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Blasting wave pattern recognition based on Hilbert-Huang transform

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Abstract. Rockburst is becoming more serious in Chinese coal mine. One of the effective methods to control rockburst is blasting. In the paper, we monitored and analyzed the blasting waves at different blast center distances by the Hilbert-Huang transform (HHT) in a coal mine. Results show that with the increase of blast center distance, the main frequency and amplitude of blasting waves show the decreasing trend. The attenuation of blasting waves is slower in the near blast field (10-75 m), compared with the far blast field (75-230 m). Besides, the frequency superposition phenomenon aggravates in the far field. A majority of the blasting waves energy at different blast center distances is concentrated around the IMF components 1-3. The instantaneous energy peak shows attenuation trend with the blast center distance increase, there are two obvious energy peaks in the near blast field (10-75 m), the energy spectrum appears "fat", and the total energy is greater. By contrast, there is only an energy peak in the far blast field, the energy spectrum is "thin", and the total energy is lesser. The HHT three dimensional spectrum shows that the wave energy accumulates in the time and frequency with the increasing of blast center distance.

Keywords: blasting wave; rockburst; HHT; instantaneous energy

1. Introduction

In recent years, with the rapid development of Chinese economy, there is a substantial increase in energy demand. With significant attention being paid to the concept of "less gas and oil", as the primary energy source, coal production have witnessed significant increase. In 2014, the total output of Chinese coal is 35 million tons, which accounts for more than half of the total output globally. About 95% of the coal in China is extracted from underground mining (http://www.stats.gov.cn/). In recent years, with the increase of coal mining depth and mining intensity, the geology and geomorphology of coal mines have become rather more complex, and the underground mining industry is facing significant challenges due to the increasing in the risk of

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accidents and other environmental hazards when mining at greater depths. Nowadays, the "three high and one low" combination (high stress, high gas pressure, high temperature and low permeability) has been very common, rockburst is becoming more serious in deep mining. Besides, rockburst may trigger gas outburst and gas explosion, such as the case happened in the Sunjiawan mine, Liaoning Province, China, where on February 14, 2005, a rockburst triggered abnormal effusion of gas, which subsequently led to gas explosion, and killed 214 people (State Administration of Work Safety http://www.chinasafety.gov.cn/newpage/). Therefore, it is urgent need to carry out scientific and reasonable actions to prevent rockburst. It is well-known that rockburst often occurs in coal seams with burst tendency and high pressure. These coal seams are characterized by the hard roof above the coal seam, which causes high stress degree in the working area. When the hard roof fractures suddenly, it releases a huge of energy, which can cause significant damage (property and lives loss).

The common methods adopted in coal mines to control rockburst including hydraulic measures (hydraulic fracturing, water injection softening, hydraulic cutting roof, etc.), blasting for pressure release, big diameter drilling and so on (Dvorsky and Konicek 2005, Liu *et al*. 2015, Zou and Lin 2015). Among these methods, blasting is the most widely used method because it can crush the thick and hard roof quickly and effectively, and reduce the degree of stress concentration, which can greatly eliminate the risk of rockburst. Being an important engineering technology, blasting is increasing used in military; mining; and railway, highway, port, airport, tunnel construction and in other fields (Ak and Iphar 2009, Kuzu and Guclu 2009, Dindarloo 2015, Kuzu 2008, Lu *et al*. 2010). While analyzing the effect of blast induced seismic wave on coal and rock masses is complex, because solving it requires the knowledge of geophysics, explosion mechanics and structural dynamics, etc. Therefore, understanding and solving this problem has high theoretical and practical importance.

Many scientific studies in the field of rock mechanics have been carried out on the mechanism, propagating laws of blasting vibration, blasting vibration control technology, monitoring method, and the failure criterion (Downing 1985, Wang *et al*. 2008, Khandelwal and Singh 2006, Wu *et al*. 1998, Lucca 2003). Almost all of these studies present useful and valuable results. In essence, the blasting seismic effect could be defined as the propagation of blasting energy through the medium in the wave form, the central topic for studying the wave effect is to accurately and scientifically evaluate the influence range of the blasting vibration (Li *et al*. 2010). The impact of blasting wave on coal rock masses mainly involves two aspects: (1) blasting seismic wave characteristics; and (2) coal rock masses dynamic response characteristics affected by blasting, which can be controlled based on the blasting parameters. However, due to the blasting wave instantaneity, complexity and the multilateral quality of the blasting medium and hosting conditions, the blasting vibration randomness is very obvious. The blasting wave is a complex nonstationary random signal, which possesses the characteristics of short duration and fast changing. Thus, analyzing the blasting wave characteristics forms the basis to understand the mechanism of blasting, the propagation law, and the safety assessment and vibration control. However, during the propagation process, the intensity and frequency of blasting wave are closely related to the factors such as explosive source, physical properties of the propagation medium and so on. Until now, the blasting wave propagation law has not been understood completely.

Blasting vibration wave is a typical nonlinear and nonstationary signal. In the past, because of the limitations of signal analysis theory and computing power, blasting vibration signal analysis has some limitations. In recent years, with the rapid development of science and technology, signal analysis and data processing theory are becoming more and more perfect. Thus, the analysis and processing of nonlinear and nonstationary random signals are becoming increasingly important. Many researchers have studied the blasting signals using different methods. The most common tools adopted for blasting vibration signal analysis, including Fourier transform, fast Fourier transform (FFT), short-time Fourier transform, wavelet transform, wavelet packet transform and Hilbert-Huang transform (HHT). Among these methods, Fourier transform possesses the following characteristics: good frequency domain resolution, obvious physical meaning, and easy calculation of basis function and components size. Thus, it is not surprising that Fourier transform is the most wide used tool for signal detection (Song *et al*. 2015, Arash *et al*. 2014, Vinoth and Kumar 2014). But, some crucial restrictions exist when using the Fourier transform (Huang *et al*. 1998). For example, the signal to be analyzed must be strictly periodic or stationary; otherwise, the Fourier spectrum will provide little physical sense. Therefore, the Fourier transform often cannot completely provide an in-depth analysis of blasting vibration. By contrast, the time-frequency analysis methods can generate both time and frequency information simultaneously by mapping the one dimensional signal to a two dimensional time frequency plane. In real time signal analysis, it is assumed that the frequency resolution of the low frequency component is higher, and the time resolution of the high frequency component is higher. Among all the available time frequency analysis methods, the wavelet transform is regarded as a better one, and thus has been widely applied for vibration signal analysis (Daubechies 1992, Morlet *et al*. 1982, Chen and Cheng 2016). However, the wavelet transform also has some inevitable deficiencies (Peng *et al*. 2002), including the interference terms, border distortion and energy leakage, all of them will generate many small undesired spikes all over the frequency scales, which makes the results confused and difficult to interpret. What's more, due to the limitation of Heisenberg-Gabor inequality, the wavelet transform cannot achieve the fine resolutions in both time domain and frequency domain simultaneously. Therefore, although the wavelet transform has good time resolution in the high frequency region, it often cannot separate those impacts, as the time interval among them is usually too small.

