Analysis of Fractal Features of Blasting Vibration Signal Based on EEMD Decomposition

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Abstract. In order to study the propagation characteristics of blasting seismic waves by using the analysis and research of blasting vibration monitoring data of Urumqi subway tunnel excavation, the blasting vibration signal has been decomposed into several IMF components by EEMD decomposition and fractal theory has been used to calculate the correlation dimension in this paper. The results show that the IMF component can reveal the frequency characteristics in the blasting vibration signal clearly. As the measuring point is far away from the explosion source, the complexity of the frequency component of the vibration signal gradually decreases. The seismic wave interacts with the rock and soil medium in the propagation process, make it shown non-linear characteristics, which are not easily to be observed by conventional measurement methods. This paper introduces fractal dimension to study the nonlinear characteristics of blasting vibration signals and achieves the purpose of analysing the law of blasting seismic wave propagation. This study achieves a quantitative description of the effects of site media on seismic waves, and at the same time, it lays a theoretical foundation for predicting the vibration effect analysis of seismic waves reaching the target position.

Keywords. Blasting vibration, signal analysis, EEMD decomposition, correlation dimension.

1. Introduction
In blasting engineering, especially for the blasting excavation process of urban tunnel construction, the blasting vibration effects may induces tunnel collapse, uneven settlement of ground, and even cause the damage to the foundations of nearby buildings for [1]. Therefore, studying the characteristics of blasting vibration during tunnel excavation would make great significance to construction safety and protecting surrounding environment.

The seismic wave is a typical non-stationary random signal which caused by blasting, and it is extremely complicated. The blast signal is a typical non-stationary random signal [2], and the Fourier transform and wavelet transform have certain limitations in analysing these signals [3]. It is because the Fourier transform has no time-frequency effect, and there cause different results in the choosing wavelet basis in wavelet analysis. The HHT transform proposed by Huang is a highly adaptive time-frequency analysis method [4], which consists of two parts: EMD decomposition and Hilbert transformation has a good effect on the processing and analysis of non-stationary signals. Li Xi-bing [5] first introduced the HHT transform to the field of blasting vibration signal processing and removed unnecessary IMF components according to the characteristics of the decomposed signal which could achieve the purpose of filtering and denoising in same time. In this way, the non-linear characteristics of the signals can be preserved. Huang improved the theory on the basis of EMD decomposition, and
proposed EEMD decomposition (Ensemble Empirical Mode Decomposition) [6], which further developed the method of HHT transformation. With the deepening of people’s understanding of blasting vibration signals, fractal theory in nonlinear scientific research has also been introduced into the research field of blasting vibration signals. Xie Quan-min [7] combined fractal and wavelet packet technology, which based on the consistency of fractal theory and wavelet analysis methods in understanding the process and essence of things, draw the conclusion that The larger box dimension of the blasting signal box, the more high-frequency components of the signal will be, and so did the signal curve more complex. These studies have enriched the research system of blasting signal analysis and laid the foundation for further research on the nonlinear characteristics of blasting signals.

This paper combines the EEMD decomposition and fractal theory based on previous research achievements to study the propagation rules and fractal characteristics of blasting seismic waves by using the blasting vibration monitoring signal during the construction of Urumqi Metro Line 1. By introducing the dimensionless parameter of fractal dimension, the frequency characteristics, peak velocity and correlation dimension of vibration signals at different distances from the explosion source are studied. These works laid the foundation for studying adjacent structures and evaluating the impact of blasting vibration.

2. EEMD Decomposition and Signal Reconstruction

HHT transformation consists of two parts: empirical mode decomposition (EMD) and Hilbert transformation. The core part is EMD decomposition, which decompose the signal in several intrinsic modal functions (IMF) component, which has different fluctuation levels according to its own temporal scale characteristics. However, EMD decomposition has a modal aliasing phenomenon, and severe distortion at the endpoints will occur when processing part of the signal, which is limited in the application of processing signals. Huang prevents the diffusion of low-frequency modal components by adding small amplitude white noise to the data [8], which had alleviated the modal aliasing and end effects. The average value of the white noise sequence in the time domain will cancel each other, and then the true component of the signal will be obtained, and this is EEMD decomposition (Ensemble Empirical Mode Decomposition).

