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Features of energy distribution for blast vibration signals based on wavelet packet decomposition①

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Abstract: Blast vibration analysis constitutes the foundation for studying the control of blasting vibration damage and provides the precondition of controlling blasting vibration. Based on the characteristics of short-time non-stationary random signal, the laws of energy distribution are investigated for blasting vibration signals in different blasting conditions by means of the wavelet packet analysis technique. The characteristics of wavelet transform and wavelet packet analysis are introduced. Then, blasting vibration signals of different blasting conditions are analysed by the wavelet packet analysis technique using MATLAB; energy distribution for different frequency bands is obtained. It is concluded that the energy distribution of blasting vibration signals varies with maximum decking charge, millisecond delay time and distances between explosion and the measuring point. The results show that the wavelet packet analysis method is an effective means for studying blasting seismic effect in its entirety, especially for constituting velocity-frequency criteria.

Key words: blasting vibration; non-stationary random signal; energy distribution; wavelet transform; wavelet packet decomposition

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1 INTRODUCTION

Blasting vibration analysis constitutes the foundation for studying the control of blasting vibration damage and provides the precondition of controlling blasting vibration. In the past, the main means of analysis and processing for blasting vibration signals was to use the Fourier Transform (FT). By examining considerable amounts of blasting vibration data, the signals have a distinct characteristic of short-duration and abrupt change in the signal structure, including its spectrum. These characteristics are attributed to typical non-stationary random signal[1, 2]. Due to the lack of progress in theoretical development of non-stationary signal processing in the past, researchers had to simplify the blasting vibration signals as stationary signals (fake stability) that can be analysed and they were processed by the Fourier Transform (FT).

However, with recent developments and progress in science and technology, time-frequency methods can now be applied to signal processing in the field of engineering. Recently, many researchers have shown interest for non-stationary signal processing by wavelet transform. Unfortunately, blasting vibration signal processing by wavelet transform is still at its infancy, and many researchers are attempting to explore the potential of such a technique[3, 4]. In this paper, blasting vibration signals are analysed on the basis of non-stationary characteristics and these are processed by the wavelet packet decomposition method. The study concludes that energy distribution of blasting seismic wave during propagation varies with maximum decking charge, millisecond delay time and distance between the blasting centre and measuring point. The method is an effective means for investigating blasting seismic effect, especially for constituting velocity-frequency criteria.

2 WAVELET PACKET DECOMPOSITION AND ENERGY FOR BLAST VIBRATION SIGNALS

2.1 Wavelet packet analysis and its characteristics

Wavelet transform can decompose a signal into an "approximation" and a "detail" of the signal.

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The approximation is the low-frequency components and the detail is the high-frequency components of the signal. The approximation is itself then decomposed into a second-level approximation and detail, and the decomposition process can be repeated. It can be seen from the structure of wavelet decomposition that with increasing frequency, the resolution power of frequency reduces considerably. In wavelet packet analysis, the details as well as the approximations can be separated. The wavelet packets decomposition can select self-adaptation correspondent frequency band to match the spectrum of signal on the basis of signal characteristics. This is a better method than wavelet decomposition because the wavelet packets decomposition was developed from rigorous mathematical theory and supported by numerical calculation verification. Many monographs have since been written and expounded[4-6].

2.2 Wavelet packets decomposition of blasting vibration signals

When signals are decomposed by wavelet packets, the decomposition layers are decided by the signal and working frequency band of the seismic instrument. In this paper, the lowest working frequency of the seismic instrument is 5 Hz. Because the frequency of blasting vibration signals is commonly less than 200 Hz, the sampling rate of signal is set for 2 500 Hz on the basis of sampling theorem[7]. Its Nyquist frequency is 1 250 Hz. So, the signal can be decomposed to the eighth layer, and its lowest frequency band is between 0 - 4.883 Hz. Using simple mathematics for wavelet packets decomposition, the range of frequency band for reconstructed signal is shown in Table 1.

2.3 Token of energy for different frequency bands

The analysed signal is decomposed to the eighth layer. Supposing $E_{8,j}$ represents the energy of $S_{8,j}$, then[8]

$$E_{8,j} = \int |S_{8,j}|^2 \mathrm{d}t = \sum_{k=1}^{m} |x_{j,k}|^2 \tag{1}$$

where $x_{j,k}(j=0, 1, 2, \cdots, 2^8-1;\ k=1, 2, \cdots, m)$ represents the discrete sampling amount of signal representing the amplitude of vibration of reconstructed signal $S_{8,j}$.