Given the limitations of wavelet transform, another time-frequency analysis method named HHT (Huang *et al*. 1998, Huang *et al*. 1999) has become increasingly popular in recent years. The HHT method uses empirical mode decomposition (EMD) to ensure that the signal is smooth and the signal is decomposed by its fluctuation trend or amplitude. In the method, a series of different modes called intrinsic mode function (IMF) are generated, and then Hilbert transform is used to obtain the time-frequency characteristics of the signal. The HHT method is considered to be a major breakthrough in the linear and steady spectrum analysis. The method possesses the following advantages (Huang *et al*. 1998, Huang *et al*. 1999): (1) there is no prior basic function, thus makes the HHT more adaptive; (2) EMD is the best method to extract signal trend or mean in current, and it can better deal with the strong intermittent signal; (3) with the application of Hilbert transform, the instantaneous frequency presents clear physical meaning, which can provide information about the local features of the signal; and (4) the HHT three dimensional spectrum can accurately reflect the nonlinear characteristics with intra wave modulation mechanism. By performing an envelope analysis on each IMF component, it is possible to extract the characteristics of the original signal with greater veracity and validity. In addition, the frequency components involved in each IMF not only to the sampling frequency but also to changes in the signal itself. That is, EMD can be regarded as a self-adaptive signal processing method that can be applied to nonlinear and nonstationary process (Yang *et al*. 2007). Many scholars have applied this method in many fields, including seismic signal analysis (Loh *et al*. 2001, Shen *et al*. 2003), blasting vibration analysis (Li *et al*. 2016a, b, Liu 2010), damage analysis (Li *et al*. 2005, Li *et al*.

2016a, b, Yu *et al*. 2005), structural energy response analysis (Tan *et al*. 2004), seismic liquefaction analysis (Liu *et al*. 2009), and vibration table model test of concrete frame structures (Zhang *et al*. 2003, Hu *et al*. 2004). These results demonstrate the excellent application of the HHT method for nonstationary signal analysis.

In the blasting vibration control technology, the attenuation law of blasting seismic wave is considered to predict the spectrum and frequency range of blasting wave at a specific blasting source, site and distance. The data from such analysis provides a relatively accurate estimation of the blasting wave. During blasting, the seismic intensity and blasting range (chamber and deep borehole blasting) are relatively large, and thus, increasing attention is paid to study the blasting effect. By contrast, very limited studies have been carried out on vibration triggered by shallow and medium deep borehole blasting in the coal mine. In this paper, the HHT method was used to analyze the blasting signals in the coal mine, to obtain an in-depth understanding of the blasting propagation regularity and influence scope. Thereby provide a scientific basis for drilling borehole in the coal mine at appropriate distance, which would better to reduce the accidents during underground mining. The research results could provide valuable insights for prevention and control of rockburst in the coal mine.

2. Hilbert-Huang transform theory

2.1 Empirical mode decomposition

In the EMD method, IMF satisfies the following two conditions (Huang *et al*. 1998, Huang *et al*. 1999): (1) for the entire data range, the extreme points number and zero crossings must be equal or differ at most 1; (2) at any point, the average value of the upper envelope formed by all maximum and minimum value points is 0. The decomposition is based on the following conditions: (1) there are at least 2 extreme points (1 maximum and 1 minimum) of the signal to be decomposed; (2) the local characteristic time scale is defined as the time interval of two adjacent extreme points or the minimum of the signal; (3) if there is no extreme point in the signal, but it contains a number of inflection point, the signal can still differ 1 or a few times, thus reveals the extreme points. The final score can be obtained by the final decomposition results.

An important advantage of the EMD method is that the processing steps are very simple. The basic idea for calculation is as follows: if the maximum or minimum $x(t)$ number of the original data sequence is 2 (or > 2), then the data sequence needs to be processed smoothly. The specific treatment method is as follows:

First, the cubic spline function $x(t)$ of the local maximum and minimum points are fitted to the upper and lower envelopes of $x(t)$. Then the mean value of the two envelopes is calculated as m_1. After obtaining the original data sequence, $x(t)$ is subtracted from m_1. Thus, a new data sequence h_1 of the low frequency can be obtained

$$h_1 = x(t) - m_1 \tag{1}$$

In general, h_1 is not the final IMF component, so it requires repeating the aforementioned process k times (k times "filter" process) until the resulting average envelope value tends to 0, then

$$h_{1k} = h_{1(k-1)} - m_{1k} \tag{2}$$

Where, h_{1k} is the data after k times screening; $h_{1(k-1)}$ is the data after k-1 times screening; m_{1k} is the mean value of $h_{1(k-1)}$ upper and lower envelope, which can be used to determine the value of standard deviation I_{SD}. The value of I_{SD} is used to determine whether or not each screening result is an IMF component

$$I_{SD} = \sum_{k=1}^{T} \frac{\left| h_{1(k-1)}(t) - h_{1k}(k) \right|}{h_{1(k-1)}^2(t)} \tag{3}$$

Where, T is for the time signal length, the value of I_{SD} is often taken from 0.2 to 0.3.

When h_{1k} meets the I_{SD} requirements, then through $c_1 = h_{1k}$ to get the signal $x(t)$. That is, c_1 is the first IMF component, which represents the most high frequency component of the original data sequence. By subtracting the primary data series $x(t)$ from the first IMF component c_1, the high frequency component can be removed, and the resulting data sequence r_1 can be obtained

$$r_1 = x_{(t)} - c_1 \tag{4}$$

If r_1 still contains longer local characteristic time scale information of $x(t)$, then r_1 will be used as a decomposed signal to repeat the Eqs. (1)-(4), until the information contained in r_n becomes very small, or r_n is a monotonic function. At the point r_n represents the mean or trend of the original data sequence.

Thus, we can obtain a series of IMF components $c_1, c_2, \ldots, c_n$ from the signal $x(t)$

$$r_1 - c_2 = r_2 \ ,?r_2 - c_3 = r_3 \quad r_{n-1} - c_n = r_n \tag{5}$$

The original data series can be represented by these IMF components and a mean or trend item. That is

$$x_{(t)} = \sum_{i=1}^{n} c_i + r_n \tag{6}$$

Because each IMF component represents a set of feature scale data sequences, the whole process is actually a superposition of the waves with different characteristics; the waves are decomposed from the original wave, and each IMF component is either linear or non-linear.