The composition of blasting seismic waves is very complicated, including not only the multiple disturbance effects of stage blasting, but also various interference noises during data acquisition. After EEMD decomposition, unnecessary IMF components can be filtered effectively, and the dominant IMF components can be recombined into a reconstructed signal, which fully retains the inherent nonlinear and non-stationary characteristics of the signal itself [9], that has a great effect further analysis of the blasting vibration signal.

The signal \( x(t) \) can be represented as multiple IMF components \( c_i(t) \) and one residue \( R \):

\[
x(t) = \sum_{i=1}^{n} c_i(t) + r_n
\]

The vibration velocity signal collected by one blasting vibration is shown in figure 1, and the reconstructed signal after EEMD decomposition can be seen in figure 2. The initial signal can be decomposed into 11 IMF components of different fluctuation scales and 1 residue after EEMD decomposition, as shown in figure 3. As the order of the IMF component increases, the scale of signal fluctuations and the frequency of the signal gradually decrease. The high-frequency content of the first and second-order components is higher, but the amplitude is very small. This type of component generally contains more noise signals. The interference of signal analysis is large; It can be seen from the 4th-order IMF component of figure 3(d), that the obvious time delay characteristics of sectional blasting, the original messy signal is split into relatively independent blasting vibration responses; The frequency of the IMF components is getting lower and lower, and the amplitude is getting smaller and
smaller; figure 3(l) is the residual term, which represents the signal trend or instrument drift, generally in a monotonous direction.

Figure 1. Original blast signal.  
Figure 2. Reconstructed blast signal.

(a) The 1st order IMF component.  
(b) The 2nd order IMF component.  
(c) The 3rd order IMF component.  
(d) The 4th order IMF component.  
(e) The 5th order IMF component.  
(f) The 6th order IMF component.  
(g) The 7th order IMF component.  
(h) The 8th order IMF component.  
(i) The 9th order IMF component.  
(j) The 10th order IMF component.  
(k) The 11th order IMF component.  
(l) The 12th order IMF component.

Figure 3. The IMF component of one single blasting vibration signal.
It can be seen that neither the larger frequency nor the smaller IMF component is an effective form of the blasting vibration signal, and components, which has the smaller amplitude, will interfere with the analysis of the blasting vibration signal. Take the dominant components and recombine it into a new reconstructed signal as shown in the figure as shown in figure 2, obtain the maximum vibration velocity and main frequency information for each IMF component. Those data are shown in tables 1-2.

**Table 1. The max velocity and main frequency data of all signals.**

| Signal                  | Original Signal | 1<sup>st</sup> IMF | 2<sup>nd</sup> IMF | 3<sup>rd</sup> IMF | 4<sup>th</sup> IMF | 5<sup>th</sup> IMF | 6<sup>th</sup> IMF |
|-------------------------|-----------------|--------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Max Velocity (cms<sup>-1</sup>) | 8.693           | 0.381              | 0.585             | 0.921             | 5.052             | 2.432             | 1.700             |
| Main Frequency (Hz)     | 32              | 3235               | 838               | 369               | 37                | 48                | 32                |

It can be seen from the data in tables 1-2 that the main frequency of the high-order and low-order IMF components is too large or too small. Generally, the main frequency of the blasting vibration signal is between 10Hz and 100 Hz, which means that only 4th, 5th and 6th order IMF components is the dominant blasting vibration signal. They can be recombined into a new reconstructed signal and the main frequency and maximum vibration velocity data are shown in tables 1-2, and the image is shown in figure 2.

