Analysis on Time-frequency Characteristics and Delay Time Identification for Blasting Vibration Signal by Hilbert-Huang Transform in Fangchenggang Nuclear Power Station

Yongqing Zeng, Haibo Li, Xiang Xia, Bo Liu, Hong Zuo, and Jinlin Jiang

Abstract—**The accurate identification on time-frequency characteristics and delay time for blasting vibration signal of rock millisecond blasting for foundation excavation has a great significance on reducing damage degree of bedrock in Fangchenggang Nuclear Power Station. The regressive analysis about propagation characteristics of blasting vibration signal along the horizontal radial, horizontal tangential and vertical direction was expressed by Sadaovsk Formula and it is noteworthy that we should take three different direction components of particle vibration velocity rather than single direction into account as safety criteria for blasting vibration. The data about blasting vibration velocity versus time was analyzed by Empirical Mode Decomposition based on Hilbert-Huang transform and was decomposed into 8 intrinsic mode functions from c1 to c7 and R for residual error, The blast energy of original vibration signal mainly concentrates on the region where frequency is below 200 Hz and has two sub-bands which vary from 10 Hz to100Hz and from 120Hz to 200Hz, respectively while time varies from 0.10s to 0.45s. The instantaneous energy method based on Hilbert−Huang transform was used to identify delay time of millisecond blasting in Fangchenggang Nuclear Power Station, it is shown that actual interval time is located within the range of theoretical interval time and the precision for those batches of electric detonator is reliable by comparison between actual interval time and theoretical interval time with identifying saltation point of instantaneous energy variation curve.**

Index Terms—**blasting vibration signal, time-frequency characteristics, delay time identification, hilbert-huang transform**

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I. Introduction

THE analysis technique of blasting vibration signal has a great significance on initiative control of blasting vibration damage. There are some internal difficulties of analyzing and processing blasting vibration signal because blasting vibration signal has irregular, non-stationary and complex characteristics [1], in order to overcome those problems, Hilbert-Huang transform was put forward by Norden E. Huang as the latest and best signal analysis method in processing irregular, non-stationary and complex signal [2].

At present, the studies on effect of blast vibration signal by Hilbert-Huang transform mainly concentrate on high-ways, architectural structure, coal mine, and shallow tunnels; for example, Chen [3] conducted time-frequency characteristics extraction of vehicle-track coupling system based on Hilbert-Huang transform. Li al. [4-5], Zong [6-7], and Wang [8] analyzed blasting seismic wave signal in coalmine roadway excavation based on HHT method. Zou al. [9] investigated the relationship between the time and frequency of blasting vibration signal from the construction of a shallow tunnel in Qingdao crossing underneath buildings. Moreover, the identification method of detonator's actual firing delay time based on HHT and its application in millisecond blasting under urban environment and gold-copper mine is investigated by Gong et al.[10] and Shi et al.[11], respectively. However, those studies have seldom referred to blasting vibration effect for rock excavation blasting in nuclear power station. Nuclear power has a giant using value as a clean and economic energy when energy problem is becoming more and more urgent along with the rapidly social and economic development. Blasting method is still an available and relatively economic method for bedrock excavation in the process of nuclear power station construction; it inevitably involves blasting vibration monitoring and initiative control of blast vibration damage [12-13]. The study on how to determine vibration characteristics and delay time of blasting vibration signal has important and imminently practical significance.

In the present paper, the regressive analysis about propagation characteristics of blasting vibration signal along the horizontal radial, horizontal tangential and vertical direction is expressed by Sadaovsk Formula; in addition, the time-frequency characteristics and delay time identification for blasting vibration signal are studied based on

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Hilbert-Huang transform in order to reduce the damage extent to bedrock for rock excavation blasting located at Fangchenggang Nuclear Power Station in china. The original vibration signal is decomposed into 8 intrinsic mode functions, of which distinctly physical implication is introduced and the corresponding blast time-frequency energy region of original vibration signal has been analyzed in detail. Finally, delay time of millisecond blasting is identified by instantaneous energy method based on Hilbert−Huang transform, the results show Hilbert-Huang transform has an excellent recognition capability for non-stationary blasting signal.