2.2 Hilbert spectral analysis

At first, each IMF component is subjected to Hilbert spectral analysis, namely the Hilbert transform and then corresponding analytical signal for the IMF component $c_i(t)$ is determined

$$H\left[c_i(t)\right] = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{c_i(t)}{t-\tau} d\tau \tag{7}$$

$$A\left[c_i(t)\right] = c_i(t) + jH\left[c_i(t)\right] = a_i(t) e^{j\theta_i(t)} \tag{8}$$

$$a_i(t) = \sqrt{c_i^2(t) + H^2\left[c_i(t)\right]} \tag{9}$$

$$\theta_i(t) = arctan\frac{H[c_i(t)]}{c_i(t)} \tag{10}$$

The corresponding instantaneous frequency is given as follows

$$\omega_i(t) = \frac{d\theta_i(t)}{dt} \tag{11}$$

Thus $c_i(t)$ can be expressed as

$$c_i(t) = \mathrm{Re}\left\{a_i(t)exp\left[j2\pi\int\omega_i(t)dt\right]\right\} \tag{12}$$

$c_i(t)$ is expressed in the joint time frequency plane, then we can obtain the Hilbert spectrum of $c_i(t)$.

$$H_i(\omega,t) = \begin{cases} a_i(t), \omega = \omega_i(t) \\ 0, \omega \neq \omega_i(t) \end{cases} \tag{13}$$

Next, $x(t)$ is analyzed by the Hilbert spectrum, through the Eq. (14)

$$x(t) = \mathrm{Re}\left\{a_i(t)exp\left[j2\pi\int\omega_i(t)dt\right]\right\} \tag{14}$$

In the same way, the amplitude and instantaneous frequency can be represented in the three dimensional graph using Eq. (14), which presents an outline of the amplitude in the joint time frequency plane. This amplitude frequency time distribution is defined as the original signal $x(t)$ of Hilbert amplitude spectrum $H(\omega,t)$.

3. Basic information about the study mine

3.1 Basic characteristics of mine and working face

The Qianqiu coal mine started production in 1958 and belongs to the Henan Energy Chemical Group Co. Ltd. Location of the Qianqiu coal mine is shown in Fig. 1. It is one of the primary mines of Yima coal group, and its production capacity is 2.1 million t/a. The main mining layer is 2-1 seam, and the average coal seam layer thickness is 3.9 m and it increases with the mining depth. The coal seam elevation in south is higher than in north. The top coal seam is consisted of mudstone (average thickness 24 m). This layer is characterized of uniform densification and less fissures. The coal sample compressive strength is 19.7 MPa, elastic modulus is 1.52 GPa, poisson ratio is 0.16. The rock type is complex, and consists of a combination of sandstone, siltstone, and mudstone as well as clay rock (thickness 0.3-32.81 m). Geological histogram of the mine is shown in Fig. 2.

The 21141 working face is located in the west wing of the working field No. 21. On its northern side is the 21121 working goaf. The virgin field 21161 forms the southern side. The average mining depth is 684.4 m. The immediate roof is composed of dark gray mudstone with

Fig. 1 Location of the Qianqiu coal mine

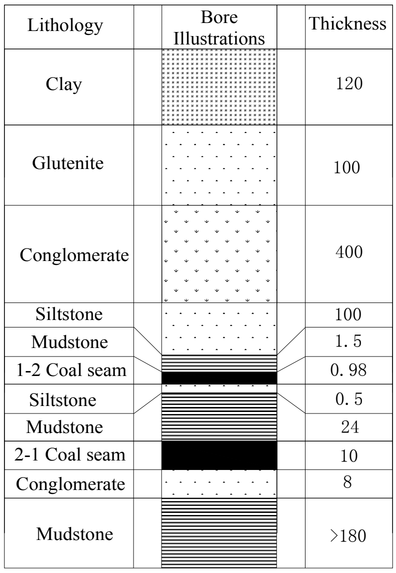


Fig. 2 Column illustration of the Qianqiu coal mine

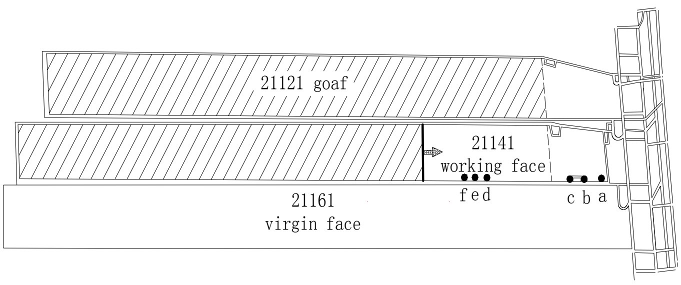


Fig. 3 Layout of the 21141 working face

Table 1 Blasting parameters

Test point	Burst distance/m	Distance of roof /m	Borehole diameter /mm	Borehole depth /m	Borehole inclination /°	Charge weight /Kg	Seal length /m	Connection mode
a	10	1.8	75	25	5	10.8	6.5	series connection
b	55	1.2	75	20	7	10.8	6.5	series connection
c	75	0.5	75	20	8	10.8	6.5	series connection
d	200	1.4	75	20	10	10.8	6.5	series connection
e	220	2.2	75	20	14	10.8	6.5	series connection
f	230	2.3	75	20	11	10.8	6.5	series connection

average thickness 25.44 m. The main roof is composed of mottled sand, coarse conglomerates, and sandstone. Its maximum thickness is up to 612 m). The work surface covered with F16 subduction thrust faults is relatively complex. Fig. 3 shows the layout of the 21141 working face.

