Research on Time-frequency Characteristics for Blasting Vibration Signal of CO_2 Blasting by Frequency Slice Wavelet Transform

Yongqing Zeng, *Member, IAENG,* Haibo Li, Xiang Xia, Shouchun Deng, Hong Zuo, Haozhen Yue and Hua Luo

***Abstract*—With the advancement of theoretical and practical research for high pressure gas fracturing technology, carbon dioxide (CO_2) fracturing technology will have broad application prospects in the national economic construction, the study on attenuation law of peak particle velocity (PPV) with distance and time-frequency characteristics for blasting vibration signal of CO_2 fracturing technology will be of great significance. On behalf of speeding up the excavation progress and studying the vibration effect of carbon dioxide blasting, liquid carbon dioxide phase change fracturing is used as the blasting source to bench excavation of mountain. The regressive analysis about propagation characteristics of blasting vibration signal along the horizontal radial, horizontal tangential and vertical direction was expressed by power function formula. The peak particle velocity of residential building is in the safety range during the CO_2 blasting, which show the excellent control effect on CO_2 blasting damage for near building. In terms of altogether 9 blasting vibration data along the horizontal radial, horizontal tangential and vertical direction recorded from 3 vibration monitoring points at a distance of 5 m, 15 m and 30 m away from the borehole, the dominating frequency of particle vibration produced by carbon dioxide blasting varies form 4.4 Hz to 63.7 Hz; In the process of analyzing CO_2 blasting vibration signal, FSWT has good time and frequency resolution, it shows that the vibration intensity of CO_2 blasting vibration sub-band signal decreases with the increase of frequency, the main energy concentrates in the range of 0-100 Hz, the CO_2 blasting vibration signal in the frequency range of 0-20 Hz is more obvious and reach 92.9% of the total energy, meanwhile, the CO_2 blasting vibration energy within 20-100 Hz is relatively small with 6.4% energy percentage. The analysis results can provide reference for similar design and construction of carbon dioxide blasting.**

***Index Terms*—blasting vibration signal, attenuation law, time-frequency characteristics, CO_2 blasting, frequency slice wavelet transform**

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I. INTRODUCTION

As a traditional engineering technology for rock excavation, mining and tunneling, emulsion explosive blasting still plays an irreplaceable role in the national economic construction due to high efficiency, economy and simple operation[1-3], however, with the deterioration of domestic and international anti-terrorism situation and the enhancement of people's awareness of environmental protection, the defects of emulsion explosive and the harm caused by the explosion have been paid more and more attention [4-5]. First of all, explosive are unstable energetic material, therefore, a series of strict, special and complex control measures must be followed in production, transportation, storage and use. Secondly, explosive blasting will produce a large amount of dust and harmful gas, which can cause pollution to the natural environment; the toxic substances in underground space such as tunnel and coal mines are not easily to be released, it may lead to gas explosion and cause disastrous loss of life and property.

In recent years, a new and efficient fracturing and tunneling technology, namely carbon dioxide (CO_2) fracturing technology, has been gradually promoted in the field of rock excavation and coal mining [6-7]. The technology uses liquid CO_2 as the medium, encapsulating liquid CO_2 and heating pipe in a sealed container, when the heating pipe is excited by ignition device to produce high temperature above 800 C in 0.1 s, the liquid CO_2 will be instantaneously vaporize and become expanding gaseous CO_2 to produce high pressure [8]. The pressure release hole is preset on the sidewall of the container, when the pressure inside the container exceeds the shear strength of the cutting plate, the cutting plate is cut off, the high pressure gas is released rapidly from the release hole and acts on the surrounding coal or rock mass resulting in the cracking of the coal seam or rock mass. CO_2 fracturing mechanism is a physical change, heating activating agent material encapsulated in the liquid storage tube, low temperature and high pressure CO_2 gas environment generated by the CO_2 blasting can create inert atmosphere, eliminating the possibility of methane explosion and secondary chemical reaction with other gases; There is no open flame or spark in the process of using the carbon dioxide fracturing technology, which improve safety in all aspects, therefore, it is widely used in coal mine, open-pit mine, foundation excavation engineering and can replace explosive as an excitation source for seismic exploration. With the advancement of theoretical and practical research for high pressure gas fracturing technology, CO_2 fracturing technology will have broad application prospects in the national economic construction, the study on attenuation law of peak particle velocity (PPV) with distance and time-frequency characteristics for blasting vibration signal of CO_2 fracturing technology will be of great significance.

There are some internal difficulties of analyzing and processing blasting vibration signal by traditional Fourier transform (FT) using a series of harmonic wave to simulate blasting vibration signal because blasting vibration signal has irregular, non-stationary and complex characteristics [9-10]. At present, time-frequency analysis method has achieved great development, Fast Fourier transform (FFT), Wavelet transform (WT) and Wavelet packet transform (WPT) are more and more widely used in analysis on blasting vibration signal and achieved remarkable results; however, there are some limitations in the application of these methods [11-12], for example, the Fast Fourier transform cannot simultaneously extract time and frequency information of the signal and is also incapable of local characteristics of the non-stationary signal; Wavelet transform and Wavelet packet transform have the problem on selection of better wavelet basis function and proper decomposition scale, if the selection is improper, it may lead to unreasonable or even wrong analysis results.

Yan et al. [13-15] put forward the theory of Frequency Slice Wavelet Transform (FSWT) and applied it to transient vibration signal analysis, which can realize signal filtering and segmentation flexibly. By introducing the frequency slicing function, the traditional Fourier transform realized the function of time-frequency analysis and FSWT can be transformed into FT, STFT, Gabor, Molet wavelet transform under certain conditions. In the meantime, FSWT can not only accurately describe local characteristics of signal by simultaneously extracting features at time and frequency domain, but also reconstruct signal in any frequency band by inverse transformation and can adjust time-frequency resolution by changing relevant parameters, then, FSWT is more accurate and flexible than wavelet transform. Zhao et al. [16] effectively identify subsynchronous oscillation (SSO) and obtain the oscillation characteristic of power system by using Frequency Slice Wavelet Transform. The Frequency Slice Wavelet Transform is applied to extract the gear fault characteristics under the condition of strong noise, which has the ability to separate the desired components from the noise signal, and the ideal effect is obtained for the feature extraction of gear fault diagnosis [17,18]. Wang [19] proposed an efficient recognition method for underdetermined signals by combining the features of Frequency Slice Wavelet Transform (FSWT) and Denoising Source Separation (DSS) to deal with the Blind Source Separation (BSS) problem of rotating machineries, it showed that the FSWT-DSS method is indeed efficient in fault diagnosis and has an important engineering significance for fault detection of rotating machines. In addition, typical microseismic signals and emulsion explosive blast vibration signals of mine rock mass are studied by using Frequency Slice Wavelet Transform, it shows that the energy of the two kinds of signals are both mainly distributed below 100 Hz, and the energy of rock mass microseismic signals are mainly concentrated in the band between 0-50 Hz, but the blast vibration signals energy of emulsion explosive are concentrated more obviously in the band between 50-100 Hz [20].