Supposing the total energy of signals is E_0, then

$$E_0 = \sum_{i=0}^{2^8-1} E_{8,j} \tag{2}$$

The proportion of different frequency band energy to the total energy of the analysed signal is defined as

$$E_j = \frac{E_{8,j}}{E_0} \times 100\% \tag{3}$$

where $j=0, 1, 2, \cdots, 2^8-1$.

So, energy of different frequency bands for signals is obtained by wavelet packet analysis. Thereafter, we can determine the law of energy distribution for blasting vibration signals during propagation.

3 LAWS OF ENERGY DISTRIBUTION FOR DIFFERENT FREQUENCY BANDS

3.1 Monitoring experiments of blast vibration

Blast vibration monitoring experiments have been conducted in an underground mine. The signals obtained at four measuring points were analysed. The blasting parameters of the four measuring points are summarised in Table 2, and the velocity-time curves of blasting vibration at these four measuring points are shown in Fig. 1.

Table 1 Range of frequency band for reconstructed signal by wavelet packet coefficient

Layer	$S_{i,0}$	$S_{i,1}$	$S_{i,2}$	…	$S_{i,j-1}$	$S_{i,j}$
1	0 - 625.000					625.000 - 1 250.000
2	0 - 312.5.000	312.500 - 625.000	625.000 - 937.500			937.500 - 1 250.000
3	0 - 156.250	156.250 - 312.500	312.500 - 468.750			1 093.750 - 1 250.000
4	0 - 78.125	78.125 - 156.250	156.250 - 234.375	…	1 093.750 - 1 171.875	1 171.875 - 1 250.000
5	0 - 39.063	39.063 - 78.125	78.125 - 117.188	…	1 171.875 - 1 210.937	1 210.937 - 1 250.000
6	0 - 19.531	19.531 - 39.063	39.063 - 58.594	…	1 210.937 - 1 230.469	1 230.469 - 1 250.000
7	0 - 9.766	9.766 - 19.531	19.531 - 29.297	…	1 230.469 - 1 240.234	1 240.234 - 1 250.000
8	0 - 4.883	4.883 - 9.766	9.766 - 14.649	…	1 240.234 - 1 245.117	1 245.117 - 1 250.000
…	…	…	…	…	…	…

Note: $S_{i,j}$ represents the reconstructed signal of ith layer and jth wavelet packet decomposition coefficients, $j=0, 1, 2, \cdots, 2i-1$; $i=1, 2, 3, \cdots, n$.

Table 2 Blasting parameters at four measuring points

Ser. No.	Distance between measuring point and explosion centre/m	Maximum decking charge/ kg	Total charge/ kg	Delay tag
1	23.6	84	484	2, 4, 5, 6, 7, 9
2	57.5	84	484	2, 4, 5, 6, 7, 9
3	23.6	170	1 200	2, 4, 5, 6, 7, 8, 9
4	57.5	170	1 200	2, 4, 5, 6, 7, 8, 9