3.2 Blasting and monitoring scheme

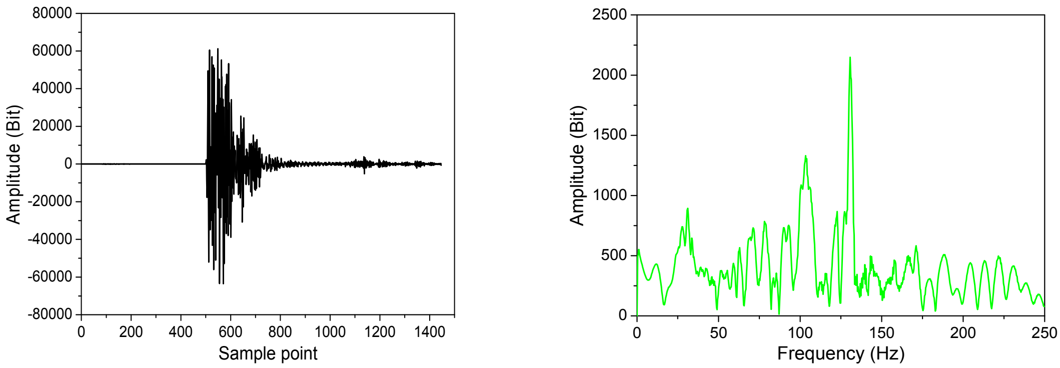
According to the field survey, most of the rockbursts were caused by roof rupture, and they often occured in the low lane of 21141 working face. Therefore, to reduce the risk of rockburst, we conducted blasting for roof pressure relief in different positions of the 21141 low lane. Because the coal seam is not stable, the distance of the borehole from bottom to roof, borehole depth and borehole inclination are not same for each borehole. The detailed parameters of the boreholes are as follows: the borehole diameter is 75 mm, mine safety emulsion explosive cartridge diameter is 70 mm and the explosive weight is 10.8 Kg. Once charging is completed, special sealing materials and sealing equipment are used to seal the blasting borehole, the sealing length is 6.5 m, and the blasting borehole specific parameters (i.e., azimuth, angle and the length of drilling), are presented in Table 1. The specific locations of test points are drawn in Fig. 3. A millisecond delay electric detonator initiation system was used in this study.

Blasting vibration test is the basis for vibration signal analysis, and is performed to study the blasting wave propagation law and its effect on the coal rock masses. To study the effects of blast vibration in the Qianqiu coal mine, data measurement was obtained using a seismographs device (ARAMIS, made in Poland). The sampling frequency of this device is 500 Hz.

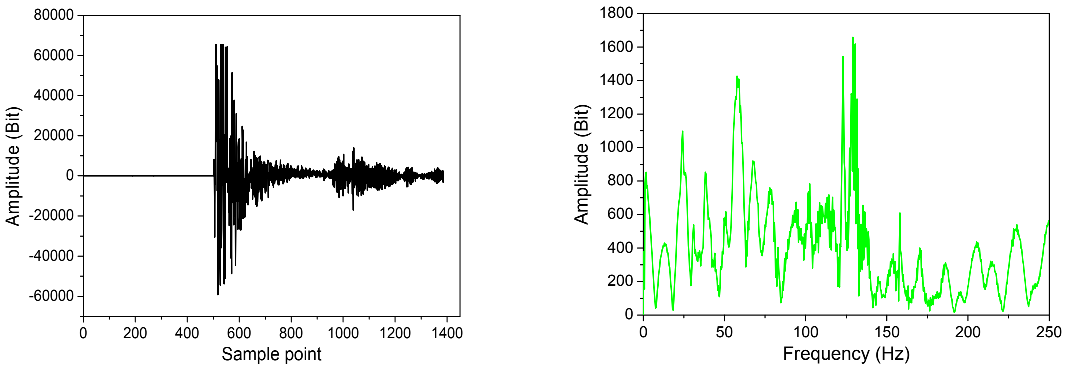
4. Preliminary analysis of monitoring data

While the blasting wave transports in the coal rock masses, there would be the energy transformation. It is affected by the blasting energy source and coal rock dynamic characteristics.

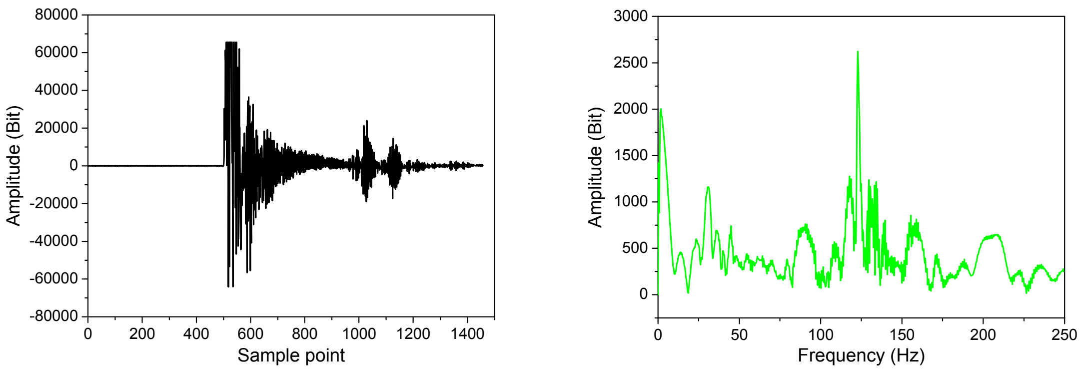
When the blasting wave propagates in the coal rock masses, the attenuation law of blasting wave with different frequency components is different. The attenuation mechanism depends on the characteristics of blasting source, and is determined by the geological conditions of working site. To study the propagation law of different frequency components of blasting wave at different blasting center distance, it is necessary to study each component separately, which helps us to extract the seismic wave signal from the frequency signal.



