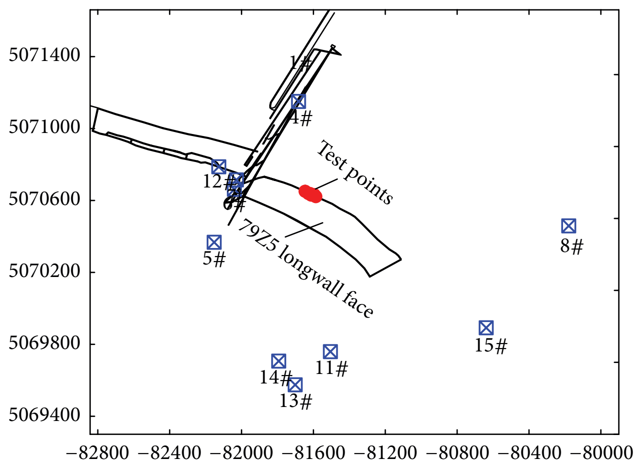


FIGURE 3: Plan of sensors layout.

the Taoshan Coal Mine northeast of China. This mine is a thin coal seam laid coal mine. The mining activity had a smaller destruction to the surrounding rock, with a little shockwave damping change and more accurate results.

13 of 16 sensors of the system were arranged underground totally from sensors 4# to 16#, where sensor 12# was mounted on the floor bolt end in the coal roadway and others were mounted in rock roadway (Figure 2). The other 3 sensors, namely, 1#, 2#, and 3#, were arranged on the ground. Due to the soft medium at the locations of sensors 12#, 1#, 2#, and 3#, obviously different from others, they were not applied to analyze in the test. The sensors arrangement is shown in Figure 3, where the sensors constitute a monitoring network in space layout. Because the coal mining earthquake source induced by roof stratum breakup or fault sliding is a bi-couple model [15] and the source of coal pillar instability is a single-couple model, the energy radiation for shockwave is directional. As a result, the data of natural mining earthquake monitored by sensors located in different directions cannot be applied to evaluate the mining earthquake source parameters. On the contrary, the blasting seismic sources accord with the point source model, the P wave vibration and energy radiation of which have a spherical diffusion. So the shockwave transmitting from the seismic source in different directions has the same strength; namely, the shockwave strength is related to transmitting distance but unrelated to the direction of the transmission. Thus, the seismic source is available by blasting in the test.

TABLE 1: Basic parameters in the in situ tests.

Test number	Position X	Y	Z	Monitored energy (J)
1	−81586.7	5070621.5	−424.1	296.0
2	−81646.2	5070651.1	−424.3	96.4
3	−81612.2	5070629.9	−424.4	400.0
4	−81627.7	5070638.6	−424.1	54.3
5	−81596	5070632.3	−424.5	96.3
6	−81619.6	5070638.8	−424.9	72.8