In the present paper, the principle of carbon dioxide fracturing blasting is introduced, the vibration effect of carbon dioxide fracturing blasting in rock excavation is monitored by the TC-4850 blasting vibration monitoring system, in which the attenuation law of peak particle velocity (PPV) with distance is obtained and the time-frequency characteristics of CO_2 blasting vibration signal are analyzed by using Frequency Slice Wavelet Transform (FSWT) from the perspective of frequency spectrum and energy spectrum distribution, it provides a scientific reference for the accurate identification of the vibration signal and safe control of vibration effect for carbon dioxide fracturing blasting.

II. THEORY

A. *Theory on Carbon Dioxide Fracturing Blasting*

CO_2 is a colorless, odorless, non-flammable and non-toxic gas at room temperature, the transition among gaseous, liquid and solid state is called phase change, which belongs to physical change and is controlled by the change of pressure and temperature [21]. There is a special supercritical state apart from the general gaseous, liquid and solid state; the relationship of CO_2 phase, pressure and temperature is shown in Fig. 1, the CO_2 turn into the supercritical fluid state when pressure is higher than 7.38 MPa and temperature is higher than 31.3 °C, which has a high molecular diffusion coefficient close to gas and has a high density close to liquid. It can continuously change from the normal state at normal temperature and normal pressure to the supercritical fluid state.

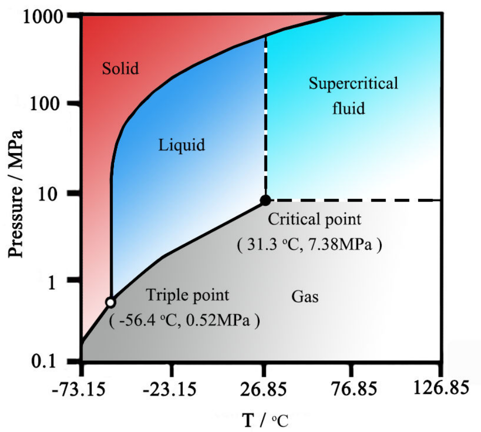
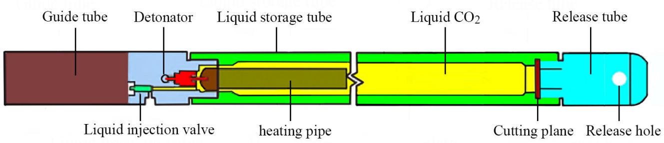


Fig.1. Three phase diagram of CO_2

The CO_2 blasting device is composed of guide tube, liquid storage tube and release tube, where liquid storage tube contains liquid injection valve, detonator, heating pipe and liquid CO_2; in addition, release tube contains a cutting plate and release hole [7]. The schematic and physical diagram of CO_2 blasting device is shown in Fig. 2.



(a) The schematic diagram of CO_2 blasting device

(b) The physical diagram of CO_2 blasting device

Fig. 2. The schematic and physical diagram of CO_2 blasting device

The liquid storage tube is injected with liquid CO_2, firstly, by activating the detonator, special chemicals in the heating pipe begin to react and a lot of heat could be released immediately, liquid CO_2 will rapidly vaporize with the volume expansion more than 600 times because of the occurrence of phase change, when the gas pressure in the liquid storage tube reach the limit strength of the cutting plate, the cutting plate is break off, carbon dioxide with high pressure enters the release tube and forms shock wave acting on the rock body. According to laboratory test results, the damage pressure of the cutting plate is approximately 270 MPa, which means the pressure of carbon dioxide acting on the rock body is also approximately 270 MPa [7].

B. Theory on Characteristics of Wave Propagation

Assuming structural body vibrates for the effect of disturbance, according to elasticity theory and wave theory [10], 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 the structure for blasting is proportional to vibration velocity of the particle and that the particle vibration velocity is an important physical quantity of structural damage, in which the vibration velocity can effectively reflect the blast-induced damage [22].

The attenuation law of peak particle velocity (PPV) with distance is fitted according to the power function.

$$PPV = K\left(R\right)^{-\alpha} \tag{4}$$

where R is the distance between the monitoring point and blasting point, K is field coefficient and α is attenuation coefficient.

C. Theory on Frequency Slice Wavelet Transform

Frequency Slice Wavelet Transform is a new kind of time–frequency signal analysis method, by means of extension of short time Fourier transform (STFT) defined directly in frequency domain. FSWT is more flexible to fit ever-changing signals and is convenient to analyze and control in application. FSWT can not only individually represent each modal signal in frequency domain, but also accurately show its details in time domain. It is a more available tool for simultaneously analyzing signal in time–frequency domain and further to refine the wavelet theory [13].

(1) Frequency slice wavelet transform

For any function $f(t) \in L^2(R)$, where R denotes the set of real numbers and $L^2(R)$ denotes the vectors space of measurable, square integrable one-dimensional functions; if the Fourier transformation of $p(t)$ exists, the Frequency Slice Wavelet Transform (FSWT) is defined directly in the frequency domain as

$$W\left(t,\omega,\lambda,\sigma\right) = \frac{1}{2\pi}\lambda\int_{-\infty}^{\infty}\hat{f}(u)\hat{p}^{*}\left(\frac{u-\omega}{\sigma}\right)e^{iut}du \tag{5}$$

where the σ is scale factor ($\sigma \neq 0$), λ is energy coefficient ($\lambda \neq 0$) and σ , λ are constants or they are functions of ω and t . Here we call ω and t the observed frequency and time, and u the assessed frequency. $\hat{p}(\omega)$ is the Fourier transformation of the function $p(t)$ and is also called frequency slice function; the star '*' means the conjugate of a function.

By using Parseval equation, we can translate Eq. (5) into its time domain.

$$W\left(t,\omega,\lambda,\sigma\right) = \sigma\lambda e^{i\omega t}\int_{-\infty}^{\infty} f(\tau)e^{-i\omega\tau}p^{*}\left(\sigma\left(\tau-t\right)\right)d\tau \tag{6}$$

In the actual analysis, it is unnecessary to concern the definition of Eq. (6) in time domain because it is not easy to analyze in the frequency domain even though the function type of p (t) and $\hat{p}(\omega)$ are known, Hence, we will pay more attention to the frequency slice function (FSF) $\hat{p}(\omega)$. It is easy to know that FSF is a filter, therefore many methods can be used to design the filter; the following are several designing conditions to create an FSF, but they are not necessarily simultaneous: ① $\hat{p}(0)\neq 0$ or $\hat{p}(0)=1$, ② $\int_{-\infty}^{\infty}\left|\hat{p}(\omega)\right|^2 d\omega<\infty$,③ $\left|\hat{p}(\pm\infty)\right|^2=0$, ④ $\left|\hat{p}(\omega)\right|< \hat{p}(0)\neq 0$ or $\left|p(t)\right|< p(0)$.

(2) Scale selection

It is easy to understand that the scale parameter σ is more sensitive and important than parameter λ in FSWT. Assuming that $\lambda=1$, $\sigma\propto\omega$ on account of the Morlet transform idea, taking

$$\sigma = \frac{\omega}{k} \tag{7}$$

and

$$W\left(t,\omega,\lambda,\mathrm{k}\right) = \frac{1}{2\pi}\lambda\int_{-\infty}^{\infty}\hat{f}(u)\hat{p}^{*}\left(k\frac{u-\omega}{\omega}\right)e^{iut}du \tag{8}$$

where $k>0$ is assumed, k is not directly related to ω and u, and it can be adjusted to tune the transform to be more sensitive to frequency or more sensitive to time.