(a) Blasting wave and frequency spectrum at blasting center distance 10 m

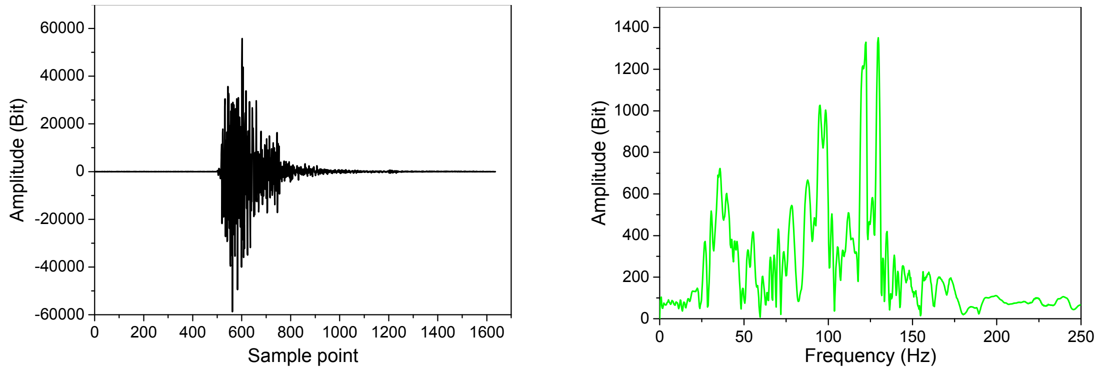


(b) Blasting wave and frequency spectrum at blasting center distance 55 m

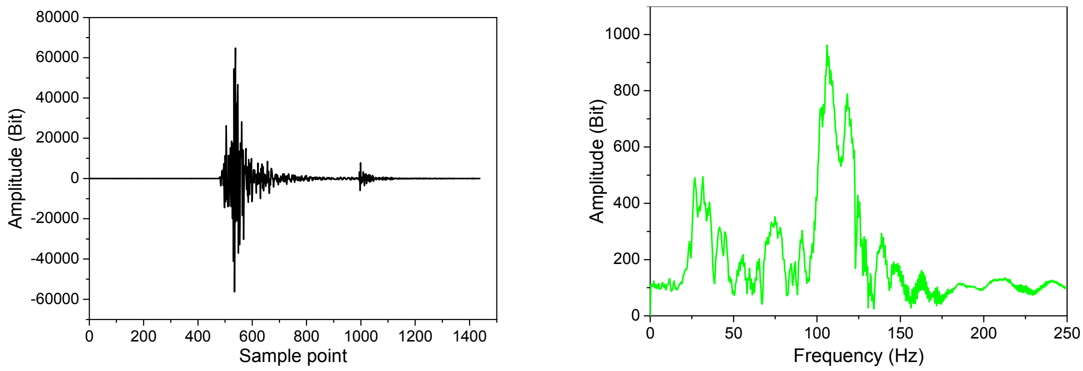


(c) Blasting wave and frequency spectrum at blasting center distance 75 m

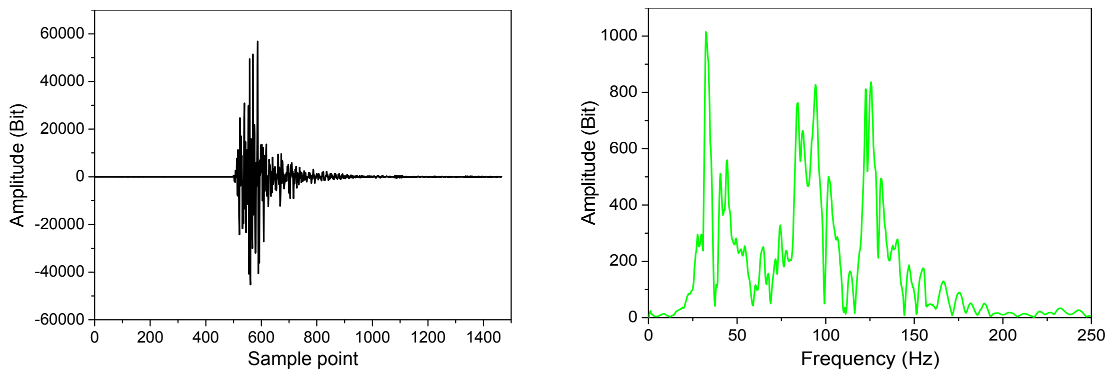
Fig. 4 Blasting waves and the corresponding spectra diagram at different blasting center distances



(d) Blasting wave and frequency spectrum at blasting center distance 200 m



(e) Blasting wave and frequency spectrum at blasting center distance 220 m



(f) Blasting wave and frequency spectrum at blasting center distance 230 m

Fig. 4 Continued

FFT analysis is a kind of very important wave analysis method, although it requires the analyzed signal should be linear and stationary, it still provides a valid method for monitoring the whole wave energy frequency distributions. So FFT method is used to obtain the frequency spectrum characteristics of blasting waves at different blast center distances, the results are shown in Fig. 4. From Fig. 4, it can be seen that the blasting waves are not very obvious difference at different blasting center distances. All of them reach a peak moment at shock point and the blasting duration is relatively short. Besides, the frequency variation is relatively small, and the overall frequency distribution in the low frequency region is within the 0-150 Hz range.

The blasting wave propagates in the complex geological conditions, which experiences the superposition of wave reflection and refraction. According to the frequency distribution of the blasting wave, three main frequencies can be noted, the first dominant frequency is about 30 Hz, the second is at around 60 Hz and the third is at 130 Hz. While the blasting center distance is 10 m, the main frequency and frequency band width are 130 Hz and 25-150 Hz, respectively. With the increase of blasting center distance, the dominant frequency of the blasting wave decreases to the low frequency. When the blasting center distance is 230 m, the main frequency is 35 Hz and frequency band width is 30-120 Hz. In addition, the amplitude also reduces from 2149 mV (blasting center distance is 10 m) to 1015 mV (blasting center distance is 230 m).

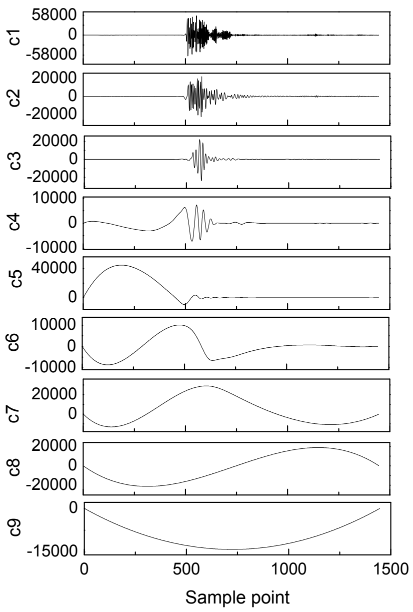
However, FFT needs many additional harmonic components to simulate non- stationary data that are non-uniform globally. Therefore, it spreads the energy over a wide frequency range (Huang *et al*. 1998). When the Fourier based analysis method is adopted, both non-stationarity and nonlinearity of the data can reduce spurious harmonic components, which would cause the energy dissipation.

5. HHT analysis of blasting vibration data

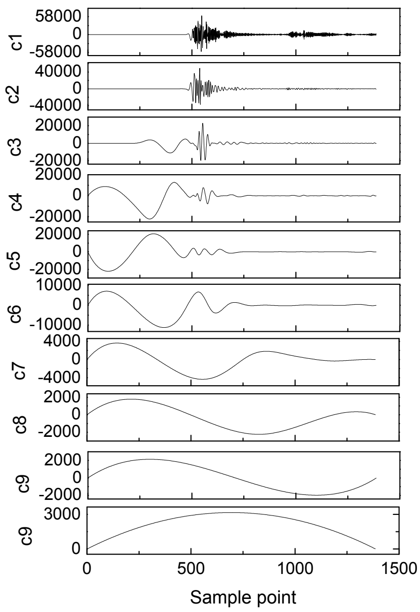
The EMD method is used to decompose the blasting waves at different blasting center distances, and the IMF components are shown in Fig. 5. It can be seen that all the original blasting waves could be decomposed into 8-10 IMF components, and in accordance with the time scale order, they are decomposed from high frequency to low frequency. From these IMFs, one can notice that a majority of the wave energy concentrates in the first three components. IMF components 1, 2 and 3 are the shortest in the time scale but highest in the frequency scale. The amplitude of these components is very large, and they make up most of the signal energy. With the decomposition processing, the time scale of each IMF becomes longer while the frequency starts to lower. It stops until the last IMF component whose time scale is the longest and frequency is the lowest.