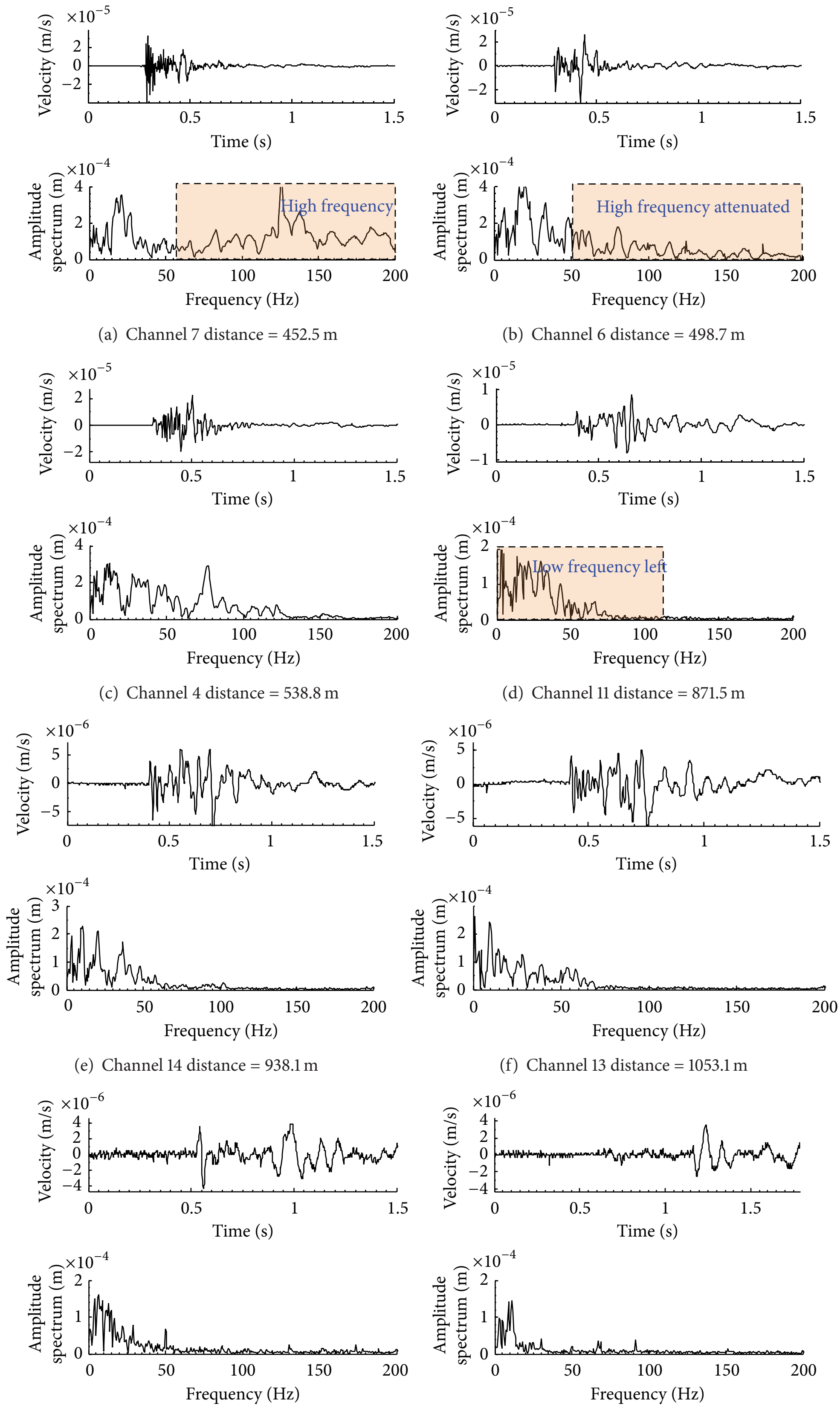
In the test, the blasting in coal seam was applied to make seismic source. The blasting drill holes were operated on the coal wall in the roadway of longwall mining face 79Z5, where the microseismic monitoring network has a better envelope as shown in Figure 3. Each drilling hole is 3 m deep and 42 mm in diameter and is filled with 1 kg ammonium nitrate explosive. Six blasting tests were done totally, and the basic blasting parameters are shown in Table 1. It is known from the energy monitored by the SOS system that the energy is in a great difference despite the same dynamite amount. The reason may be related to calculation error and energy released from coal and rock mass in the process of blasting. The bigger the released energy is released by coal and rock mass, the poorer the test reliability is. Hence, the effective tests that can be applied to analyze should be the ones with no coal wall falling around blasting holes.

3.2. Analysis of Shockwave Transmission. The shock waveform recorded in six tests has been analyzed to obtain the propagation laws of shockwave. In the analysis, the channels with little disturbing noise and clear signal were selected. The similar conclusions were drawn through analysis on shock waveform in the 6 tests. Figure 4 shows the shock waveform and corresponding frequency spectrum recorded by eight channels near the location of Test 1. For the sake of brevity, other test results are not listed here. The following laws are got through analysis on shock waveform and frequency spectrum of all the 6 tests.

(1) The maximum particle peak vibration velocity is generally in the long vibration period and with low frequency, which is the main component that induces high mining dynamic load.

(2) The low-frequency component of shockwave damps slowly and the high-frequency one damps fast in transmission.

Figure 5 shows the attenuation law of particle peak vibration velocity with transmitting distance of the six tests. As shown in this figure, the particle peak vibration velocity



(a) Channel 7 distance = 452.5 m
(b) Channel 6 distance = 498.7 m
(c) Channel 4 distance = 538.8 m
(d) Channel 11 distance = 871.5 m
(e) Channel 14 distance = 938.1 m
(f) Channel 13 distance = 1053.1 m
(g) Channel 8 distance = 1458.1 m
(h) Channel 9 distance = 2125.7 m

Figure 4: Shockwave and frequency spectrum features in Test 1.