There are two eclectic parameters η and υ defined to estimate the scale k

$$\eta = \frac{\Delta\omega}{\omega} \tag{9}$$

$$0 < \upsilon \le 1 \tag{10}$$

where η is called frequency resolution ratio; ν is called expected response ratio of amplitude, which is used to distinguish two frequency signals or two time pulse signals for FSWT.

Usually, ν is set to $\sqrt{2}/2$, 0.5 or 0.25, etc.

It is easily establish the following inequalities by using the Dirac function recorded by $\delta(\cdot)$.

(1) If $f(t) = e^{i\omega_0 t}$, and its FSWT satisfies that

$$\left|W(t,\omega_0+\Delta\omega,\lambda,\sigma)\right| / \left|W(t,\omega_0,\lambda,\sigma)\right| \le \nu \tag{11}$$

then

$$\left|\hat{p}(\frac{\Delta\omega}{\sigma})\right| \le \upsilon \left|\hat{p}(0)\right| \tag{12}$$

$$\left|\hat{p}(k\eta)\right| \le \upsilon \left|\hat{p}(0)\right| \tag{13}$$

(2) If $f(t) = \delta(t-t_0)$, and its FSWT satisfies that

$$\left|W(t_0+\Delta t,\omega,\lambda,\sigma)\right| / \left|W(t_0,\omega,\lambda,\sigma)\right| \le \nu \tag{14}$$

then

$$\left|p(\sigma\Delta t)\right| \le \upsilon \left|p(0)\right| \tag{15}$$

$$\left|p(\frac{\mu}{k\eta})\right| \le \upsilon \left|p(0)\right| \tag{16}$$

where $\mu = \Delta\omega\Delta t$.

(3) If frequency slice function is Gaussian function $\hat{p}(\omega) = e^{-(1/2)\omega^2}$, then $\mu = 1/2$. From inequalities (13) and (16) respectively, we have

$$k \ge \frac{\sqrt{2\ln(1/\upsilon)}}{\eta} \tag{17}$$

$$k \le \frac{\mu}{\eta\sqrt{2\ln(1/\upsilon)}} \tag{18}$$

If inequalities (17) and (18) are satisfied simultaneously in time–frequency domain, then they have a unique solution: $\upsilon = e^{-(1/2)\mu} \approx 0.7788$ and $k = 0.707/\eta$.

(3) Inverse transform

Generally, A signal is decomposed by using FSWT in time and frequency domain, it is necessary that FSWT should be reversible for signal filtering or segmenting. When reconstructing a signal by inverse transform, there are many ways to reconstruct it. One of the simplest and most effective ways is given.

If the $\hat{p}(\omega)$ satisfies $\hat{p}(0)=1$,then the original signal *f(t)* can be reconstructed by

$$f(\mathrm{t}) = \frac{1}{2\pi\lambda}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} W(\tau,\omega,\lambda,\sigma)e^{i\omega(\mathrm{t}-\tau)}\,\mathrm{d}\,\tau\,\mathrm{d}\,\omega \tag{19}$$

where the reconstructed transform Eq. (19) is not directly related to the frequency slice function $p(t)$ or $\hat{p}(\omega)$, the reconstructed signal can be obtained directly by the Fast Fourier transform (FFT).

For any selected time interval (t_1, t_2) and frequency interval (ω_1, ω_2), the signal component can be computed:

$$f'(t) = \frac{1}{2\pi\lambda}\int_{\omega_1}^{\omega_2}\int_{t_1}^{t_2} W(\tau,\omega,\lambda,\sigma)e^{i\omega(t-\tau)}d\tau d\omega \tag{20}$$

(4) Energy distribution characteristics

FSWT can easily reconstruct the signal in any frequency band and is not limited by wavelet basis function; we can construct a reasonable sub-band to analyze the signal in more detail. Define the energy of any frequency band as

$$E_{i,j} = \int_{T_1}^{T_n} f(t)dt = \sum_{k=1}^{n}\left|x_k\right|^2 \tag{21}$$

where $E_{i,j}$ denotes the energy of signal in the frequency range varying from *i* Hz to *j* Hz, x_k (k=1, 2, … , n) is the amplitude of each sampling point in the corresponding frequency band.

The total energy E of signal can be expressed as

$$E = \int_T f(t)dt = \sum_{k=1}^{n}\left|x_k\right|^2 \tag{22}$$

The ratio of the energy of each sub frequency band to the total energy of signal is expressed as

$$P_{i,j} = \frac{E_{i,j}}{E_0}\times 100\% \tag{23}$$

III. Case Study

A. Experimental site details

In order to widen the building area, a mountain near residential building in Jingshan City of Hubei Province, China needs excavation and field leveling. In the process of advanced mechanical excavation, because the rock is limestone with high mechanical properties, in which the compressive strength is 50-200 Mpa, the tensile strength is 5-20 Mpa, the cohesion is 10-50 Mpa and the friction angle is 35-50 degree [23-24], the mechanical digger is used with low efficiency. On behalf of speeding up the excavation progress and studying the vibration effect of carbon dioxide blasting, liquid carbon dioxide phase change fracturing is used as the blasting source to bench excavation of mountain. The blasting vibration monitoring system for bench excavation and the layout of blasting vibration monitoring points is shown in Fig. 3 and Fig. 4, respectively.

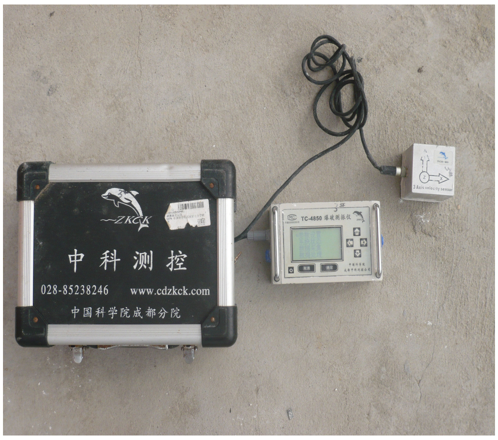


Fig. 3. Blasting vibration monitoring system

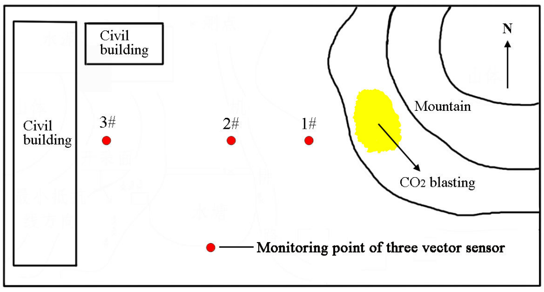


Fig. 4. The layout of blasting vibration monitoring points

Blast design parameters used at site for rock excavation of CO_2 blasting is shown in Table I, total two carbon dioxide fracturing tube with 6 mm thickness cutting plate is used, in which diameter of blast hole and liquid storage tube is 115 mm and 95 mm, respectively; the burden, spacing and depth of blast hole is 1.2 m, 3.5 m and 3.0 m, respectively; in addition, the mass of activating agent material and liquid CO_2 is separately 640 g and 3500 g.