II. Theory

A. Theory on Characteristics of Wave Propagation

Assuming structural body vibrate for the effect of disturbance, according to elasticity theory and wave theory, we can find that:

$$\sigma = E\varepsilon \tag{1}$$

$$\varepsilon = \frac{v}{c} \tag{2}$$

Where σ is the stress of structure body for blasting, E is elastic modulus, ε is strain and v , c is particle vibration velocity, propagation speed of vibration wave, respectively.

Substitution of EQ. (1) into EQ. (2) gives:

$$\sigma = \frac{Ev}{c} \tag{3}$$

It can be seen from EQ.(3) that the stress of structure body for blasting is proportional to particle vibration velocity. Therefore, blast-induced damage is proportionally depending on particle vibration velocity and we mostly believe particle vibration velocity can be index for blast-induced damage.

In general, ground vibration velocity is approximately related to the distance between the monitoring point and blasting point, R, and the maximum explosive weight per delay, Q. According to safety regulations for blasting, the Sadaovsk Formula points out [14]:

$$v = K\left(\frac{Q^{1/3}}{R}\right)^{\alpha} \tag{4}$$

Where Q is the maximum explosive weight per delay, R is the distance between the monitoring point and blasting point, and K, a is field constant.

B. Theory on Hilbert-Huang Transform

Hilbert-Huang transform is composed of Empirical Mode Decomposition (EMD) and Hilbert Spectrum Analysis (HSA). N.E.Huang believes that arbitrarily complicated signal can be composed of a series of Intrinsic Mode Function (IMF) which is simple, inharmonic and separate from each other. Hilbert-Huang transform was put forward based on above views and Empirical Mode Decomposition is the most important procedure of Hilbert-Huang transform [15].

Using Empirical Mode Decomposition, a raw signal $X(t)$ can be expressed as follows [16]:

$$X(t) = \sum_{i=1}^{n} c_i(t) + r_n(t) \tag{5}$$

Where $X(t)$ is a raw signal; $c_i(t)$ is intrinsic mode function and $r_n(t)$ is residual error.

Using Hilbert-Huang transform for every intrinsic mode function $c(t)$

$$H\left[c(t)\right] = \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{c(t')}{t-t'} dt' \tag{6}$$

Where PV is Cauchy principal value, we can obtain analytic signal $z(t)$

$$z(t) = c(t) + jH\left[c(t)\right] = a(t)e^{j\Phi(t)} \tag{7}$$

Where $a(t)$ is amplitude value function:

$$a(t) = \sqrt{c^2(t) + H^2\left[c(t)\right]} \tag{8}$$

And $\Phi(t)$ is phase function:

$$\Phi(t) = \arctan \frac{H\left[c(t)\right]}{c(t)} \tag{9}$$

Transient frequency is determined by derivation for phase function $\Phi(t)$

$$\omega(t) = \frac{d\Phi(t)}{dt} \tag{10}$$

The amplitude and frequency derived from Hilbert-Huang transform is a function about time, by expressing the change of amplitude as frequency and time change, we can obtain Hilbert spectrum

$$H(\omega,t) = \mathrm{Re}\sum_{i=1}^{n} a_i(t)\mathrm{e}^{\int \omega_j(t)dt} \tag{11}$$

Hilbert energy spectrum $ES(w)$ is obtained from the time integration of the square of Hilbert spectrum amplitude $H(w,t)$

$$ES(w) = \int_0^T H^2(w,t)dt \tag{12}$$

Hilbert energy spectrum $ES(w)$ provides an expression of energy calculation for every frequency and is defined as total energy accumulation in long-term span for every frequency.

TABLE I
COMPARISONS OF DIFFERENT SIGNAL ANALYZING METHODS

Name	Fourier	Wavelet	Hilbert
Basis function	a priori	a priori	adaptive
Frequency	convolution: global, uncertainty	convolution: regional, uncertainty	differentiation: local, certainty
Presentation	energy-frequency	energy-time-frequency	energy-time-frequency
Nonlinear	no	no	yes
Non-stationary	no	yes	yes
Feature extraction	no	discrete: no, continuous: yes	yes
Theoretical base	theory complete	theory complete	empirical

In contrast with traditional Fourier transform using a series of harmonic wave to simulate vibration signal and Wavelet transform with the problem on selection of wavelet basis function, Hilbert-Huang transform has no constant and preset basis function and has better identifying ability in local region of blasting vibration signal [17-19]. A summary of comparison between Fourier transform, Wavelet transform and Hilbert-Huang transform is given in the Table Ⅰ above.