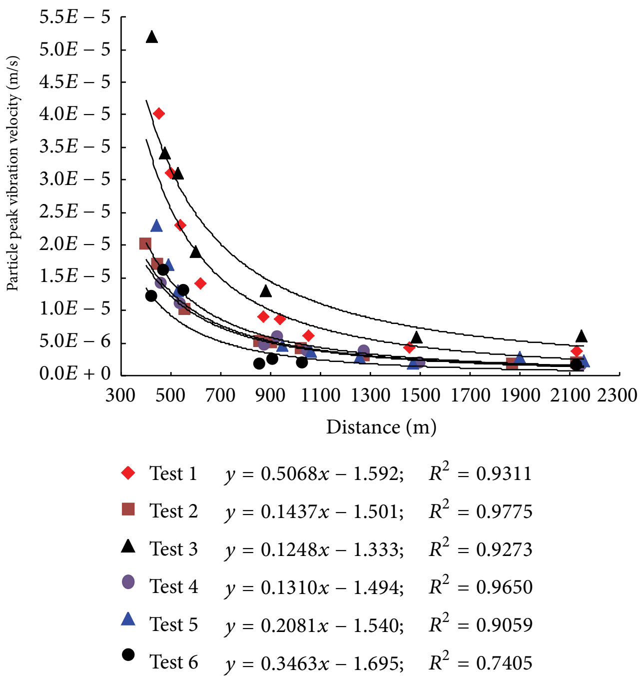


Figure 5: Particle peak vibration velocity damping law of Test 1.

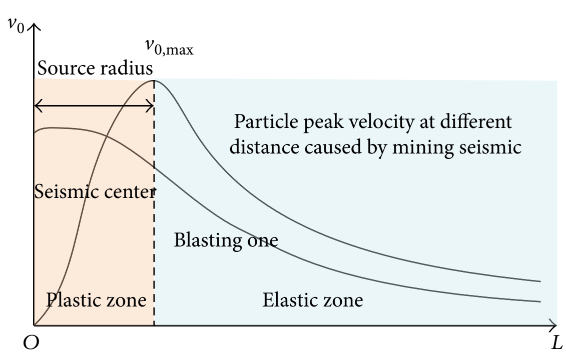


Figure 6: Sketch map of particle peak vibration velocity changing with transmitting distance.

damps with transmitting distance at attenuation of a power function in Expression (7):

$$v_0(L) = v_{0,\max} L^{-\lambda}, \tag{7}$$

where $v_{0,\max}$ is the particle peak vibration velocity, which is thought as the maximum particle peak vibration velocity in the process of shockwave transmission as shown in Figure 6; L is the shockwave transmitting distance; and λ is attenuation coefficient of particle peak vibration velocity. Figure 6 shows that the particle vibration velocity generated by natural mining earthquake or blasting has a power function relation with transmitting distance in the elastic zone, but uncertain in the plastic zone source of the mining earthquake. The particle vibration velocity form of natural mining earthquake and blasting may be different at the seismic center, but the maximum value should be at the point of elastic and plastic junction around seismic source.