The blasting wave is a kind of complex and unstable random signal with bandwidth frequency. When determining the impact of blasting wave, one should not only consider the particle vibration velocity, dominant frequency and duration, but also the characteristics of blasting structures. According to the structural dynamics theory (Yu 1987, Adhikari *et al*. 2004), due to the resonance effect, there would cause serious destruction when the main frequency of the blasting wave closer to the natural frequency of coal rock masses. The HHT instantaneous energy of blasting wave provides a quantitative comparison of the peak value of the waveform signal. The instantaneous energy of the blasting waves generated from different blasting center distances is shown in Fig. 6. It can be seen from the Fig. 6 that the instantaneous energy general appears “fat” in the near blasting zone (10-75 m), the energy dispersion and peak energy are high. Before attaining the peak energy, however, there is an obvious energy drop with a longer duration. Besides, the instantaneous energy pattern is generally “thin” in the far blasting zone (75-230 m), the energy concentration and the energy peak are relatively lower, and there is only one peak value.

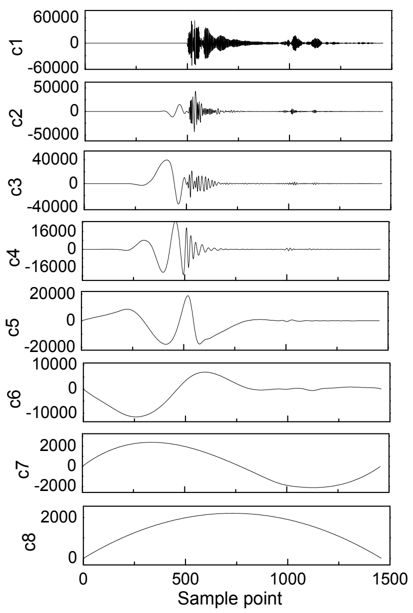
From the view of stress, in the near blasting zone (10-75 m), the millisecond delay blasting has a significant influence to the coal rock masses. In this case, attenuation is relatively smaller and the energy is larger. By contrast, in the far blasting zone (75-230 m), the high frequency energy attenuates quickly and the signal is superimposed. With the increasing of blasting center distance, the instantaneous energy peak of the blasting seismic wave decreases. The duration of instantaneous energy is consistent with the vibration duration, and it demonstrates multi peak characteristics, which is related to the superposition of seismic wave with millisecond delay blasting.



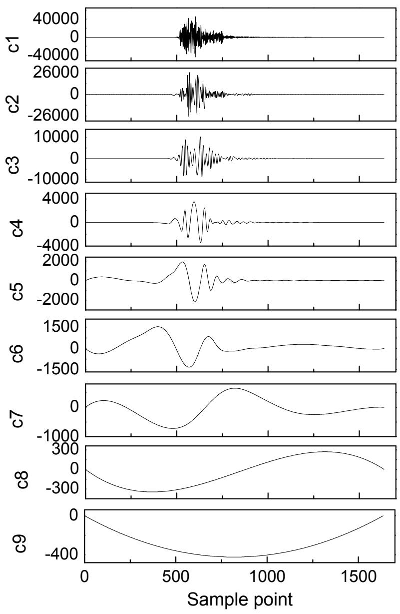
(a) IMF components at blasting center distance 10 m



(b) IMF components at blasting center distance 55 m

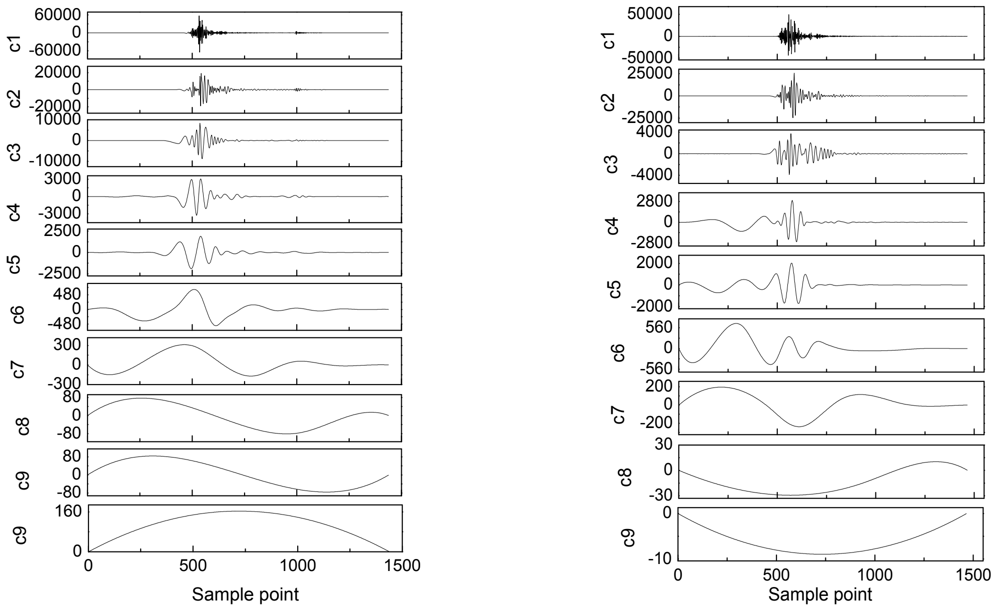


(c) IMF components at blasting center distance 75 m



(d) IMF components at blasting center distance 200 m

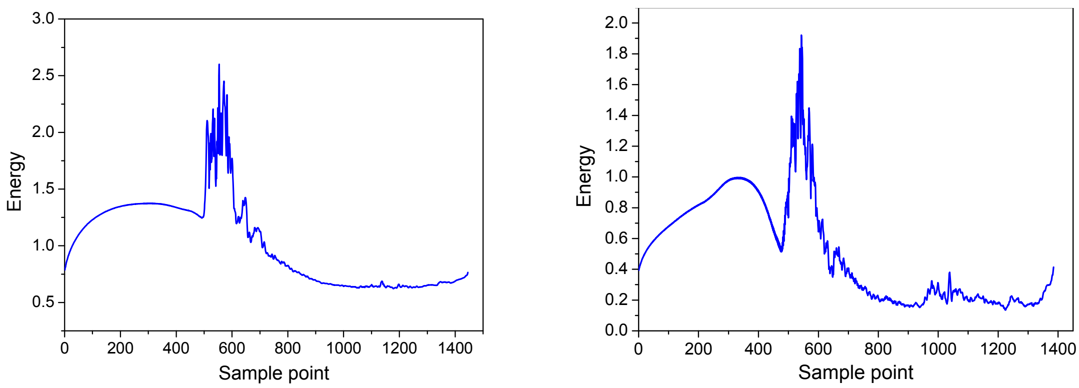
Fig. 5 IMF components at different blasting center distances