III. CASE STUDY

A. Introduction to Fangchenggang Nuclear Power Station

The project, Fangchenggang Nuclear Power Station, is located in Fangchenggang city, the south of Guangxi Province, China. In construction site of the blasting for bedrock excavation, the blasting seismic monitoring has been conducted in order to reduce the damage extent to bedrock for rock excavation blasting; the blasting vibration monitoring system for bedrock excavation blasting and the layout of blasting vibration monitoring points is shown in Fig. 1, Fig. 2, respectively.

Fig. 1. Blasting vibration monitoring system

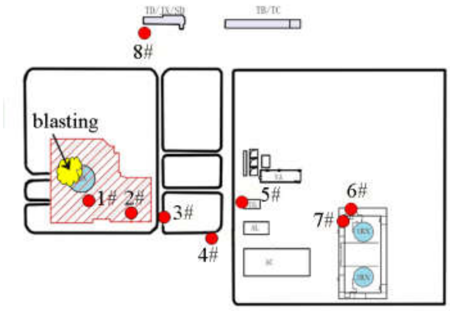


Fig. 2. The layout of blasting vibration monitoring points

B. Monitoring and Analysis for Blasting Vibration Signal

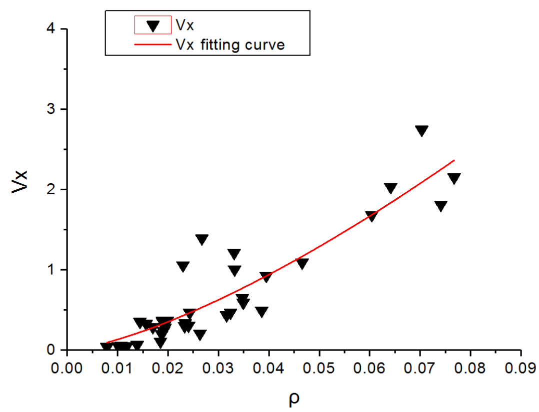
Altogether 234 blasting vibration data along the horizontal radial, horizontal tangential and vertical direction were recorded from 78 blasts. Parts of monitoring results of peak particle velocity under explosion are shown in Table Ⅱ.

Total 114 blasting vibration data from 38 blasts from bench blasting and controlled blasting are selected to fit in the form of power function based on EQ.(4) for bedrock excavation blasting. The regression analysis results of peak particle velocity along the horizontal radial, horizontal tangential and vertical direction are shown in Fig. 3.

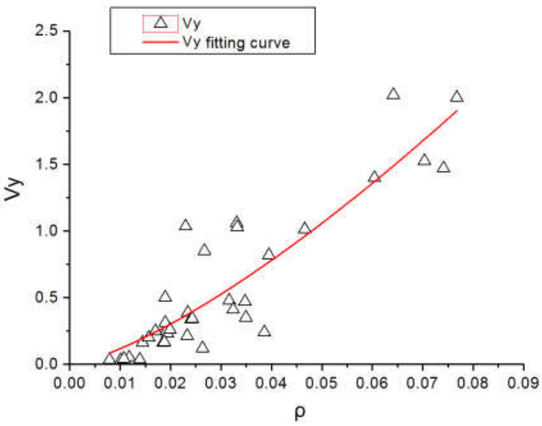
The Sadaovsk Formula on regressive analysis along the horizontal radial, horizontal tangential and vertical direction is expressed as EQ.(13), EQ.(14), and EQ.(15), respectively.