**Table 2. The max velocity and main frequency data of all signals.**

| Signal                  | Reconstructed Signal | 7<sup>th</sup> IMF | 8<sup>th</sup> IMF | 9<sup>th</sup> IMF | 10<sup>th</sup> IMF | 11<sup>th</sup> IMF |
|-------------------------|----------------------|--------------------|------------------|-------------------|-------------------|-------------------|
| Max Velocity (cms<sup>-1</sup>) | 8.546               | 0.899              | 0.567            | 0.454             | 0.251             | 0.097             |
| Main Frequency (Hz)     | 32                   | 21                 | 9.4              | 3                 | 2.1               | 1.45              |

Comparing figures 1-2, as well as the main frequency and maximum vibration velocity of the original signal and the reconstructed signal, it can be found that the reconstructed signal well reflects the relevant characteristics of the original signal. After removing other IMF components, the original signal has also been denoised. This method of filtering and reducing noise has good adaptability and can retain the important information in the original signal more than simple digital filtering. The reconstructed signal after eliminating the noise interference is very important for the fractal analysis of blasting vibration effects.

3. Calculation of Blasting Vibration Signal’s Correlation Dimension

In the 1970 s, B. Mandelbort first proposed fractal theory. After many years’ development, fractal theory has been widely used in various research fields of natural sciences and social sciences [10-11]. Fractal theory has been used to study nonlinear systems and can be used to describe the unity of determinism and randomness. A large number of research results have shown that the blasting vibration signal is a random fractal that satisfies the statistical self-similarity [12]. At present, the main method of fractal analysis is to calculate the fractal dimension of the research object. Commonly used calculation methods of calculation dimension include box dimension, information dimension, correlation dimension and so on. The correlation dimension has been used to calculate in this article.

3.1. Correlation Dimension and the GP Algorithm

The blasting vibration signal is essentially the concentrated manifestation of the disturbance phenomenon of the blasting seismic wave to the medium along the way during the propagation process, which means that the one-dimensional time series reflected by the vibration signal is the
mapping phenomenon from the higher-dimensional into nonlinear system in the low-dimensional. The evolution rules of the complex multi-dimensional system reflected by the signal must extend the one-dimensional time series to a higher dimensional space to study the changing rules of the seismic wave system. In 1983, Grassberger and Procaccia [11] established a method for calculating the correlation dimension of system singular attractors from time data series, that is, the GP algorithm, which can be used to calculate correlation dimensions, and its main part includes phase space reconstruction and calculation of correlation integrals [13].

Phase space reconstruction [14] is a method of extending one-dimensional signal into high-dimensional space. The time delay method has been usually used to construct the phase space. Through the time delay \( \tau \), the original time series \( \{x_1, x_2, x_3, \ldots, x_n\} \) can be embedded into the phase space of dimension \( m \). And the points of the new phase space are:

\[
X_i(n) = \{x_i(n), x_i(n + \tau), x_i(n + 2\tau), \ldots, x_i(n + (m-1)\tau)\}, i = 1, 2, \ldots, N
\] (2)

In equation (2), \( N = n + (m-1)\tau \) is the number of points in the new phase space, so that the original time series \( \{x_i\} \) can be reconstructed into a \( m \times N \) phase space. In this process, the choice of time delay \( \tau \) is very important. If \( \tau \) is too large, the points in the phase space will have no correlation. If \( \tau \) is too small, the correlation will be too strong. Only when the time delay \( \tau \) is selected reasonably can it be based on topological equivalence. Restore the dynamic performance of the original system.

There are many methods to determine the time delay, such as autocorrelation function method, mutual information method [15] and so on. The mutual information method has been used in this paper, which has a good effect on non-stationary sequences.

The GP algorithm is the core of calculating the correlation dimension. Its basic definition is that within a given neighbourhood radius \( r \), the correlation integral can be defined:

\[
C(m, r) = \sum_{(i \neq j)} H \left( r - \|X_i - X_j\| \right)
\] (3)

In equation (3), \( H(\bullet) \) is the Heaviside jump function

\[
H(x) = \begin{cases} 
0, & x < 0 \\
1, & x \geq 0 
\end{cases}
\]