View of the detonation sequence and post blast view for rock fragmentation of CO_2 blasting is depicted in Fig. 5 and Fig. 6, respectively; In the process of CO_2 blasting, there is a dull sound, small decibel, less dust and fewer fly rock, the radial throw distance of rock blocks is less than 2 m, it shown little influence on the surrounding environment; At the same time, the size of fractured rock fragmentation is moderate, which is convenient for the removal of residual rock by construction machinery.

TABLE I
BLAST DESIGN PARAMETERS USED AT SITE FOR ROCK EXCAVATION OF CO_2 BLASTING

Diameter of blast hole (mm)	Number of hole	Burden (m)	Spacing (m)	Depth of blast hole (m)	Thickness of cutting plate(mm)	Diameter of liquid storage tube(mm)	Mass of activating agent material(g)	Mass of liquid CO_2(g)
115	2	1.2	3.5	3.0	6	95	640	3500

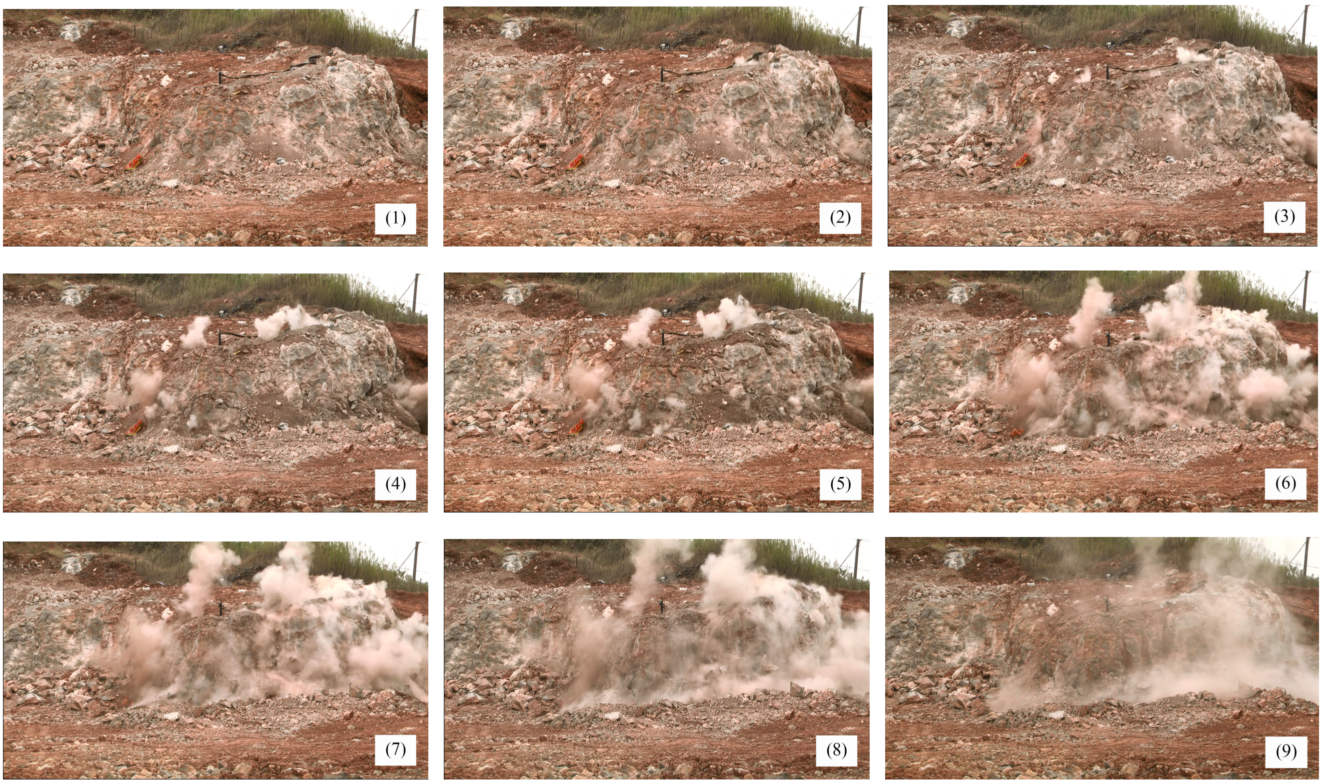


Fig. 5. View of the detonation sequence of CO_2 blasting

Fig. 6. Post blast view for rock fragmentation of CO_2 blasting

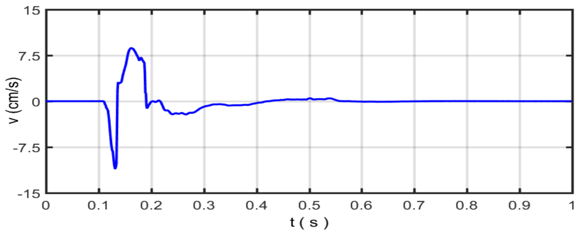
B. Monitoring and Analysis for Blasting Vibration Signal

Altogether 9 blasting vibration data along the horizontal radial, horizontal tangential and vertical direction are recorded from 3 vibration monitoring points at a distance of 5 m, 15 m and 30 m away from the borehole, the particle velocity curve and power spectral density about blasting vibration signal is shown in Fig. 7 and Fig. 8, respectively; the sampling points are 1000 and sampling interval time is 0.001 s.

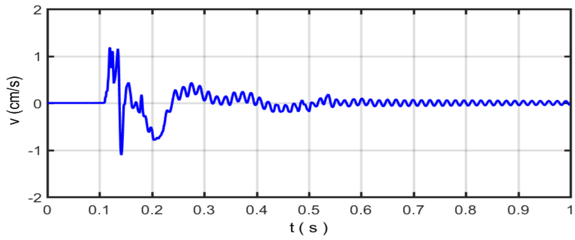
The monitoring results of peak particle velocity under CO_2 blasting are shown in Table II, which are selected to fit in the form of power function based on EQ.(4) for bench excavation blasting. The power function formula on regressive analysis and attenuation curve of peak particle velocity along the horizontal radial, horizontal tangential and vertical direction is expressed as EQ.(24-26) and Fig. 9, respectively.