TABLE II
PARTS OF MONITORING RESULTS OF PEAK PARTICLE VELOCITY UNDER EXPLOSION

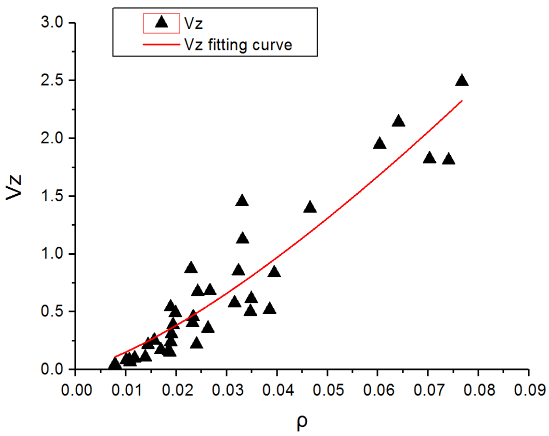
Maximum explosive weight per delay (kg)	Total explosive weight (kg)	Distance (m)	Horizontal radial direction V_x (cm・s^{-1})	Horizontal tangential direction V_y (cm・s^{-1})	Vertical direction V_z (cm・s^{-1})
6.0	440.5	39	1.091	1.013	1.394
6.0	440.5	68	1.392	0.851	0.680
6.0	440.5	96	0.365	0.312	0.238
6.0	440.5	126	0.352	0.163	0.213
9.5	539.6	33	2.030	2.020	2.140
9.5	539.6	67	0.433	0.478	0.576
9.5	539.6	111	0.237	0.248	0.306
9.5	539.6	195	0.035	0.028	0.066
8.9	576.8	27	2.150	2.000	2.490
8.9	576.8	64	0.467	0.410	0.851
8.9	576.8	89	0.298	0.214	0.404
8.9	576.8	176	0.046	0.051	0.098
11.2	642.6	58	0.491	0.240	0.518
11.2	642.6	93	0.304	0.339	0.217
11.2	642.6	121	0.107	0.161	0.161
11.2	642.6	285	0.038	0.033	0.045
11	482.2	30	1.810	1.470	1.710
11	482.2	64	0.650	0.471	0.500
11	482.2	95	0.336	0.388	0.455
11	482.2	220	0.050	0.031	0.082
11.4	740.0	32	2.743	1.525	1.821
11.4	740.0	68	1.210	1.060	1.450
11.4	740.0	98	1.056	1.035	0.871
11.4	740.0	119	0.354	0.501	0.540



(a) Horizontal radial direction



(b) Horizontal tangential direction



(c) Vertical direction

Fig. 3. The regression analysis of blast vibration velocity

$$v_x = 89.2\left(\frac{Q^{1/3}}{R}\right)^{1.41} \quad (13)$$

$$v_y = 63.6\left(\frac{Q^{1/3}}{R}\right)^{1.37} \quad (14)$$

$$v_z = 73.5\left(\frac{Q^{1/3}}{R}\right)^{1.35} \quad (15)$$

The blast-induced wave propagation law is obtained in the form of EQ.(13), EQ.(14), and EQ.(15), based on the above equation, we can effetely present the blasting design about the maximum explosive weight per delay, Q, according to the allowable peak particle velocity , v_{max}, at different distance from the center of explosion, R, in terms of requisition of damage depth to different layer of rock excavation, which show the excellent control effect on blasting damage depth of the rock mass.

It is observed in EQ.(13), EQ.(14), and EQ.(15) that the range of variation for K is from 63.6 to 89.2 and α is from 1.35 to 1.41 where it has been observed that K , α of horizontal radial direction is largest, this is, 89.2 and 1.41, respectively but K , α of horizontal tangential direction is 63.6 and 1.37, respectively and K , α of vertical direction is 73.5 and 1.35, respectively.

In term of Sadaovsk empirical formula in EQ.(4), parameter K is directly proportional to particle vibration velocity and parameter α represent declining speed of particle vibration velocity where the bigger of α , the faster of velocity attenuation along propagation distance. By comparing the difference of α and K for horizontal radial, horizontal tangential and vertical direction, we easily find that the K of horizontal radial direction is more than horizontal tangential and vertical direction while α of horizontal radial direction is also more than horizontal tangential and vertical direction which show that horizontal radial direction has faster speed of velocity attenuation, it imply that even though particle velocity of horizontal radial direction is generally larger than horizontal tangential and vertical direction in the near-blasting field, however, the particle velocity of horizontal radial direction will be lower than horizontal tangential and vertical direction in the far-blasting field which is consistent with the results shown in Table Ⅱ. So it is noteworthy that we should take three different direction components of particle vibration velocity rather than single direction into account as safety criteria for blasting vibration.