The correlation integral is actually a cumulative distribution function [16], which describes the probability that the distance between any two points in the phase space is less than the radius of the neighbourhood and describes the degree of aggregation of the phase points. When \( r \) is small, the distance between all phase points is greater than \( r \), that is, no point falls within the radius of the neighbourhood, then the correlation integral is zero, when \( r \) is too large, all phase points fall within the radius of the neighbourhood, The associated score is 1. For each step length \( r \), a corresponding correlation integral \( C(r) \) can be calculated, and the correlation dimension \( D \) at this time can be calculated as equation (4):

\[
D = \frac{\ln r}{\ln C(r)}
\] (4)

When \( r \) changes within a certain range, the distribution probabilities of a series of phase space points can be obtained. For different embedding dimensions \( m \), a series of \( r \) and relations can be obtained. When the embedding dimension \( m \) is transformed, the time series is extended to high-dimensional space, which is equivalent to changing the observation scale. Due to the invariance of the fractal scale, when the embedding dimension increases to a certain value, the correlation dimension \( D \) no longer changes drastically as the embedding dimension \( m \) increases, and gradually converges to a stable at this time, the correlation dimension \( D \) [17] is obtained.
3.2. Fractal Characteristics of IMF Reconstructed Signal
Since the correlation dimension of the blasting vibration signal reflects the nonlinear characteristics of the blasting seismic wave, noise interference has a great influence on the correlation dimension. The initial signal contains a large amount of noise information, which oscillates violently in the correlation dimension calculation and does not converge. And the correlation dimension calculation of the reconstructed signal is relatively stable.

Figures 4-5 are the double logarithmic curve diagram and the correlation diagram of the correlation dimension and the embedding dimension when the reconstructed signal is embedded multiple times with different values of m. It can be seen from figure 4 that when the value of r is small, the correlation integral $C(r)$ is not stable. It changes drastically as r gradually increases, and gradually tends to 1 as r increases. During this process, a scale-invariant zone appears, which is in middle section of the curve in figure 4. The linearity is good, and the slope of the fitted line at this area is the correlation dimension value of the embedding dimension. As can be seen in figure 5, as the embedding dimension increases, the correlation dimension gradually stabilizes, as Simple calculation, take the average of the maximum and minimum in the stable interval of the correlation dimension as the correlation dimension of the signal, so the correlation dimension of the signal is $D = 2.347$.

![Figure 4. Double logarithmic graph.](image)

![Figure 5. Correspondence graph of embedding dimension and correlation dimension.](image)

4. Blasting Vibration Monitoring and Signal Analysis
In order to study the disturbance effect of the nearby buildings (structures) during the blasting of the urban subway, and the fractal characteristics of the blasting vibration signal, the vibration signals collected during the blasting and excavation construction of Urumqi Metro Line one. Program the algorithm by using Matlab which could extracts the dominant component after EEMD to form a reconstructed signal, and calculates the peak vibration velocity, dominant frequency and correlation dimension that is calculate by GP algorithm of the signal.

4.1. The Monitoring Method of Blasting Vibration
The measurement area is located in the interval from Zhongyinggong Station to Xiaoxigou Station on Urumqi Rail Transit Line one. The layout of the vibration measuring instruments is shown in figures 6-8. The measuring points are all arranged on the ground, and the instrument interval is 10 m. Data was collected during the two times blasting during excavation processes. Schematic diagram of blast-hole is shown in figure 9. Benching tunneling method is used for construction, the advance for per cycling blasting is 1m and the maximum charge amount per delay interval is 4.5 kg. During the first blasting, measuring point 1# was directly above the tunnel face, and measuring points 2# to 5# were arranged in sequence behind the tunnel face. In the second blasting, measuring point 1# was still arranged directly above the tunnel face. Layout measuring points 2~3 along the back of the tunnel face and measuring points 4#–5# along the excavated area in front of the tunnel face. The plane graph for each monitor point can be seen in figures 6, 8. The type of monitor is TC4850 wireless network.
vibrometer with a sampling frequency of 8000 Hz. The instrument collects radial, axial and vertical velocities at the same time. Due to the large value of the axial velocity, the following data are all axial vibration data.

