Dynamic response analysis of surrounding rock under the continuous blasting seismic wave

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Abstract. The blasting vibration that is caused by blasting excavation will generate a certain degree of negative effect on the stability of surrounding rock in underground engineering. A dynamic response analysis of surrounding rock under the continuous blasting seismic wave is carried out to optimize blasting parameters and guide underground engineering construction. Based on the theory of wavelet analysis, the reconstructed signals of each layer of different frequency bands are obtained by db8 wavelet decomposition. The difference of dynamic response of the continuous blasting seismic wave at a certain point caused by different blasting sources is discussed. The signal in the frequency band of natural frequency of the surrounding rock shows a certain degree of amplification effect deduced from the dynamic response characteristics of the surrounding rock under the influence of continuous blasting seismic wave. Continuous blasting operations in a fixed space will lead to the change of internal structure of the surrounding rock. It may result in the decline of natural frequency of the whole surrounding rock and it is also harmful for the stability of the surrounding rock.

1. Introduction
The continuous harmful effect of blasting vibration may cause the instability of the surrounding rock of underground carven, then resulting in huge losses of lives and properties [1, 2]. The safety criterion of blasting earthquake effect has attached the attention of a large number of blasting researchers because of it is directly related to the safety of buildings and residents around the blasting area. The particle vibration velocity has been used as the building blasting seismic effect safety criteria for a long time. With the progress of a large number of monitoring and experimental and theoretical research works, the frequency is found to be a non-negligible factor for the safety criterion of blasting seismic effect [3, 4]. Research on safety criterion of the blasting seismic effect has become an urgent problem in the field of engineering blasting [5, 6].

Wavelet transform theory, which with a good time and frequency domain analysis characteristic, has been introduced into the analysis of typical non-stationary stochastic signals such as blasting vibration signals for a long time. The application of the wavelet transform theory has already achieved fruitful results so far. Ling et al. [7] used the time-energy distribution of wavelet transform to determine the actual delay time of the micro-blasting. The energy distribution characteristic that is based on the time-frequency characteristic and hierarchical decomposition of wavelet transform was analyzed [8]. Based on the time-frequency characteristic of wavelet transform, the characteristics of vibration signals of different measuring points, inside and outside the building, were analyzed. In the meanwhile, the dynamic response characteristics of building under blasting earthquake were extracted [9]. Based on the wavelet transform theory, Song et al. [10] established a time-energy density function...
to analyze the time-frequency domain characters of response signals for the surrounding rock in underground tunnel.

In this paper, the variation characteristics of the vibration signals at the same monitoring point are analyzed for continuous blasting. The time-frequency characteristics of the blasting vibration signals are obtained by using the decomposition and hierarchical reconstruction technique according to the wavelet transform theory. In the meanwhile, the dynamic effect of continuous blasting for surrounding rock structure is analyzed.

2. Test site
The main and deputy plant of Jixi pumped storage power station is located in Anhui province. The upstream is connected with the upstream reservoir through the diversion system. The downstream is connected with the main change hole through the bus hole. The surrounding rock structure of the underground powerhouse is mainly composed of block and sub-block structure. Parts of the underground powerhouse are composed of the mosaic structure. The carven wall of the underground plant is basically stable.

The stability of the plant wall is very important for engineering construction. The plant wall is the key research area for blasting damage control. The side wall of the plant is blasted by using the method of prescribing glossy layer, while 6 rows of holes are drilled. There is a row of peripheral holes with the spacing of 40-50mm and the charge line density of 120g/m. A row of slow punching holes with the distance of 70mm and the spacing of 80mm and the charge quantity of 1.4kg per hole are arranged outside. The spacing of the remaining 4 rows of holes is 100mm. The row spacing is 95mm and the charge quantity of every single hole is 2.4kg, respectively.

A vibration meter is placed in the 3# bus hole as a blasting monitoring point. The distances of the No.1 and No.2 blasting points from the monitoring point are all 34.5m. The total charge quantity of the first blasting is 72kg, while the maximum single-shot charge quantity is 14.4kg. The total charge quantity of the second blasting is 48kg. The number of blasting holes for the second blasting is less than 10 of the first blasting. The maximum single-shot charge quantity is 14.4kg. The segmented blasting technique is used, while the delaying time is 460ms.

Because of the main vibration frequency of the blasting vibration signal is generally below 200Hz, the sampling rate of the signal is set to 5000 Hz according to the sampling theorem. As a result, the Nyquist frequency is 2500 Hz. The error of signal reconstruction by using db8 wavelet is relatively small, so, the db8 wavelet is used to deal with the blasting vibration signal in this paper. The monitoring signal is decomposed to 8 layers. According to the principle of wavelet decomposition, 9 frequency bands can be got. Where a8 is the low frequency band, its bandwidth is 0-9.77Hz. And d8–d1 are the high frequency bands, their frequency distribution (Hz) as described below. There are d8: 9.77-19.53 Hz; d7: 19.53-39.06 Hz; d6: 39.06-78.13 Hz; d5: 78.13-156.25 Hz; d4: 156.25-312.5 Hz; d3: 312.5-625 Hz; d2: 625-1250 Hz; d1: 1250-2500 Hz.