TABLE II
MONITORING RESULTS OF PEAK PARTICLE VELOCITY UNDER CO_2 BLASTING

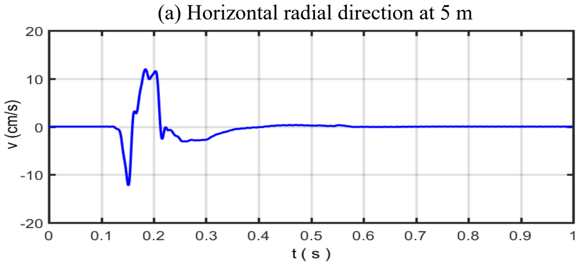
Distance (m)	Horizontal radial direction		Horizontal tangential direction		Vertical direction	
	Vx (cm/ s)	f (Hz)	Vy (cm/ s)	f (Hz)	Vz (cm/ s)	f (Hz)
5	11.037	6.4	1.171	4.4	12.017	6.1
15	0.812	7.1	0.718	16.9	0.175	16.2
30	0.075	28.3	0.041	63.7	0.021	21.9



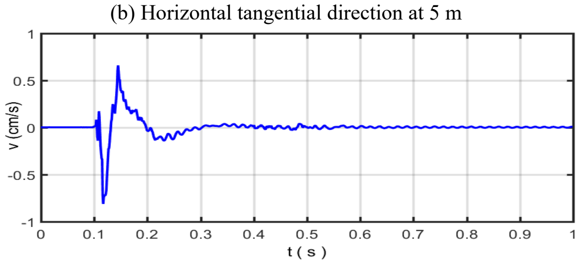
(a) Horizontal radial direction at 5 m



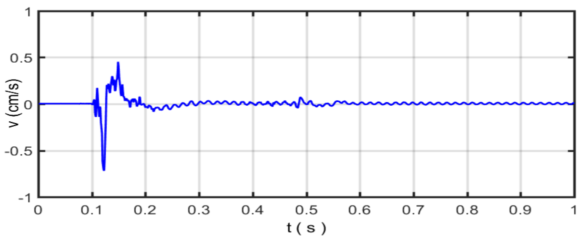
(b) Horizontal tangential direction at 5 m



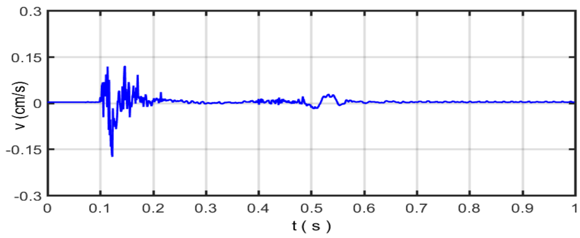
(c) Vertical direction at 5 m



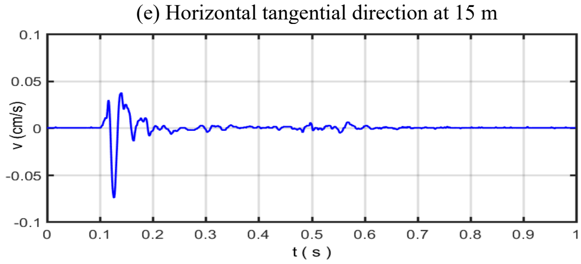
(d) Horizontal radial direction at 15 m



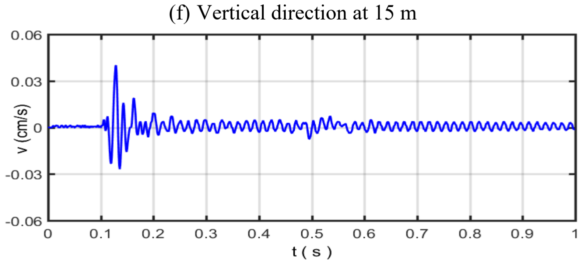
(e) Horizontal tangential direction at 15 m



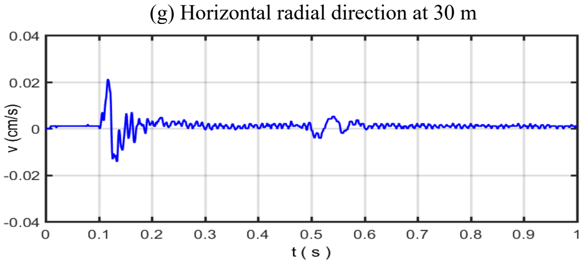
(f) Vertical direction at 15 m



(g) Horizontal radial direction at 30 m

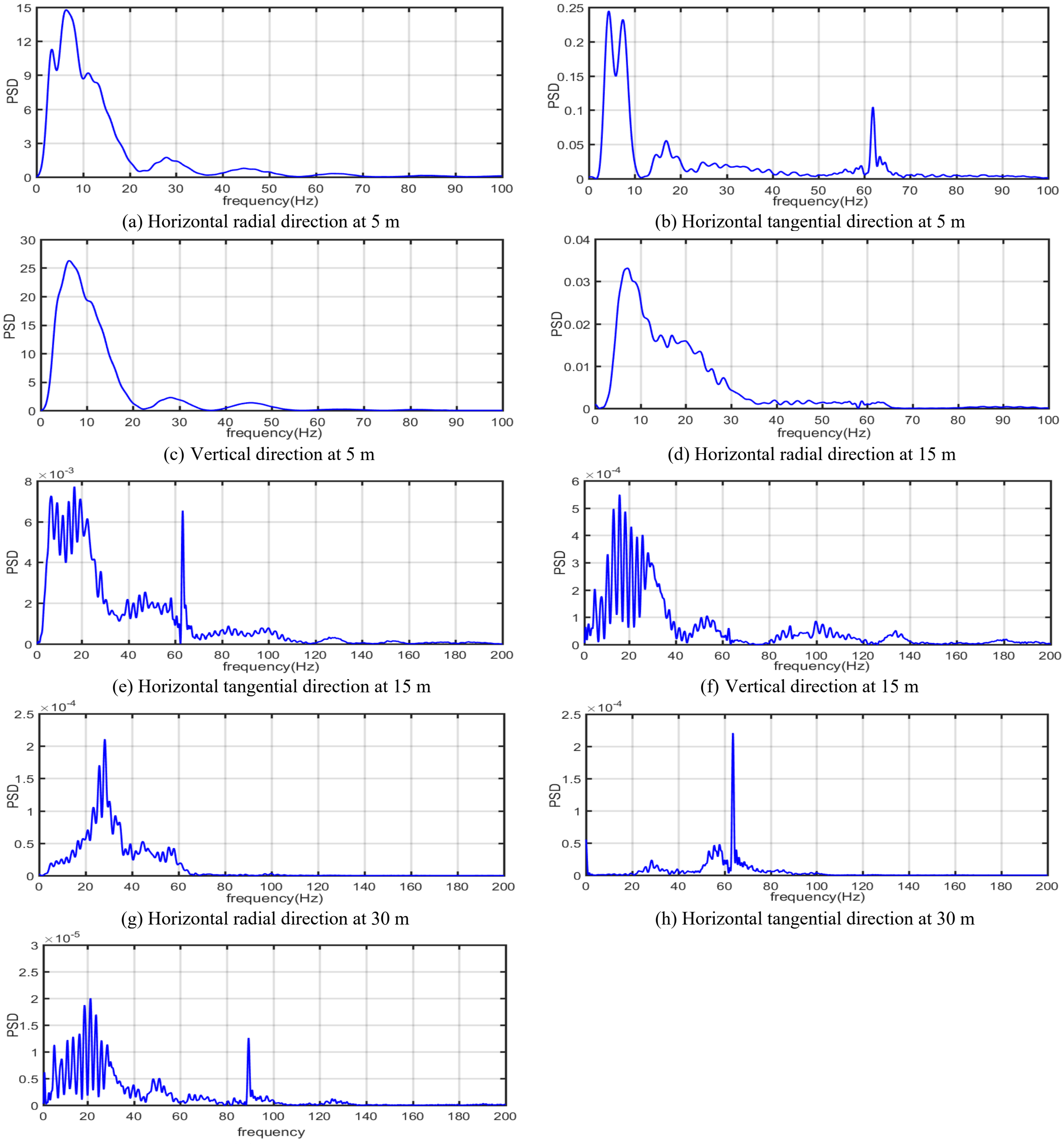


(h) Horizontal tangential direction at 30 m



(i) Vertical direction at 30 m

Fig. 7. The particle velocity curve at different distance from the CO_2 blasting hole