C. Time-Frequency Characteristics

As seen in Fig. 4, there is a typical multiple section raw signal of blasting seismic wave. The sampling points are 1000 and sampling interval time is 0.001s. The original vibration signal (Fig. 4) is decomposed and reconstructed by Empirical Mode Decomposition, the decomposed vibration signal is shown in Fig. 5 and the reconstructed vibration signal and relative error are shown in Fig. 6.

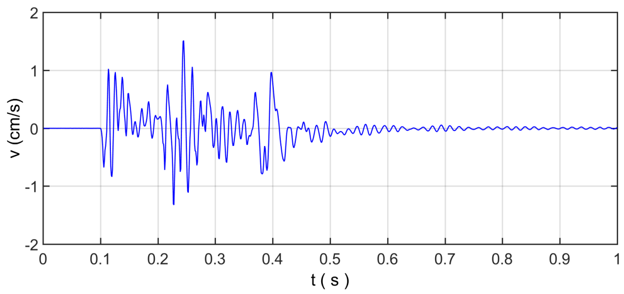


Fig. 4. The velocity curve of original vibration signal

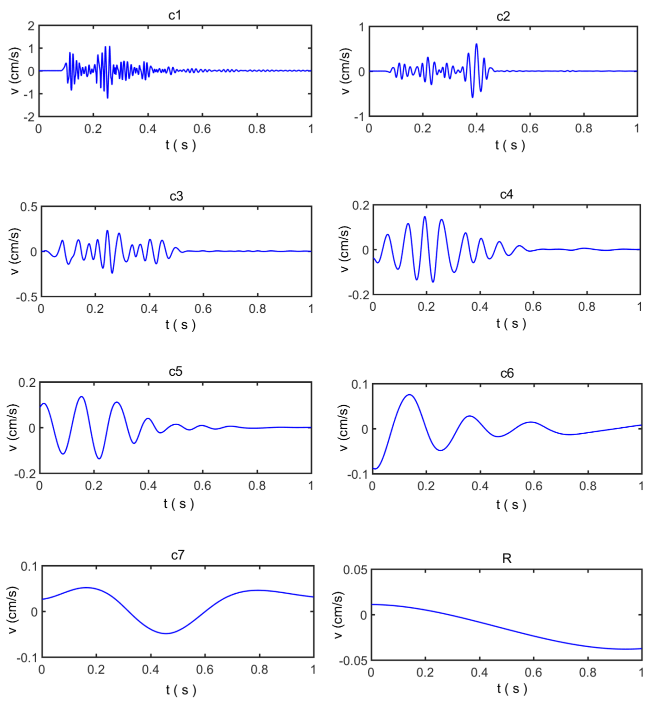
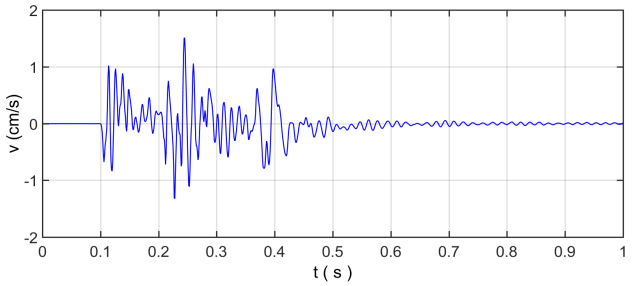
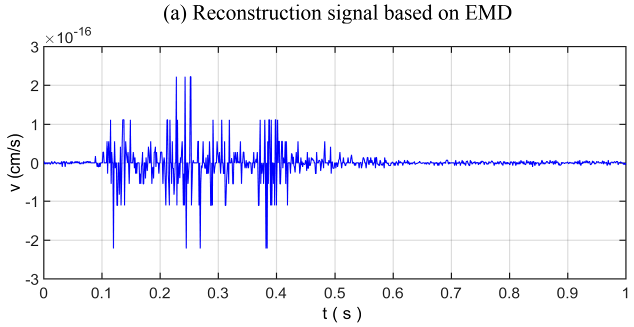