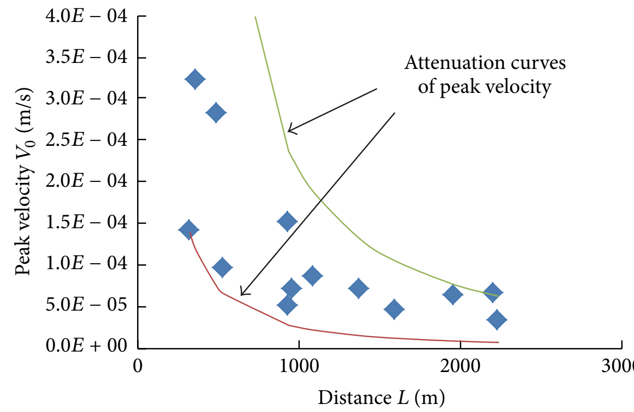


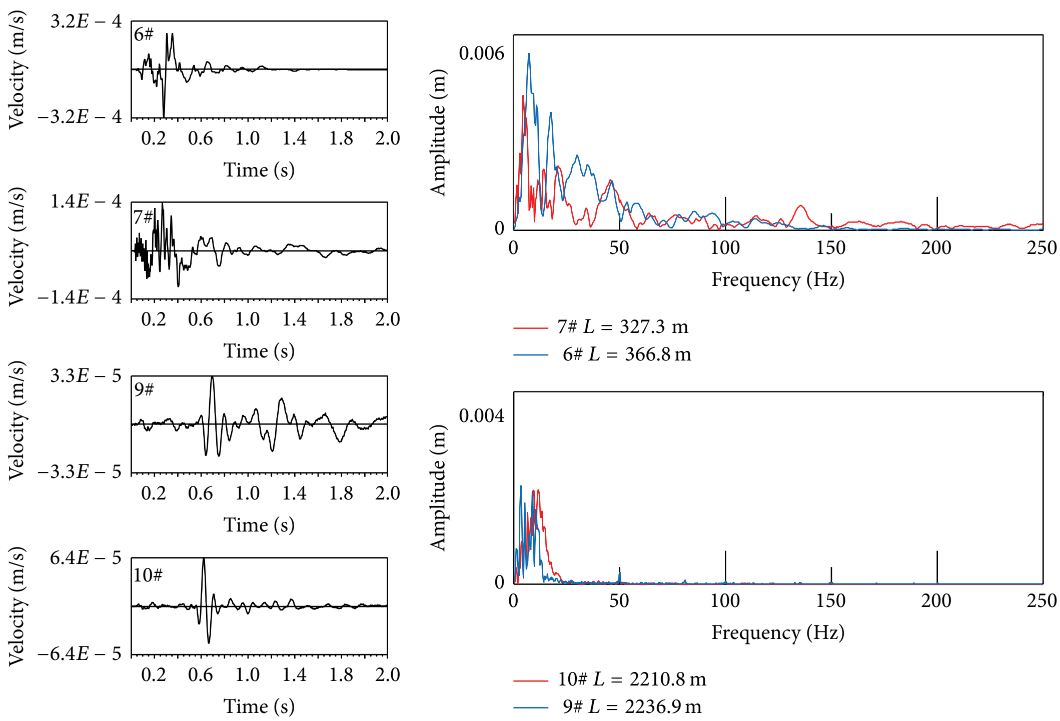
Figure 7: Back calculation of particle peak vibration velocity range.

The relation between particle peak vibration velocity and distance is fitted by the least square method, and the values of λ got are the following: 1.501, 1.333, 1.494, 1.592, 1.540, and 1.695, respectively. Their mean value is 1.526. The attenuation law of particle peak vibration velocity caused by the mining earthquake in the underground coal mine can be got as

$$v_0(L) = v_{0,\max} L^{-1.526}. \tag{8}$$

3.3. Assessment Method for Strain Rate Range of Mining Dynamic Load. The underground shockwave propagation law has been got in the in situ tests as shown in Expression (8). The following parameters can be obtained by monitoring method: far-field shockwave peak velocity, distance of monitoring point to seismic center, and radius of seismic source, so as to evaluate the value range of the coal-rock mass peak vibration velocity. The dominant frequency range of mining earthquake shockwave can be got by the Fourier transformation frequency-spectrum analysis, and the strain rate range of mining dynamic load from coal mining earthquake can be got by Expression (6).

The pressure relief blasting, carried out in the head entry of 79Z6 longwall face in Taoshan Coal Mine on August 21, 2010, induced rock burst and caused about two meters wide coal wall destruction around the blasting point, with a burst-out coal quantity of 2 tons and monitored seismic energy of 20119 joules. The relation between energy released by shear and tensile failure of coal and rock mass for shear and tension seismic source models and the stress drop and the seismic source radius as shown in Expression (9) is given by the literature [16], where W_1, W_2 are the energy released by the seismic source of shear and tensile failure, respectively, in the form of stress wave; G is shear modulus of source particle; E is elastic modulus of source particle; and $\Delta\tau$ and $\Delta\sigma_t$ are the stress drops of the source. From this equation, the seismic source radius can be approximately calculated. The stress drops are approximately equal to the dynamic load strength. By this, the seismic source radius can be 1.5 meters and this



(a) Shock waveform (b) Vibration frequency spectrum

Figure 8: Range of particle vibration frequency.

value also can be got roughly through a survey about seismic source destruction:

$$r_1 = \sqrt[3]{\frac{2W_1G}{\pi\Delta\tau^2}} \quad \text{or} \quad r_2 = \sqrt[3]{\frac{W_2E}{\pi\Delta\sigma_t{}^2}}. \tag{9}$$