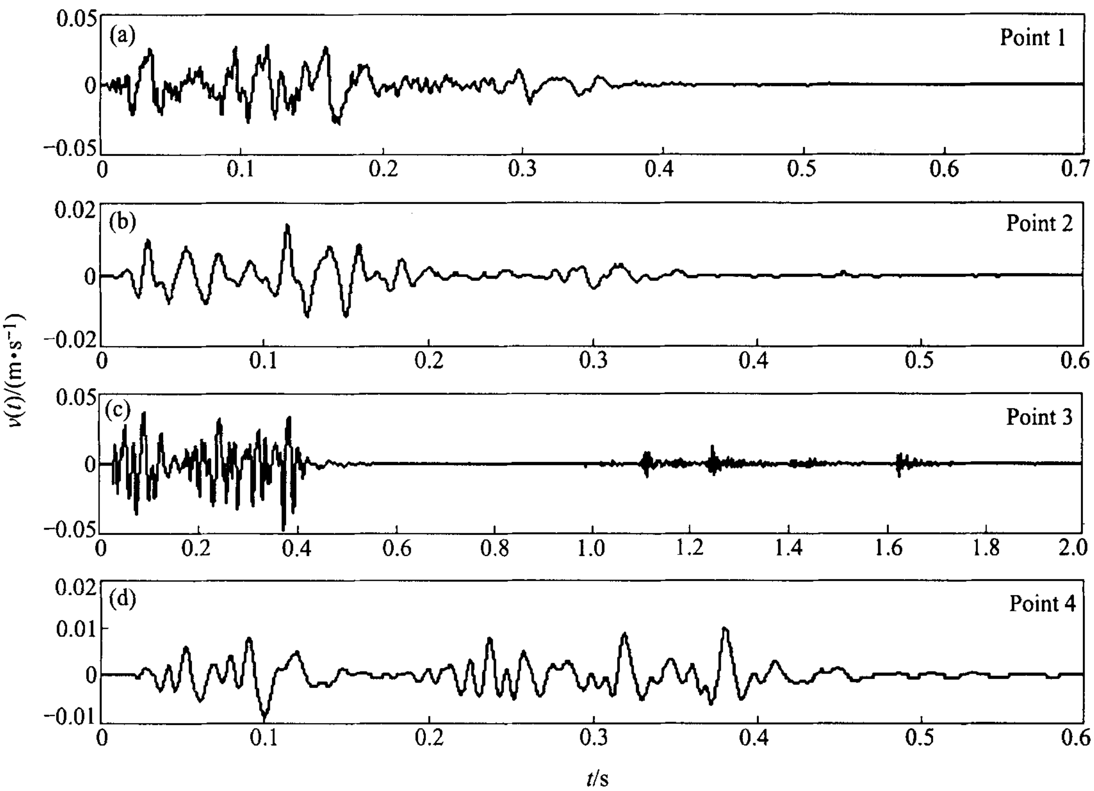

Fig. 1 Velocity vs. time curves of blasting vibration at four measuring points

3.2 Wavelet analysis of blasting vibration signals

3.2.1 Basic wavelet choice

Selecting the optimal basis wavelet when the signals are analysed by means of the wavelet packet method is important. This is because different basic wavelets can bring about different results for the same analysed signal[9-11]. In practical applications, the user should choose a function as the function that attenuates speedily and its wave shape is similar to the analysed signals. So, basic wavelet choice is related to the character and quality of the analysed signal. Considering that Daubechies wavelet series(db$N$) have the characteristics of compactly supported and approximate symmetry, it is applied successfully to process the non-stationary signals, including blasting vibration signals[12].

In using the positive integral N, the wavelet series have different sequences. At present, db3, db5, db7and db8 are applied largely in processing blasting vibration signals. Common wavelet functions of blasting vibration analysis are shown in Fig. 2. According to the requirement of basic wavelet choice and the characteristics of analysed signals, the db8 was selected as the wavelet function.

3.2.2 Wavelet packet analysis

MATLAB6.1 was used to analyse, by wavelet packet, the blasting vibration signals shown in Fig. 1. The energy distribution can be calculated numerically and these are shown in Fig. 3. For comparison, the percentage energy for blasting vibration signals at different frequency bands is shown in Table 3.

3.3 Laws of energy distribution for different frequency bands

It can be seen from Fig. 3 and Table 3 that the percentage of energy for signals in the 0 - 200 Hz range is 91.93%, 98.94%, 97.16% and 99.14% respectively. This shows that the energy of blasting vibration signals in underground engineering