(e) IMF components at blasting center distance 220 m (f) IMF components at blasting center distance 230 m

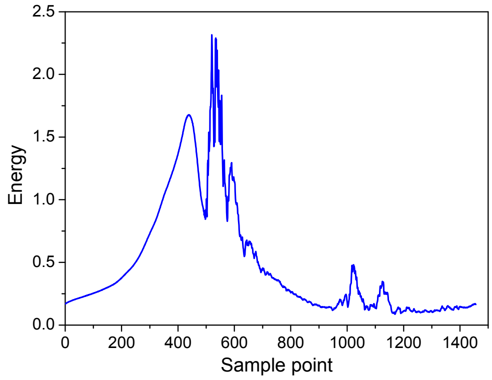
Fig. 5 IMF components at different blasting center distances

The instantaneous energy peak of blasting vibration at different blasting center distances is shown in Fig. 7. It can be seen that the instantaneous energy peak is 2.5 at the blasting center distance 10 m, and it is 1.9 for the distance 55 m. However, it is 1.27 when the distance is 230 m. This shows that the instantaneous energy attenuates with the increase of blasting center distances, but the attenuation rate is different at different blasting center distances. Overall, the blasting attenuates faster in the near blasting zone than the far blasting zone, which may be related to the geological conditions of coal rock masses.

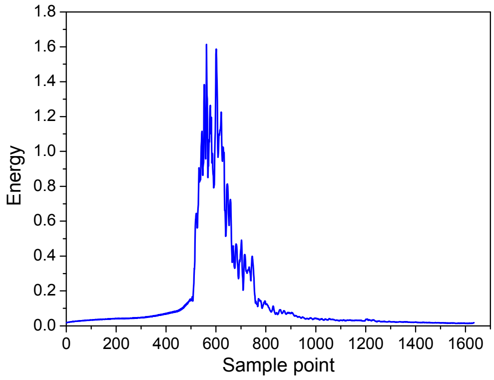


(a) Hilbert instantaneous energy at blasting center distance 10 m (b) Hilbert instantaneous energy at blasting center distance 55 m

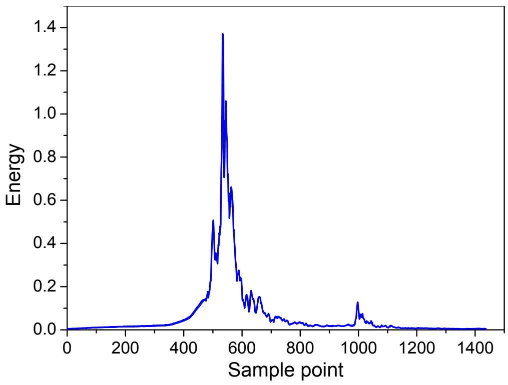
Fig. 6 Hilbert instantaneous energy at different blasting center distances



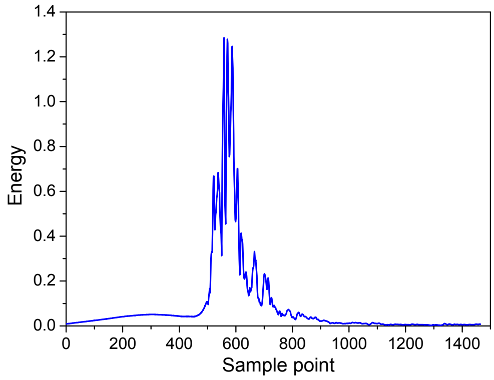
(c) Hilbert instantaneous energy at blasting center distance 75 m



(d) Hilbert instantaneous energy at blasting center distance 200 m



(e) Hilbert instantaneous energy at blasting center distance 220 m



(f) Hilbert instantaneous energy at blasting center distance 230 m

Fig. 6 Continued

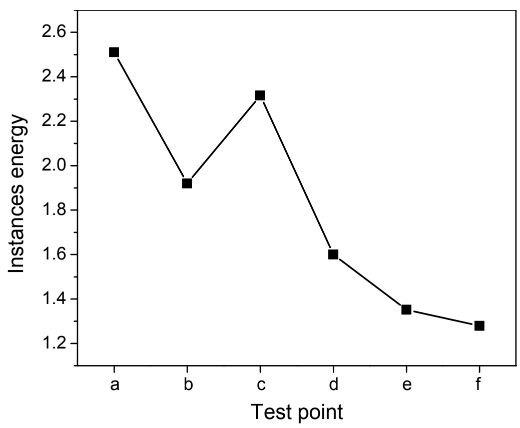
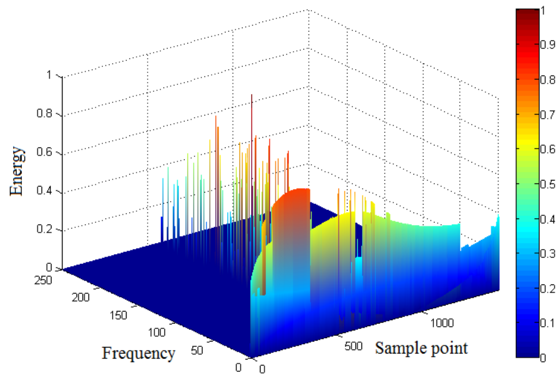


Fig. 7 Hilbert instantaneous energy peak at different blasting distances

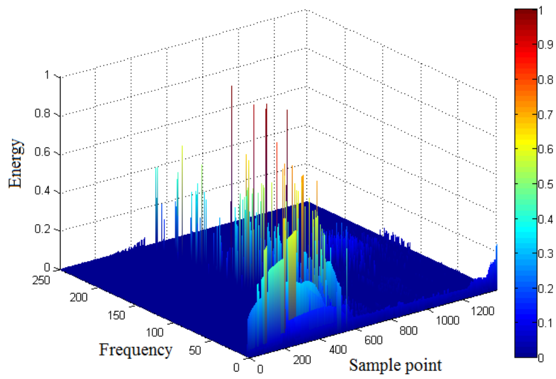
The three dimensional Hilbert spectrum is used to understand the intra wave modulation mechanism and it reflects the nonlinear characteristics of the system accurately, which is not possible through other signal processing methods. The time, frequency and amplitude of the blasting wave are included in the three dimensional Hilbert spectrum, and these parameters provide a clear understanding of the subtle changes in blasting energy along with the time and frequency. In general, the blasting wave energy is not continuous, but discrete. Ribbon and dentate graphics show that the energy distribution is relatively concentration, the concentrated degree and spectrum are the actual variation of the frequency and amplitude modulation. In the region where there is no energy, the spectral value is general 0. In contrast to other methods the false information and energy leakage would happen due to adding window.