![Figure 6](image1.png)  
**Figure 6.** The plan of vibration measurers which are above the tunnel face in 1\textsuperscript{st} time.

![Figure 7](image2.png)  
**Figure 7.** The layout of vibration measurers on the ground.

![Figure 8](image3.png)  
**Figure 8** The plan of vibration measurers which are above the tunnel face in 2\textsuperscript{nd} time.

![Figure 9](image4.png)  
**Figure 9.** Schematic diagram of blast-hole (unit: mm).

The collected vibration signals are all subjected to the correlation dimension calculation of EEMD decomposition and GP algorithm. The relevant data is shown in tables 3-4.

**Table 3.** The max velocity and main frequency data in the first blasting.

|                  | 1#  | 2#  | 3#  | 4#  | 5#  |
|------------------|-----|-----|-----|-----|-----|
| Original Signal  |     |     |     |     |     |
| Max velocity     | 8.69| 5.86| 1.81| 1.03| 0.28|
| Main Frequency   | 64.73| 4.36| 32  | 41.45| 34  |
| Reconstructed    |     |     |     |     |     |
| Max velocity     | 8.55| 5.56| 2.07| 0.97| 0.13|
| Main Frequency   | 34.73| 34.18| 32  | 41.45| 34  |
| Number of IMF    | 12  | 12  | 11  | 10  | 9   |

**Table 4.** The max velocity and main frequency data in the second blasting.

|                  | 5#  | 4#  | 1#  | 2#  | 3#  |
|------------------|-----|-----|-----|-----|-----|
| Original Signal  |     |     |     |     |     |
| Max velocity     | 1.43| 4.58| 7.04| 5.11| 2.24|
| Main Frequency   | 23.00| 20.00| 39.20| 20.00| 22.40|
| Reconstructed    |     |     |     |     |     |
| Max velocity     | 1.94| 4.01| 8.19| 4.66| 2.27|
| Main Frequency   | 22.00| 40.00| 39.20| 20.00| 22.40|
| Number of IMF    | 10  | 12  | 13  | 12  | 11  |
4.2. The Analysis of Blasting Vibration

Traditionally, the analysis of vibration generally uses the data of peak blasting vibration velocity and main frequency of vibration. Tables 3-4 are the sampling data of the first and second blasting tests. It can be seen from the tables that as the distance from the tunnel face increases, the peak vibration velocity and main vibration frequency of the measuring point have certain changes.

For the data from the first blasting, from measuring point 1# to measuring point 5# are all behind the tunnel face, which means the unexcavated area. The conclusion can be draw that the farther the distance from the tunnel face is, the smaller the impact of the blasting vibration effect, the more severe of PPV velocity is attenuated from the evolution rules of PPV (peak particle vibration) velocity. It can be seen that the reconstructed signal has no more difference from the initial signal; From the view of the main frequency, the main frequency of the first blasting changes drastically with little rules, and the overall trend is decreasing. Combining the number of IMF components, the measurement points directly above the tunnel face have the most IMF after EEMD decomposition. The farther away from the tunnel face, the less IMF component will be. It is because the geotechnical medium is a natural filter. As the blasting seismic wave travels farther, the loss of high-frequency components is more serious, and the complex components contained in the blasting seismic wave are less.

The purpose collecting data from the second blasting vibration is different from the previous ones. There are not only measuring points behind the tunnel face, but also measuring points in the area which is already excavated. This is for the hollow effect by blasting vibration on the excavated area during excavation. It can be seen from table 4 that, like the first test result, the farther away from the tunnel face, the greater the attenuation of the vibration velocity, the main frequency is decreasing, and the number of IMF components decreases, indicating the high frequency components of the blasting seismic wave are lost in the propagation process, and the overall signal components are evolving from complex to simple, but from the perspective of vibration speed, the hollow effect at measuring point 4# is not obvious.

It can be seen from tables 3-4 that only relying on the peak vibration velocity and main frequency of the particle blasting vibration to analyse and study the blasting vibration effect and the seismic wave propagation characteristics often has singularities, and some features cannot be fully displayed. This is because the measurement point is located on the surface, and the nonlinear characteristics of the blasting seismic wave are hidden by the signal itself during the propagation process. The correlation dimension that can describe the nonlinear characteristics of the blasting vibration signal can be used for further analyse.