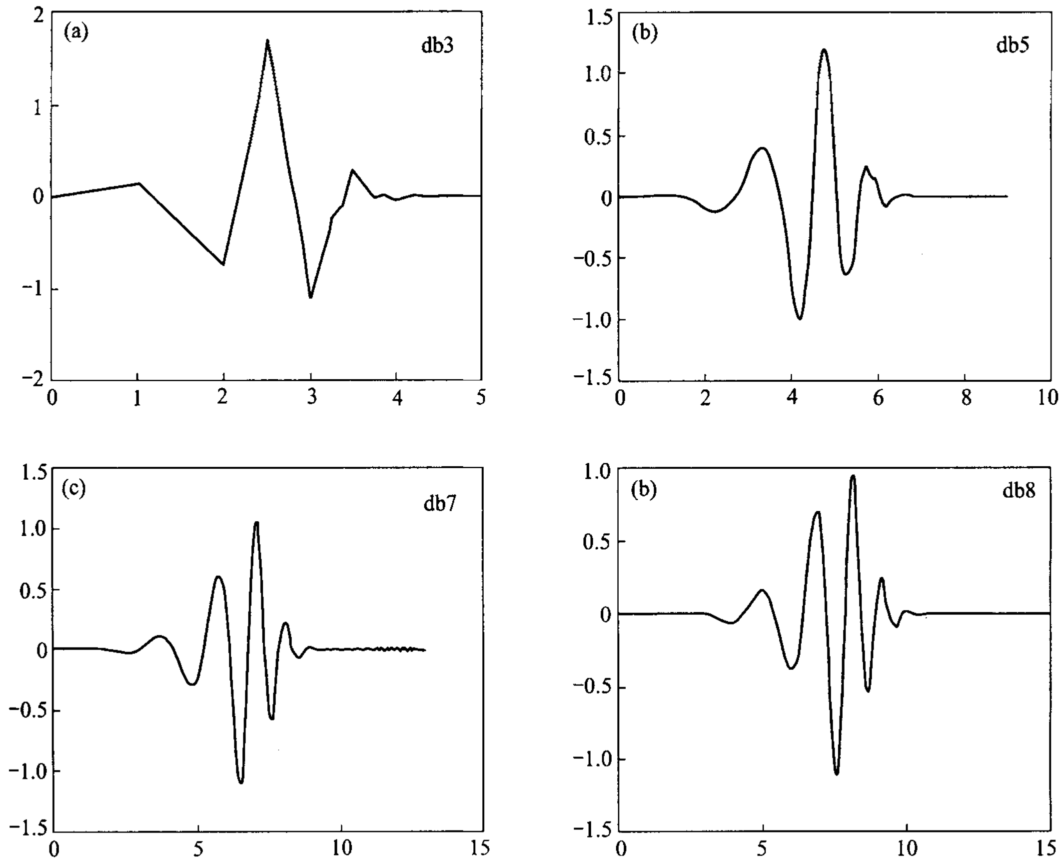

Fig. 2　Common wavelet functions of blasting vibration analysis

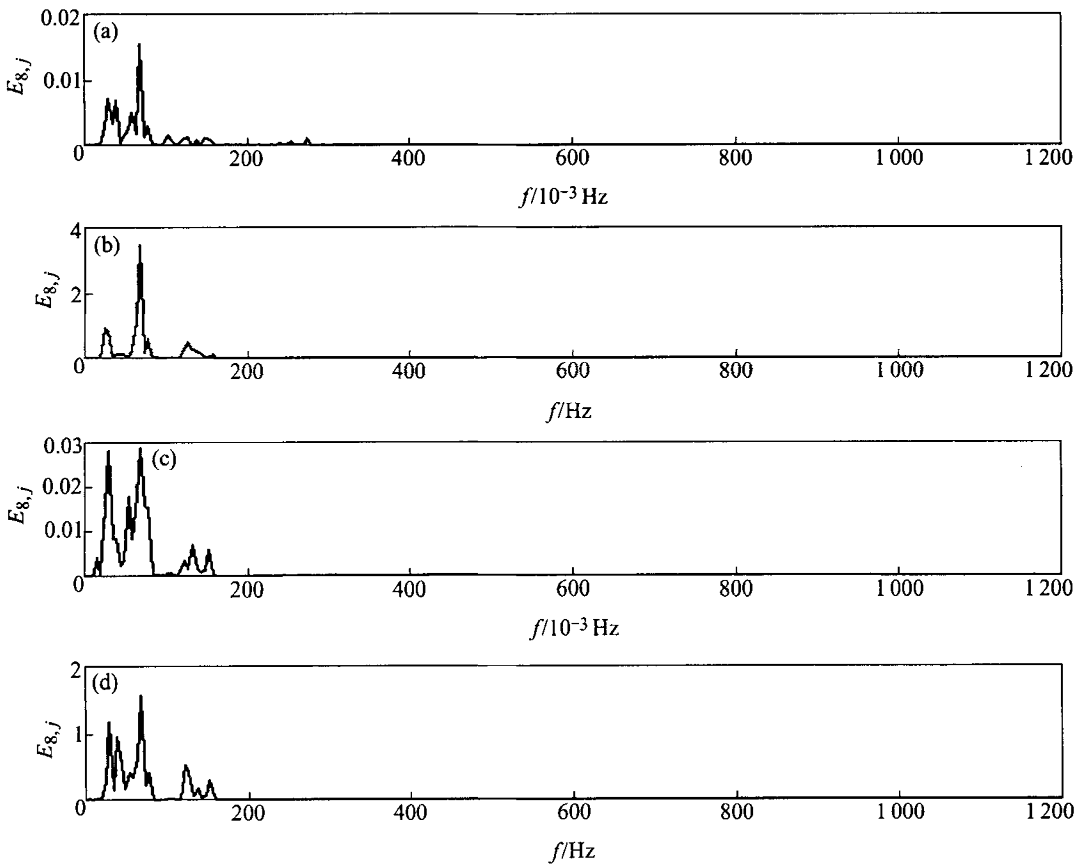

Fig. 3　Energy distribution of frequency band for blast vibration signals at four measuring points