It can be seen from Fig. 8 that the blasting waves energy mainly concentrate in the low frequency region, which mainly reflects the energy of IMF components 1-3. In the near blasting zone (10-75 m), the blasting waves energy accumulates in the low frequency zone. The smaller the blasting center distances, the more obvious is the low frequency accumulation phenomenon.

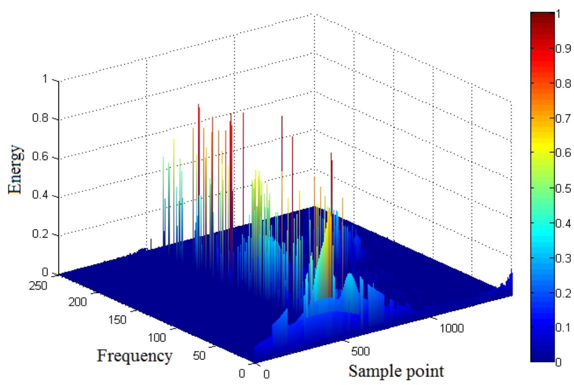
With the blasting center distance increasing, the energy distribution starts to spread in the high



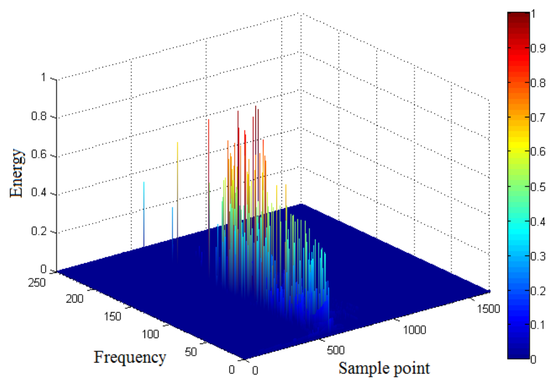
(a) Three-dimensional Hilbert spectrum at the blasting distance 10 m



(b) Three-dimensional Hilbert spectrum at the blasting distance 55 m

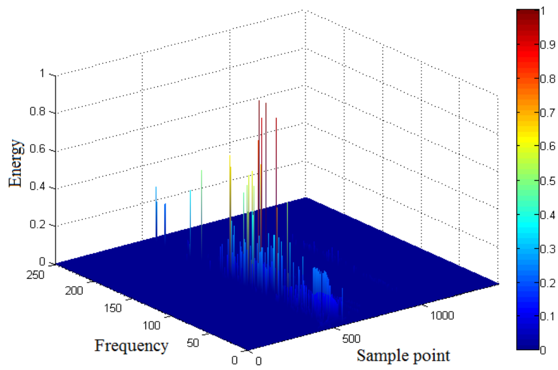


(c) Three-dimensional Hilbert spectrum at the blasting distance 75 m

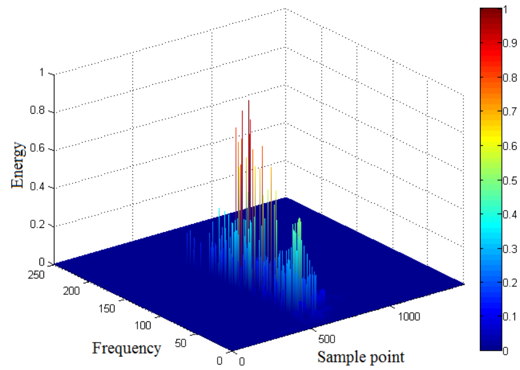


(d) Three-dimensional Hilbert spectrum at the blasting distance 200 m

Fig. 8 Time-frequency-amplitude spectra of HHT at different blasting distances



(e) Three-dimensional Hilbert spectrum at the blasting distance 220 m



(f) Three-dimensional Hilbert spectrum at the blasting distance 230 m

Fig. 8 Continued

frequency zone. When the blasting center distance is more than 200 m, the low frequency (< 30 Hz) energy becomes very low, and the energy distribution is relatively uniform in the 30 Hz-130 Hz range. However, when the blasting center distance is 230 m, the blasting signal experiences significant reduction, and the total energy becomes very low.

6. Conclusions

In this study, we analyzed the blasting wave characteristics based on Hilbert-Huang transform (HHT). The method consists of obtaining the different intrinsic modes functions (IMF) associated to the empirical mode decomposition (EMD). Applying the HHT is possible to each IMF in order to get the instantaneous energy and the three dimensional time frequency energy spectrum. Some important conclusions from this study can be delivered. First, this method is relatively simple and we have clearly demonstrated that the HHT analysis can effectively show the frequency and energy features of the blasting waves at different blasting distances. Most of the blasting wave energy concentrates on the IMF components 1-3.

Through FFT, the frequency distribution is within 150 Hz, with the increase of the blasting center distance, the dominant frequency and amplitude of blasting wave decrease to a low level. In the near blasting zone (10-75 m), the blasting wave instantaneous energy appears “fat”, and the total energy is greater. Before attaining peak energy, there is an obvious energy drop with a longer duration. The attenuation of peak energy along with the blasting center distance (from lesser to higher) is relatively small, and the energy change is relatively “steep”. In the three dimensional Hilbert spectrum, subtle changes in energy with the increasing blasting center distance are noted, and the energy distribution tends to concentration. In summary, the HHT method appears to be a promising direction for blasting wave analysis.

It is worth mentioning that the blasting wave propagation in coal rock masses is a complex process, which is influenced by many factors, including explosive source factor (explosive form), blasting conditions (initiation way, millisecond delay interval), and propagation medium (fault, crushed zone), etc. Thus, there is a need to carry out further studies to explore and analyze the changing regularities of the blasting wave.

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