Fig. 5. The decomposed vibration signal by EMD



(a) Reconstruction signal based on EMD



(b) Relative error based on EMD

Fig. 6. The reconstructed vibration signal and relative error based on EMD

Fig.5 shows that the original vibration signal is decomposed into 8 intrinsic mode functions from c1 to c7 and R for residual error. Because Empirical Mode Decomposition always decompose raw vibration signal based on time scales from big to small, the waveform of intrinsic mode functions are becoming more and more longer while the frequency is becoming more and more lower with the proceed of decomposition. The intrinsic mode functions commonly have distinctly physical implication: c1, c2, c3 have larger amplitude than other intrinsic mode functions and contain a majority of energy of original vibration signal which become main component to influence of building vibration; c4, c5, c6, c7 have less frequency, amplitude and energy of original vibration signal coming from resident signal or other factors. Residual error R reflects the zero-drift phenomenon or weak change tendency of signal with the lowest amplitude and energy.

As is shown in Fig.6, the reconstructed vibration signal based on Empirical Mode Decomposition is very consistently similar to original vibration signal with relative error is 10^{-16}, which shows that Hilbert-Huang transform and Empirical Mode Decomposition can accurately reflect the characteristics of the non-stationary signal and have an excellent suitability for analysis on blasting vibration signal.

Fig.7 shows power spectrum density of original vibration signal (Fig.4) and Fig.8 shows power spectrum density of intrinsic mode functions from c1 to c7 and R (Fig.5).

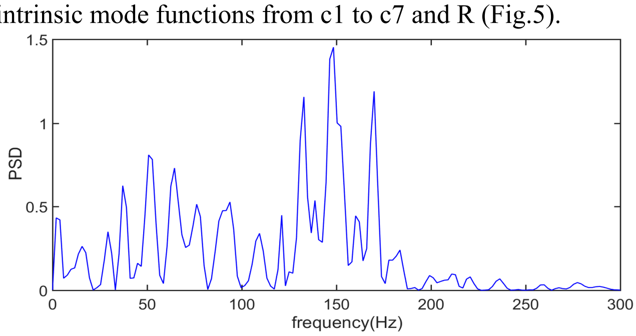


Fig. 7. The power spectral density of original vibration signal

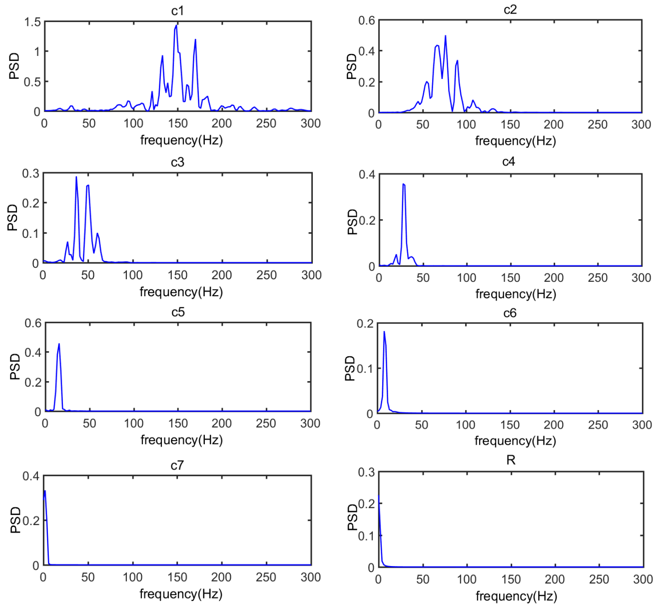


Fig. 8. The power spectral density of IMF component from C1 to C7 and R as surplus

Fig.7 indicates the blast energy of original vibration signal mainly concentrate on the region where frequency is below 200Hz and has two sub-band which varies from 10Hz to 100Hz and from 120Hz to 200Hz, respectively, in which the main energy concentrates in the range of 120Hz to 200Hz, and the energy in the range of 10Hz to 100Hz is relatively weak and uniformly distributed. The natural frequencies of common buildings are between 2Hz and 5Hz, from the perspective of security, low energy distribution in the low frequency region is beneficial to structural safety and stability of surrounding rock for reducing the probability of resonance [2, 6].