The corresponding graph of correlation dimension and PPV velocity is shown in figures 10-11. It can be seen from the figure that as the distance from the tunnel face increases, the correlation dimension gradually decreases, and the closer distance from the tunnel face, the greater the correlation dimension will be.

![Figure 10](image1.png)  **Figure 10.** The Correspondence diagram of correlation dimension and peak vibration velocity of first blasting.

![Figure 11](image2.png)  **Figure 11.** The Correspondence diagram of correlation dimension and peak vibration velocity of second blasting.
The correlation dimension of the measuring point within 10 m from the tunnel face is about 2.5 or even higher, the greater the reduction of the correlation dimension for for further the distance, and the position away from tunnel face more than 20 m, the correlation dimension are all below 1.5, then the PPV velocity at this time is also less than 4 cm/s, and the blasting energy is much smaller. The data in figure 11 shows that the hollow effect in front of the tunnel face is reflected in the correlation dimension. Although the peak vibration velocity did not increase at this place, the correlation dimension of the 4# measuring point is much higher than that of the measuring points in other positions, which requires sufficient attention. After the distance from the tunnel face exceeds 10 m, the cavity effect is no longer obvious. The correlation dimension and peak vibration velocity dropped suddenly.

It can be seen that the correlation dimension is relatively accurate in describing the internal energy of the blasting signal. Compared with other parameters that can only describe the blasting vibration effect from a single side, the correlation dimension reflects the nonlinear dynamic characteristics of the blasting seismic wave. The larger the correlation dimension, the more complex the components of the signal, the more energy it contains, the stronger the impact will be. On the contrary, the more obvious the linearity of the signal, the less energy it contains. From the data in figures 10-11, once the correlation dimension is greater than 2.5, it indicates that a relatively large blasting disturbance has occurred at this location. It is necessary to protect the surrounding buildings in time and adjust the blasting parameters. Once the correlation dimension is reduced to 1.5 An even lower value indicates that the blasting disturbance at this location is much smaller.

During the blasting construction process, the blasting source parameters can be adjusted to achieve the purpose of controlling blasting. The impact on the propagation medium can often only be estimated by empirical methods. This is because the site characteristics of the seismic wave propagation medium cannot be accurately determined and measured. Because the site characteristics cannot be accurately understood and mastered, the propagation characteristics and damage effects of blasting seismic waves cannot be accurately predicted. The introduction of fractal dimension can help study the nonlinear characteristics of blasting seismic waves, so that it is possible to quantitatively describe the characteristics of the propagation site medium and predict the effect of seismic waves reaching the target location.

5. Conclusion
(1) Construct a band-pass filter through the EMD decomposition method, which can eliminate the interference of high-frequency and low-frequency parts, while retaining the original signal characteristics to achieve good filtering characteristics. The reconstructed signal composed of the dominant IMF components can reflect the characteristics of the original signal well.

(2) During the propagation of the blasting signal, the interference and attenuation of the high-frequency part is significantly higher than that of the other parts. The farther away from the blasting source, the simpler is the composition of the frequency components in the signal. The disturbance of the low-frequency signal within 30 m of the blasting source is the impact of buildings (structures) is significant. During tunnel construction, blasting vibration monitoring should be combined to optimize blasting design parameters.

(3) The calculation of HHT transformation and fractal dimension considers the decomposition and research of signals at different scales and uses EMD decomposition to eliminate high-frequency signal interference, so as to obtain the correlation dimension and study the fractal dimension of blasting signals at different scales. Number transformation can lay a solid research foundation for further research on the energy effect and fractal characteristics of blasting seismic waves.

(4) The blasting seismic wave contains a lot of complex information, which will change with the influence of its propagation path. The fractal dimension can be used as a feature to identify the changing law of blasting seismic waves and help study the attenuation law of blasting signals.
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