(a) Horizontal radial direction at 5 m

(b) Horizontal tangential direction at 5 m

(c) Vertical direction at 5 m

(d) Horizontal radial direction at 15 m

(e) Horizontal tangential direction at 15 m

(f) Vertical direction at 15 m

(g) Horizontal radial direction at 30 m

(h) Horizontal tangential direction at 30 m

(i) Vertical direction at 30 m

Fig. 8. The power spectral density at different distance from the CO_2 blasting hole

$$PPV_x = 526.5(R)^{-2.40} \tag{24}$$

$$PPV_y = 4.4(R)^{-0.81} \tag{25}$$

$$PPV_z = 5847.8(R)^{-3.84} \tag{26}$$

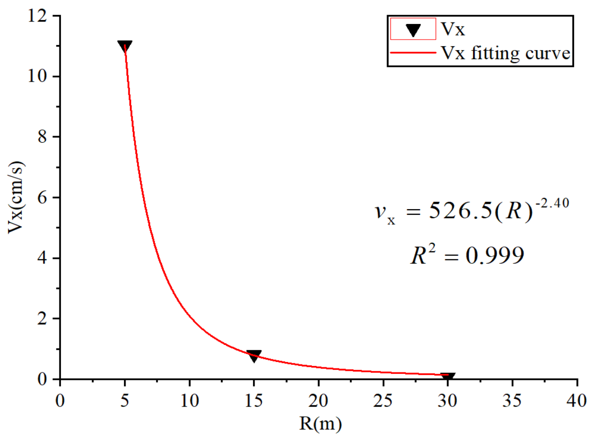
The adjacent residential building is general brick-concrete structure and belongs to common civil building; The "Safety regulations for blasting" (GB6722 - 2014) in China specified safety criterion of blasting vibration for common civil building based on peak particle velocity and the dominant vibration frequency [25], for the common civil building, the allowable limit of particle vibration velocity is 1.5-2.0 cm/s, 2.0-2.5 cm/s and 2.5-3.0 cm/s, respectively when the dominant vibration frequency is $f \le 10$Hz , $10 < f \le 50$Hz and $f > 50$Hz , respectively; the initiative control standard of particle vibration velocity is determined to [PPV_{limt}] = 1.5 cm/s, based on EQ.(24-26), the safety allowable distance of CO_2 blasting vibration is inverse computed to [R_{limt}] = 11.5 m; In the blasting site, the nearest house is 25 m away from the blasting center, it is obvious that the peak particle vibration of residential building is in the safety range during the CO_2 blasting, which show the excellent control effect on CO_2 blasting damage for near building.

It is observed in EQ.(24), EQ.(25), and EQ.(26) that the range of variation for K is from 4.4 to 5847.8 and α is from 0.81 to 3.84 where it has been observed that K , α of vertical direction is largest, this is, 5847.8 and 3.84, respectively but K , α of horizontal radial direction is 526.5 and 2.40, respectively and K , α of horizontal tangential direction is 4.4 and 0.81, respectively.

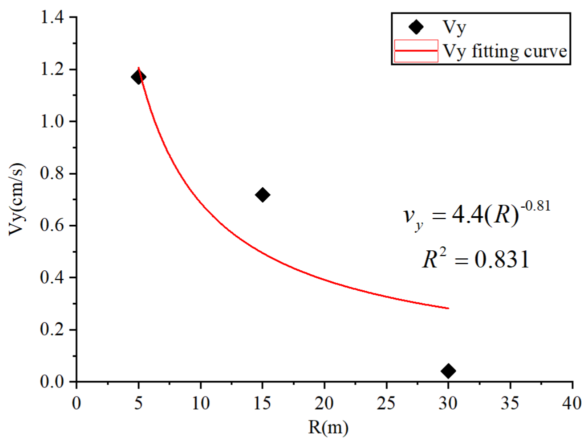
In term of power function formula in EQ.(4), parameter K is directly proportional to particle vibration velocity and parameter α represent declining speed of particle vibration velocity where the bigger of α , the faster of velocity attenuation along propagation distance.

By comparing the difference of K and α for horizontal radial, horizontal tangential and vertical direction, we easily find that the K of vertical direction is more than horizontal radial and horizontal tangential direction while α of vertical direction is also more than horizontal radial and horizontal tangential direction which show that vertical direction has faster speed of velocity attenuation, it imply that even though peak particle velocity of vertical direction is generally larger than horizontal radial and horizontal tangential direction in the near field of CO_2 blasting source, however, the peak particle velocity of vertical direction will be lower than horizontal radial and horizontal tangential direction in the far field of CO_2 blasting source, 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.

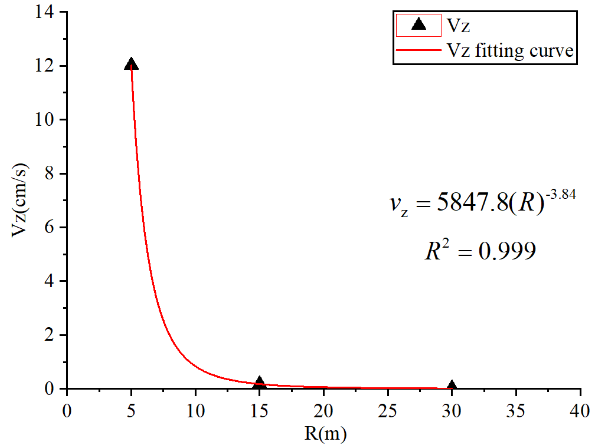
Fig. 8 shows that the dominating frequency of particle vibration produced by carbon dioxide blasting varies form 4.4 Hz to 63.7 Hz; when the distance of monitoring points is 5 m, 15 m and 30 m, the dominating frequency ranges of three mutually perpendicular directions are 4.4-6.4 Hz, 7.1-16.9 Hz and 21.9-63.7 Hz, respectively; furthermore, the CO_2 blasting energy mainly concentrated in the frequency range of 2-50 Hz, which is different from the blast vibration signals energy of emulsion explosive concentrated in the band between 50-100 Hz [20].



(a) Horizontal radial direction



(b) Horizontal tangential direction



(c) Vertical direction

Fig. 9. The regression analysis of blast vibration velocity

C. Time-Frequency Characteristics

The horizontal radial velocity curve at 5 m (Fig. 10) is selected as the typical CO_2 blasting vibration signal, and the corresponding Fourier spectrum is shown in Fig. 11. It is seen in Fig. 10 that the blasting vibration mainly concentrates in the range of 0.1-0.3 s. Similarly, Fig. 11 depict the blasting vibration energy is mainly in the range of 2-50 Hz, in which the dominant vibration frequency is 6.4 Hz.