3. Wavelet analysis of blasting vibration signal
3.1. Principle of wavelet transform
Given \( \psi(t) \in L^2(R) \) (where \( L^2(R) \) is the signal space with a limited energy), its Fourier transform is \( \psi(t) \). Then when \( \psi(t) \) meets the allowable condition: \( C_\psi = \int_R |\psi(t)|^2 dt < \infty \), herein, \( \psi(t) \) is a basic wavelet. After the basic wavelet is scaled and translated, a wavelet sequence can be obtained.

The continuous wavelet transform for any function of \( f(t) \in L^2(R) \) can be described as below.

\[
W(a,b) = \langle f, \psi_{a,b} \rangle = \left| a \right|^{-\frac{1}{2}} \int_R f(t) \overline{\psi(\frac{t-b}{a})} dt
\]  

(1)
Where \( \langle f, \psi_{a,b} \rangle \) is the inner product of \( f \cdot \psi_{a,b} \). \( \psi(t-b/a) \) is the conjugate function of \( \psi(t-b/a) \), where \( a \) is the scaling factor and \( b \) is the translation factor.

The inverse transformation of continuous wavelet is:

\[
f(t) = \frac{1}{C_\psi} \int_{\mathbb{R}} \int_{\mathbb{R}} \frac{1}{a^2} W_f(a,b) \psi(t-b/a) \, da \, db
\]

While the discrete sequence of wavelet sequences is:

\[
\psi_{j,k}(t) = 2^{-j} \psi(2^{-j} t - k)
\]

Where \( a = 2^j, b = 2^j k, (j,k \in \mathbb{Z}) \).

The discrete wavelet transform is:

\[
C_{j,k} = \int_{\mathbb{R}} f(t) \psi_{j,k}(t) \, dt = \langle f, \psi(j,k) \rangle
\]

The wavelet reconstruction formula is:

\[
f(t) = \sum_{j} \sum_{k} C_{j,k} \psi_{j,k}(t)
\]

3.2. Wavelet signal analysis results

According to the wavelet analysis theory, the db8 wavelet is used as the fundamental wave. The blasting vibration signal is decomposed into 8 layers, after that, the wavelet decomposition coefficient for each layer is reconstructed. The calculation and analysis procedures are carried out by using the Matlab software. The original signal and the reconstructed signal of each frequency band for different blasting points are shown in figure 1 and figure 2.
Figure 1. The original signal and reconstructed signal of the No.1 blasting point.

Figure 2. The original signal and reconstructed signal of the No.2 blasting point.

It can be seen from the original signal vibration waveforms that the peak value of the first blasting vibration velocity is smaller than the peak value of the second blasting vibration velocity. Even though
the total charge quantity of the first blasting is higher than the second blasting and the maximum single-shot charge quantity is similar to each other.

The reconstructed waveforms of the a8 low frequency band (0-9.77Hz) of the blasting vibration signal show a certain degree of amplitude in the first half stage, but fluctuate at zero value in the second half of the signal. It is indicated that when the blasting seismic wave reaches the measuring point, the energy of the frequency band signal generates some impacts for the side wall of bus hole in the first half section.

For the reconstructed waveforms of the d8 frequency band (9.77-19.53Hz), it can be seen that the side wall show a large amplitude vibration during the first 0-500ms, while the amplitude of vibration decreases to 0 after 500ms. It is indicated that when the blasting seismic energy reaches to the side wall of the bus hole, due to the dynamic response characteristics of the surrounding rock, some frequency bands of the blasting vibration signal will maintain a certain degree of amplitude for a relatively long time, showing a slowly energy attenuation characteristic.

It is found that the peak velocity of d7 (19.53-39.06Hz) and d6 (39.06-78.13Hz) are relatively larger compared with the peak velocities of other frequency bands of the two blasting. Therefore, it can be concluded that the natural frequency of the surrounding rock is located in the range of these two bands, in which shows a significant amplitude increasing phenomenon.

The vibration signals show a process that continuously increase to the peak value and then decrease to zero within 500ms by comparing with the vibration signals of frequency band d3 (312.5-625Hz), d4 (156.25-312.5Hz) and d5 (62.5-125Hz) of the first blasting, and the vibration signals of frequency band d4 (156.25-312.5Hz), d5 (62.5-125Hz) and d6 (39.06-78.13Hz) of the second blasting. The similarity of the signal amplitude of these two bands shows that the blasting vibration signal does not affected by surrounding rock structure. The similarity of the blasting vibration waveform attenuation of the two blasting shows that the vibration response characteristics of rock structure at the same measuring point are similar for different blasting sources. And it also shows that the natural frequency of the surrounding rock is lower before the first blasting.

4. Conclusion
The time-frequency characteristics of the blasting vibration signal obtained from the wavelet analysis can clearly reflect the difference of the blasting vibration signal caused by the slight difference of the single-shot charge quantity. It can be used to guide engineering blasting operation and optimize blasting parameters. Blasting signals may last for a long time and accompanying with a certain degree of increment when blasting signals input into the surrounding rock for the low frequency band. The continuous blasting at the same point of the surrounding rock will result in some structure changes, then reducing the natural frequency of the surrounding rock. When the next blasting seismic wave enters the surrounding rock with a frequency band near the natural frequency of the surrounding rock, the blasting vibration signal will persist for a long time and accompanying with higher amplitude. It is not conducive to the stability of the surrounding rock. The peak vibration velocity does not increase on the increase of the delayed blasting segments. Even the rational use of delayed blasting, the increase of the amount of detonation will not necessarily lead to the increase of the peak vibration velocity for the protected engineering.

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