It can be seen in Fig.8 that the blast energy of intrinsic mode function c1 has the biggest fraction for original vibration signal whose frequency mainly vary from 120Hz to 200Hz and c2 has a variation range between 50Hz and 100Hz. c3, c4, c5 constitute the spectral range from 10Hz to 50Hz and the dominant frequency of c6, c7, R is below 30Hz.

The three-dimensional energy density spectrum of original vibration signal on Hilbert-Huang transform is showed in Fig.9.

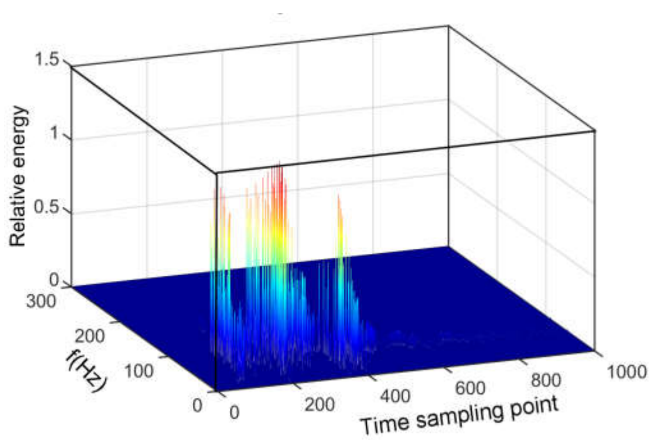


Fig. 9. Energy density spectrum based on HHT

Fig.9 presented the distribution characteristics about energy of blasting vibration signal as the variation of frequency and time; It can be more intuitive to show the distribution of energy on blasting vibration signal with time and frequency, where the color is redder, the energy is greater, we can see that the energy mainly concentrates on the range of 10Hz-200Hz and 100-450 time sampling point. Dividing time sampling point 100-450 by sampling frequency 1000Hz is 0.10s-0.45s, we can obtain the energy mainly concentrates on the range of 10Hz-200Hz and 0.10s-0.45s. The distribution characteristics about energy density spectrum of original vibration signal based on Hilbert-Huang transform is in accordance with the velocity curve of original vibration signal in Fig.4 where the time region for velocity vibration amplitude mainly vary from 0.10s to 0.45s and the power spectral density of original vibration signal in Fig.7 where the frequency region for power spectral density mainly concentrate on 10Hz-200Hz.

D. *Delay Time Identification of Millisecond Blasting*

Millisecond blasting has been adopted to reduce the damage degree to bedrock for rock blasting with foundation excavation at Fangchenggang Nuclear Power Station. Table Ⅲ provides the blasting design parameters of blasting seismic signal.

TABLE Ⅲ
THE BLASTING DESIGN PARAMETERS OF BLASTING SEISMIC SIGNAL

Total charge(kg)	Maximum charge per delay (kg)	Blast center distance(m)	Sections of electric detonator
408	93	45	5,5,6

Because millisecond blasting vibration signal is composed of many sub-segment blasting vibration signals, the occurrence of every sub-segment blasting vibration signal inevitably evokes the signal mutation of millisecond blasting vibration signal. The explosive delay time can be determined by identifying saltation point of instantaneous energy variation curve [20-21]; the instantaneous energy variation curve of blasting seismic signal is shown in Fig.10.