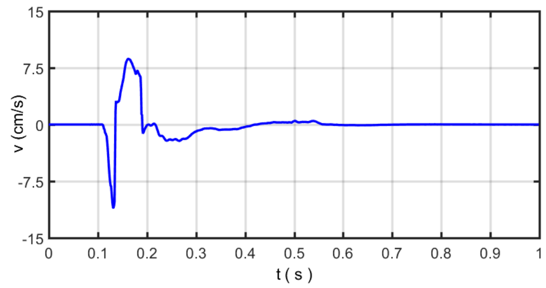


Fig. 10. The velocity curve of CO_2 blasting vibration signal

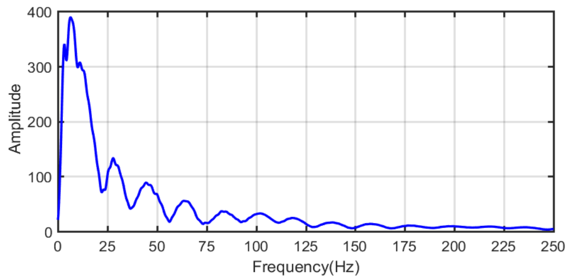
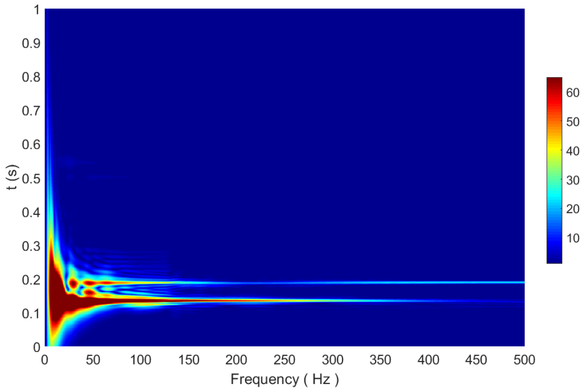


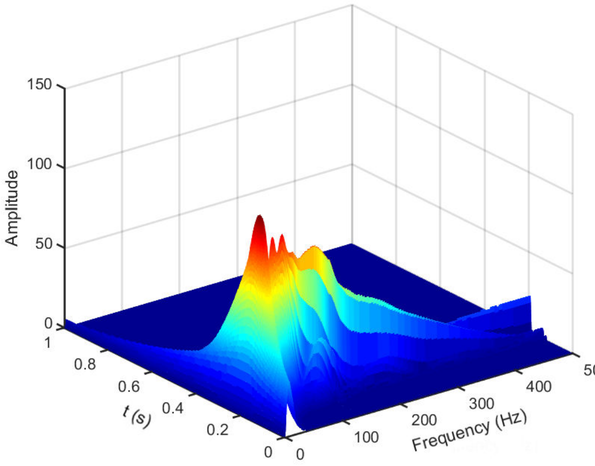
Fig. 11. The Fourier spectrum of CO_2 blasting vibration signal

TC-4850 blasting vibration monitoring system is selected as blasting monitoring instrument, the sampling frequency of the blasting vibration signal is determined as 1000 Hz; the Nyquist frequency is 500 Hz on the basis of Shannon sampling theorem [9].

Frequency Slice Wavelet Transform is used to analyze the vibration signal of carbon dioxide blasting, because the blasting frequency is basically below 500 Hz [10], 0-500 Hz is directly selected as the frequency slice interval. Firstly, let frequency slice function be Gaussian function $\hat{p}(\omega) = e^{-(1/2)\omega^2}$, According to inequality (17), we can set $k = \sqrt{2\ln(1/\upsilon)}/\eta$, and select ν =0.5, η=0.05, then k=23.55. The corresponding two dimensional and three dimensional time-frequency energy spectrum of CO_2 blasting vibration signal is obtained in Fig. 12.



(a) 2D time-frequency energy distribution of FSWT



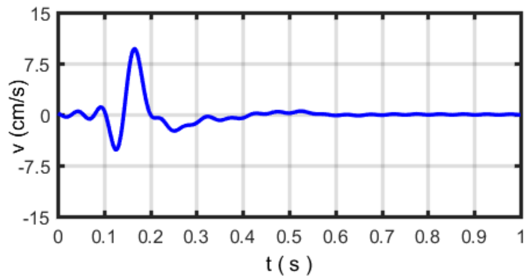
(b) 3D time-frequency energy distribution of FSWT

Fig. 12. 2D and 3D time-frequency energy distribution of FSWT

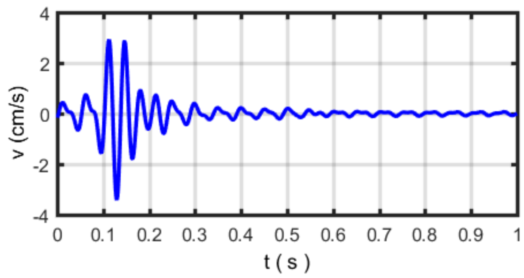
Fig. 12 presented the distribution characteristics about energy of CO_2 blasting vibration signal with the variation of frequency and time; It can be more intuitive to show the distribution of energy on blasting vibration signal with time and frequency, where the color is redder, the energy is greater, we can see that the energy mainly concentrates on the range of 2-50 Hz and 0.1-0.3 s. The distribution characteristics about energy distribution of CO_2 blasting vibration signal based on Frequency Slice Wavelet Transform is in accordance with the velocity curve of blasting vibration signal in Fig. 10 where the time region for velocity vibration amplitude mainly vary from 0.1 s to 0.3 s and the Fourier spectrum of blasting vibration signal in Fig. 11 where the frequency region for Fourier amplitude spectrum mainly concentrate on 2-50 Hz.

The energy of CO_2 blasting vibration signal is relatively concentrated in frequency domain and continuous in time domain. In the process of analyzing CO_2 blasting vibration signal, FSWT has good time and frequency resolution, therefore, FSWT time-frequency analysis method can not only observe the distribution of different frequencies at the same time and different time distributions at the same frequency, but also obtain the variation law of amplitude with time and frequency, and obtain more elaborate local time-frequency characteristics.

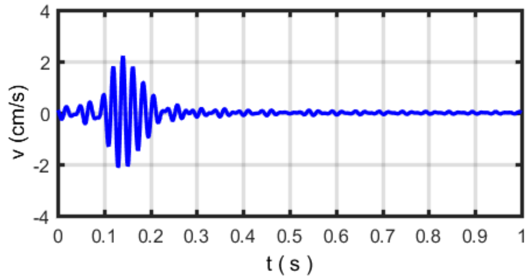
In order to determine the energy distribution of CO_2 blasting vibration signal in frequency domain, the sub-bands are constructed: every 20 Hz within 120 Hz is taken as a frequency slice interval, and above 120 Hz is taken as a single slice interval, therefore, the signal can be divided into seven sub-bands. As shown in Fig. 13, EQ.(19-20) can be used to obtain the reconstructed signal of each sub-band in the full time domain; Peak particle velocity can objectively reflect the magnitude of vibration intensity and is often used as an important indicator to evaluate vibration hazards[10]. In each sub-band, when the sub-band range is 0-20 Hz, 20-40 Hz, 40-60 Hz, 60-80 Hz, 80-100 Hz, 100-120 Hz and 120-500 Hz respectively, the peak particle velocity of blasting vibration is 9.65 cm/s, 3.40 cm/s, 2.21 cm/s, 1.24 cm/s, 1.06 cm/s, 0.95 cm/s and 0.83 cm/s, respectively, This shows that the vibration intensity of CO_2 blasting vibration sub-band signal decreases with the increase of frequency.