As shown in Figure 7, the points are the particle peak vibration velocity monitored in channels. According to Expression (8), peak vibration velocity attenuation curves can be got from seismic source to each monitoring point. All curves make up one curve family. The value taken from up and down boundaries of the curve family to the position at 1.5 m from source center is the value range of the maximum peak velocity $v_{0,\max}$. By calculation, the maximum peak vibration velocity $v_{0,\max}$ ranges from 0.52 to 4.38 m/s got for this rock burst. Figure 8 shows shock waveform and frequency spectrum of sensors 6# and 7# nearer to the seismic source and sensors 9# and 10# farther from the source. It is known by analysis that the peak vibration velocity is in long period and with low frequency. The frequency of peak velocity falls at 2~15 Hz, as Figure 8(b) shows.

By monitoring, the average velocity of longitudinal wave is about 4300 m/s, and that of shear wave velocity is 2480 m/s underground the Taoshan Coal Mine. The above parameters are substituted into Expression (7), and the loading strain rate range of the rock burst induced dynamic load can be got as shown in Table 2. Clearly, the maximum strain rate of the dynamic load is at class 10^{-3}~10^{-1} s^{-1}, which belongs to a medium strain rate range.

4. Statistical Analysis on Mining Dynamic Load Strain Rate

Calculation and statistics are carried out for dynamic load strain rate at different energy levels of mining earthquakes with the same method presented in Section 3.3. Due to having no lower limit of strain rate, the shear wave velocity is applied for estimation in statistics in order to get maximum strain rate, and the shear wave velocity is assumed as 2480 m/s. The results are shown in Table 3. The statistical results show that the higher the mining seismic energy is, the bigger its maximum peak vibration velocity is, but the lower the vibration frequency is. The final mining dynamic load strain rate increases with mining seismic energy, but the maximum strain rate is still generally less than class 10^{-1}/s.

5. Conclusions

Mining earthquake shockwave propagation can enable coal and rock mass to be loaded and unloaded. When the loading and unloading are strong and changing quickly, the dynamic load will occur in coal and rock mass. A combination of this dynamic load and static load can cause easily such disasters as rock burst, coal and gas outburst, roof fall, and water inrush.

Loading strain rate caused by shockwave in coal and rock medium is in direct proportion to shockwave frequency and particle peak vibration velocity and is inversely proportional to wave velocity. In the shockwave propagating process, the high-frequency component damps faster and the lower-frequency component damps more slowly. The particle peak

Table 2: Range of rock burst induced dynamic load strain rate.

Shockwave form	Frequency (Hz)	Maximum particle peak vibration velocity (m/s)	Velocity of shockwave (m/s)	Strain rate (s^{-1})
Longitudinal wave	2~15	0.52~4.38	4300	1.5×10^{-3}~9.6×10^{-2}
Shear wave	2~15	0.52~4.38	2480	2.6×10^{-3}~1.7×10^{-1}

Table 3: Statistics of mining dynamic load strain rate range of mining earthquakes.

Number	Monitored energy/J	Frequency/Hz	Maximum particle peak vibration velocity/(m/s)	Strain rate/(s^{-1})
1	296	5~30	0.13~0.40	1.6×10^{-3}~3.0×10^{-2}
2	400	5~30	0.18~0.66	2.3×10^{-3}~5.0×10^{-2}
3	895	3~28	0.20~0.65	1.5×10^{-3}~4.6×10^{-2}
4	1240	3~25	0.20~0.84	1.5×10^{-3}~5.3×10^{-2}
5	8270	2~18	0.34~1.00	1.7×10^{-3}~4.6×10^{-2}
6	22600	2~18	0.79~3.44	4.0×10^{-3}~1.6×10^{-1}
7	27100	1~15	0.44~3.50	1.1×10^{-3}~1.3×10^{-1}
8	50400	2.5~15	0.50~3.27	3.2×10^{-3}~1.2×10^{-1}
9	103000	0.5~12	1.23~3.65	1.6×10^{-3}~1.1×10^{-1}
10	3970000	0.4~5	8.45~12.27	8.6×10^{-3}~1.6×10^{-1}

vibration velocity is generally in the low-frequency vibration period and damps with transmitting distance by a power function.