Table 3 Percentage of energy for blast vibration signal at different frequency bands

Frequency band	Point 1	Point 2	Point 3	Point 4	Frequency band	Point 1	Point 2	Point 3	Point 4
0.000 - 4.883	0.030	0.161	0.026	0.151	102.540 - 107.420	1.250	0.021	0.291	0.285
4.883 - 9.766	0.080	0.009	0.027	0.012	107.420 - 112.300	0.270	0.152	0.062	0.029
9.766 - 14.648	0.330	0.163	1.940	0.347	112.300 - 117.190	0.550	0.410	0.542	0.219
14.648 - 19.530	0.440	0.013	0.385	0.175	117.190 - 122.070	1.650	3.261	1.718	6.065
19.530 - 24.414	3.870	9.342	7.445	3.272	122.070 - 126.950	2.030	4.972	0.768	4.720
24.414 - 29.297	10.20	8.183	13.38	13.42	126.950 - 131.840	0.150	2.555	3.315	0.746
29.297 - 34.180	5.100	0.304	3.898	1.722	131.840 - 136.720	1.500	2.221	0.873	2.038
34.180 - 39.063	10.00	1.592	3.989	10.80	136.720 - 141.600	0.110	1.650	0.479	0.594
39.063 - 43.945	0.600	1.560	1.163	6.104	141.600 - 146.480	1.510	0.648	0.693	0.723
43.945 - 48.828	2.360	1.554	1.695	2.000	146.480 - 151.370	1.710	0.522	2.879	3.341
48.828 - 53.711	3.680	0.546	8.476	4.691	151.370 - 156.250	1.070	1.495	0.413	0.736
53.711 - 58.594	7.240	2.810	3.943	3.970	156.250 - 161.130	0.010	0.003	0.020	0.002
58.594 - 63.477	2.680	11.42	8.692	7.403	161.130 - 166.020	0.010	0.003	0.021	0.002
63.477 - 68.359	22.20	34.66	13.73	17.81	166.020 - 170.900	0.020	0.003	0.018	0.001
68.359 - 73.242	1.990	1.891	7.488	2.570	170.900 - 175.780	0.240	0.003	0.014	0.002
73.242 - 78.125	4.230	6.063	7.326	4.678	175.780 - 180.660	0.020	0.004	0.053	0.007
78.125 - 83.008	0.460	0.176	0.391	0.027	180.660 - 185.550	0.090	0.009	0.035	0.002
83.008 - 87.891	0.330	0.241	0.186	0.044	185.550 - 190.430	0.270	0.003	0.020	0.002
87.891 - 92.773	0.150	0.089	0.245	0.026	190.430 - 195.310	0.030	0.004	0.038	0.002
92.773 - 97.657	0.660	0.064	0.188	0.014	195.310 - 200.200	0.390	0.027	0.044	0.006
97.657 - 102.54	2.440	0.157	0.293	0.384	200.200 - 1250.00	8.070	1.058	2.842	0.864

is distributed widely, but the major part of the energy is concentrated in the 0 - 200 Hz range. With increasing propagation distance, the percentage of the energy for high frequency decreases, especially in the 200 - 1 250 Hz range.

It can be observed in Table 3 that the percentage of energy signals in the 10 - 80 Hz range is 75.5%, 80.3%, 83.9% and 79.0%. This indicates the wide dominant frequency band that can be divided into many sub-bands. Clearly, underground structure systems with many sub-structures are complicated by joints, cracks and mine-out areas. Every sub-structure has natural characteristics. So, the vibration of underground structures has multi-mode and multi-pattern characteristics. It can be concluded that the dominant frequency bands of blast vibration signals tend towards low-frequency with increase in maximum decking charge.

4 CONCLUSIONS

The proposed method makes full use of the characteristics that wavelet packet analysis has high resolution. The signals in underground engineering are analysed by means of wavelet packet decomposition based on MATLAB, and the figures of energy distribution for different frequency bands are obtained. The method is an effective means for studying blast seismic effect in its entirety, especially for constituting velocity-frequency criteria.

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