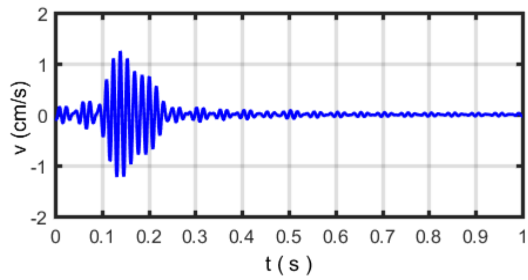
(a) 0 -20Hz



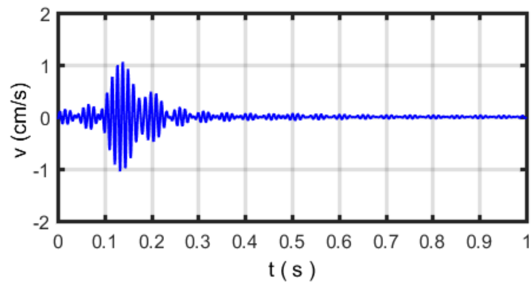
(b) 20-40Hz



(c) 40 -60Hz



(d) 60-80Hz



(e) 80 -100Hz

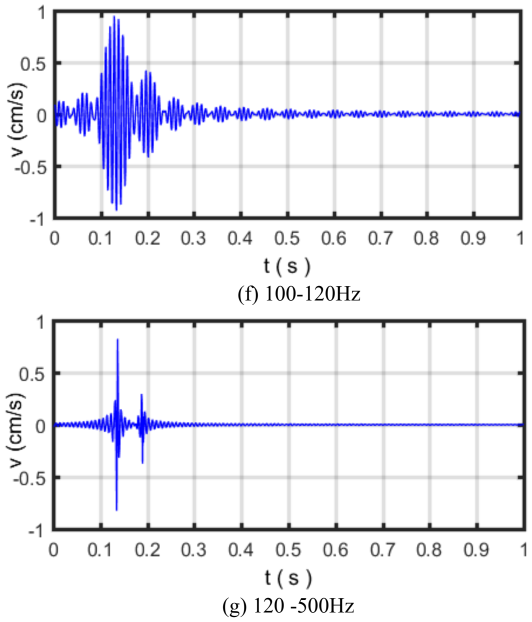


Fig. 13. Reconstructed results of blasting vibration signals in different frequency bands

According to Eq. (21) - Eq. (23), the percentage of energy distribution in each frequency band of CO_2 blasting vibration signal is shown in Fig. 14, it can be seen that the energy proportion of blasting vibration signal in each frequency band decreases in general with frequency increase, and the main energy concentrates in the range of 0-100 Hz, the blasting vibration signal in the frequency range of 0-20 Hz is more obvious and reach 92.9% of the total energy in the frequency range, meanwhile, the blasting vibration energy within 20-100 Hz is relatively small with 6.4% energy percentage; when the frequency range is higher than 100 Hz, the energy percentage of the blasting vibration signal is very small and almost negligible. The natural frequencies range of buildings roughly is 2-5 Hz [22], which is within 0 Hz and 20 Hz, thus it should be noted that CO_2 blasting may cause vibration damage for the probability of resonance.

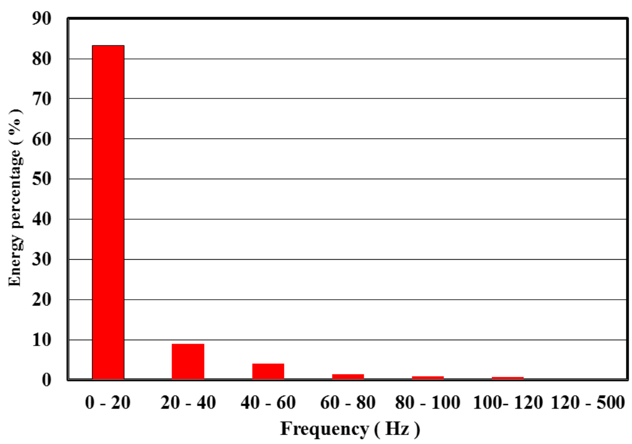


Fig. 14. Frequency band energy percentage of CO_2 blasting vibration signal

IV. Conclusion

A new and efficient fracturing and tunneling technology, namely carbon dioxide (CO_2) fracturing technology, has been gradually promoted in the field of rock excavation and coal mining; the principle of carbon dioxide fracturing blasting is introduced; the vibration effect of carbon dioxide fracturing blasting in rock excavation is monitored, in which the attenuation law of peak particle velocity (PPV) with distance is obtained and the time-frequency characteristics of blasting vibration signal are analyzed by using the Frequency Slice Wavelet Transform (FSWT), The main conclusions of the study are drawn as follows:

1) The attenuation law of peak particle velocity (PPV) with distance along the horizontal radial, horizontal tangential and vertical direction is expressed as $PPV_x = 526.5(R)^{-2.40}$, $PPV_y = 4.4(R)^{-0.81}$ and $PPV_z = 5847.8(R)^{-3.84}$. The initiative control standard of particle vibration velocity for adjacent residential building is determined to [PPV_{limt}] = 1.5 cm/s and the safety allowable distance of CO_2 blasting vibration is inverse computed to [R_{limt}] = 11.5 m, the nearest house is 25 m away from the blasting center, it is obvious that the peak particle vibration of residential building is in the safety range during the CO_2 blasting, which show the excellent control effect on CO_2 blasting damage for near building. Through theoretical analysis and experimental test, it is basically verified that the application of carbon dioxide fracturing technology to open-pit rock excavation can achieve the satisfactory effect of micro vibration, micro noise, no flying rock and no shock wave damage; it is a reliable choice for rock fracturing in complex environment.

2) As for time-frequency characteristics, the dominating frequency of particle vibration produced by carbon dioxide blasting varies from 4.4 Hz to 63.7 Hz; when the distances of monitoring points are 5 m, 15 m and 30 m, the dominating frequency ranges of three mutually perpendicular directions are 4.4-6.4 Hz, 7.1-16.9 Hz and 21.9-63.7 Hz, respectively; furthermore, the CO_2 blasting energy mainly concentrated in the frequency range of 2-50 Hz, which is different from the blast vibration signals energy of emulsion explosive concentrated in the band between 50-100 Hz.

3) In the process of analyzing CO_2 blasting vibration signal by FSWT, it shows that the vibration intensity of CO_2 blasting vibration sub-band signal decreases with the increase of frequency, the blasting vibration signal in the frequency range of 0-20 Hz is more obvious and reach 92.9% of the total energy in the frequency range; Using real CO_2 blasting vibration data, this paper demonstrates the capabilities of FSWT for analyzing important features related to CO_2 blasting energy. Because the natural frequencies range of buildings roughly is 2-5 Hz, which is within 0- 20 Hz, thus it should be noted that CO_2 blasting may cause vibration damage for the probability of resonance.

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