The dynamic load generated in coal and rock medium by mining earthquake shockwave will reach its maximum value, and its loading strain rate is generally less than class 10^{-1}/s. The dynamic mechanical characteristics of the coal and rock mass under the action of mining dynamic load should be studied by dynamic load in the strain rate range.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

Financial support for this work, provided by the National Natural Science Foundation of China (no. 51404243) and supported by the Fundamental Research Funds for the Central Universities (no. 2014QNB26), is gratefully acknowledged.

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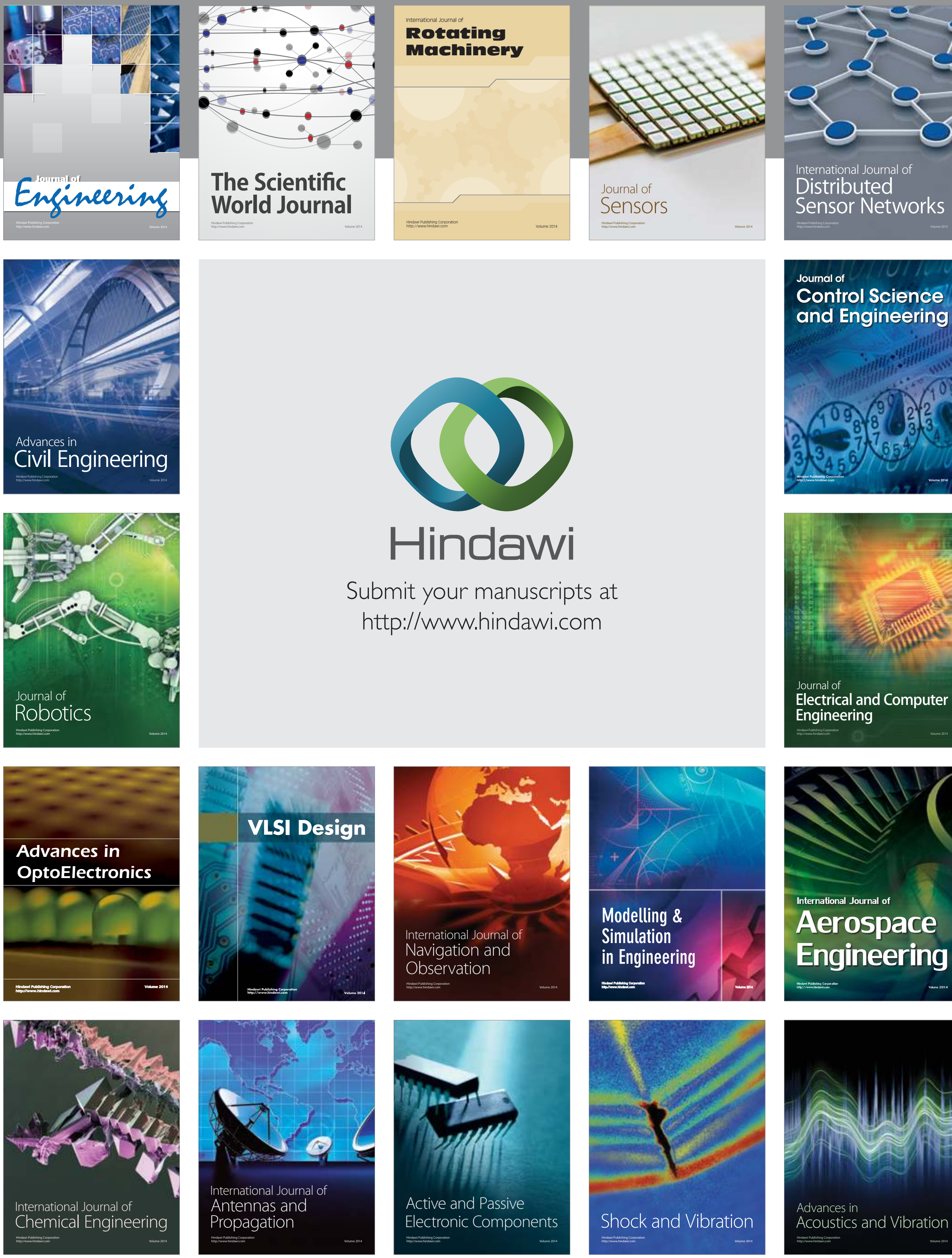
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