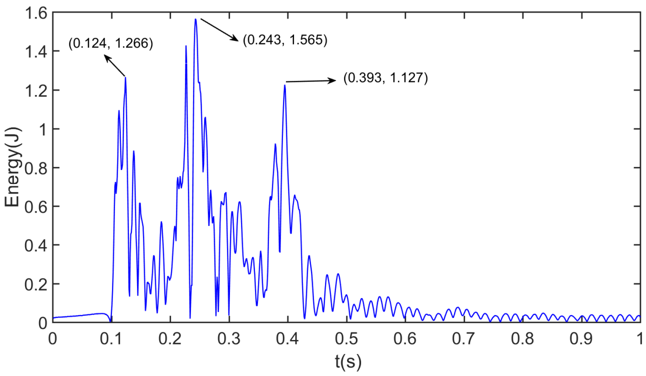


Fig. 10. The instantaneous energy variation curve of blasting seismic signal

As can be seen in Fig.10, the three saltation points are (0.124, 1.266), (0.243, 1.565), and (0.393, 1.127), therefore, the break time for each section detonator is 0s, 0.124s, 0.243s, and 0.393s, respectively where the millisecond delay time is 0.124s, 0.119s, and 0.150s, respectively [22] because millisecond delay time is the difference value between adjacent break time for each section detonator. Table Ⅳ provides the delay time design and actual interval time for sections of electric detonator.

TABLE Ⅳ
THE DELAY TIME DESIGN AND ACTUAL INTERVAL TIME FOR SECTIONS OF ELECTRIC DETONATOR

Section of electric detonator	Nominal delay time(ms)	Range of error(ms)	Theoretical interval time(ms)	Actual interval time(ms)
5	110	+20 -20	90~130	124
5	110	+20 -20	90~130	119
6	150	+25 -20	130~175	150

By comparison between actual interval time and theoretical interval time in Table Ⅳ, we can find that actual interval time for sections of electric detonator is 124ms, 119ms, and 150ms, respectively and the correspondingly theoretical interval time is 90ms-130ms, 90ms-130ms, and 130ms-175ms, respectively which shows that all actual interval time are located within the range of theoretical interval time and the precision for those batches of electric detonator is reliable which can be used securely in Fangchenggang Nuclear Power Station.

IV. CONCLUSION

The regressive analysis about propagation law of blast-induced wave, accurate identification on time-frequency characteristics, and delay time identification for blasting vibration signal of rock blast for foundation excavation have been done in Fangchenggang Nuclear Power Station; The main conclusions of the study are drawn as follows:

(1) The Sadaovsk Formula of regressive analysis about propagation characteristics along the horizontal radial, horizontal tangential and vertical direction is expressed as $v_x = 89.2(\frac{Q^{1/3}}{R})^{1.41}$, $v_y = 63.6(\frac{Q^{1/3}}{R})^{1.37}$, and $v_z = 73.5(\frac{Q^{1/3}}{R})^{1.35}$. Based on the above equations, we can effetely present the blasting design about the maximum explosive weight per delay, Q, according to the allowable peak particle velocity , v_{max}, at different distance from the center of explosion, R, in terms of the corresponding requisition of damage depth to different layer of rock excavation, which shows the excellent control effect on blasting damage depth of the rock mass. At the same time, it is noteworthy that we should take three different direction components of particle vibration velocity rather than single direction into account as safety criteria for blasting vibration.

(2) Blasting vibration signal is analyzed by Hilbert-Huang transform in Fangchenggang Nuclear Power Station. The reconstructed vibration signal based on Empirical Mode Decomposition is very consistently similar to original vibration signal with relative error is 10^{-16}, which shows that Hilbert–Huang transform is an excellent time-frequency decomposition tool that is particularly effective in extracting local information from non-stationary time series. The distribution characteristics about energy of blasting vibration signal as frequency and time show that energy density spectrum on Hilbert-Huang transform mainly concentrates

on the range of 10Hz-200Hz which has two sub-bands varying from 10Hz to100Hz and from 120Hz to 200Hz, respectively and 0.10s-0.45s, in which the main energy concentrates in the range of 120Hz to 200Hz, and the energy in the range of 10Hz to 100Hz is relatively weak and uniformly distributed. The natural frequencies of common buildings are between 2Hz and 5Hz, from the perspective of security, low energy distribution in the low frequency region is beneficial to structural safety and stability of surrounding rock for reducing the probability of resonance.

(3) The explosive delay time is 0.124s, 0.119s, and 0.150s, respectively by identifying saltation point of instantaneous energy variation curve of blasting seismic signal; The all actual interval time are located within the range of theoretical interval time and the precision for those batches of electric detonator is reliable which can be used securely in Fangchenggang Nuclear Power Station. Using real blasting vibration data, this paper demonstrates the capabilities of HHT for analyzing important features related to blasting energy, in particular the analysis of frequency spectrum feature and delay time of millisecond blasting.

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