Generalized dimension based on morphological covering for blasting vibration signal processing

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Abstract. Blasting vibration signals are the comprehensive embodiment of the blasting seismic waves with the effects of the field medium. They can reflect the characteristics of the blasting source to a certain extent. At the same time, they can reflect the features of the field medium. Motivated by this fact, this paper applies generalized dimension based on morphological covering (MC) method to characterize the nonlinearity and complexity of the blasting vibration signals. We establish the fractal dimension model according to the propagation laws and features of the signals. Based on the test data measured from rock field, the generalized dimension of the signals is calculated. Experimental results reveal that the generalized dimension of blasting vibration signals reflect the feature information of the propagation medium in the blasting field. The generalized dimension based on MC method can be regarded as a new parameter to describe the blasting vibration signal and lay the foundation for establishing a more effective prediction model of blasting vibration.

1. Introduction
Blasting seismic waves carry important information which reflects the features of the field and blasting source with the action of complex filed medium, such as the rock faults, the acoustic characteristics of the geological, charge of blasting source, blasting delay interval, etc. This information is mainly embodied in the attenuation of vibration intensity, frequency structures and signals singularity of blasting vibration signals [1-3]. Therefore, it is crucial to make a deep analysis of blasting vibration signals.

Blasting vibration signals are characterized as short duration and quick mutation. At present, various approaches using Fourier transform, short-time Fourier transform, wavelet analysis, wavelet packets analysis, Hilbert-Huang transform and other time-frequency techniques have provided effective tools for basting vibration signal processing [4-9]. However, the blasting vibration signals are often affected by some uncertain factors such as field conditions, the noises, accuracy of measuring instruments, etc. Thus, the blasting vibration signals have been found to demonstrate a complicated non-linear characteristic. Traditional signal analysis methods cannot effectively extract the non-linear features.

Fractal geometry theory is an effective method for analysing complex non-linear signals, and it has been widely applied to process the blasting vibration signal [10-14]. However, for the fact that the blasting vibration signals are not ideal self-similar fractal, a single fractal dimension (FD) is not enough to demonstrate the complexity of signals and it will lose a lot of important information [15-17]. Furthermore, the box-counting (BC) based algorithm has been proved have low accuracy in fractal estimations due to its intrinsically regular partition rule [15, 18]. An alternative approach is generalized dimension based on the morphological cover (MC) method. Different with the box counting method which transforms one-dimension signal into two-dimension image to divide the grids, the fractal
dimension based on MC method uses one-dimension morphological coverage. Therefore, it has higher calculation efficiency. Furthermore, morphological operations don’t need to divide the grids, then the calculation would not be affected by the amplitude range and the rotation of the signals, so the estimate results are more stable and accurate. At present, the fractal dimension based on MC method is broadly applied to image segmentation, image description, target detection, acoustic signals processing and medical signal processing. However, to our knowledge, the generalize dimension based on MC method has never been used for blasting vibration signals processing.

In this paper, we have investigated the application of generalized dimension for blasting vibration signal processing. The MC method, which is more computationally efficient than the traditional BC method, has been selected to calculate the generalized dimension of the signals measured from the rock field. Experimental results demonstrate that the fractal mechanism of the blasting vibration signals is closely related to the features of field medium. The generalized dimension based on MC method can reflect the characteristics information of the field medium.

2. Generalized dimension based on MC method

2.1 Basic principle of mathematical morphology
Mathematical morphology was originally put forward as an image processing methodology by Matheron and Serra. And later on, it was used for one-dimensional signal processing by Magaros and Schafer. The basic principle of morphological filtering is to match or modify the signal through the predefined structural element (SE), which based on the geometric properties of the signal structure for extracting the edge of the signal and keeping the main morphological characteristics of the signal. The basic operators of mathematical morphology include dilation and erosion. Let \( f(n) \) to be the discrete one-dimension signal over a domain \( F = \{0, 1, 2, \ldots, N-1\} \) and let \( g(m) \) be the SE over a domain \( G = \{0, 1, 2, \ldots, M-1\} \), the dilation and erosion operators are defined as:

\[
(f \oplus g)(n) = \max_{m \in G} \{f(n-m) + g(m)\} \quad (1)
\]

\[
(f \Theta g)(n) = \min_{m \in G} \{f(n+m) - g(m)\} \quad (2)
\]

Where \( \oplus \) denotes the operator dilation and \( \Theta \) denotes the operator erosion. More details about the morphological operations and the SE can be found in [24].

2.2 Generalized dimension based on BC method
At present, the main method to calculate the generalized dimension is the BC method, which has been used for calculating simple fractal and complex fractal. The BC method uses the same boxes with scales \( \epsilon \) to cover the set. The minimum box number is \( N(\epsilon) \) and the fractal dimension can be estimated by the following expression:

\[
D_{BC} = \lim_{\epsilon \to 0} \frac{\ln N(\epsilon)}{\ln(1/\epsilon)} \quad (3)
\]

Besides the standard BC method, the researchers also proposed some improved BC methods. The most effective algorithms are the difference BC method [27] and the relative difference BC method [28]. The latter one was proposed for segmentation of two-dimension texture images, and it was easy to be applied to estimate the fractal dimension of one-dimension signals. Its calculation method is as follows:

Divide the one-dimension signal into \( M \) grids with windows of scales \( \epsilon \), the maximum and minimum value of the signal in each window is \( o \) and \( p \) respectively, then the box number required to cover this grid can be defined as:

\[
n_{\epsilon}(i) = o - p \quad i = 1, 2, \ldots, M(\epsilon) \quad (4)
\]

The box number required to cover the whole signal can be defined as:

\[
N(\epsilon) = \sum_{i=1}^{M(\epsilon)} n_{\epsilon}(i) \quad (5)
\]
The probability distribution function of scales $\varepsilon$ is calculated by:

$$P(\varepsilon) = \frac{n_i(\varepsilon)}{\sum_{i=1}^{N(\varepsilon)} n_i(\varepsilon)} \quad (6)$$

For the given parameter $q$, the generalized information entropy can be expressed as:

$$K_q(\varepsilon) = \frac{\ln \sum_{i=1}^{N} [P(\varepsilon)]^q}{1-q} \quad (7)$$

Then the generalized dimension can be defined as:

$$D_q = \lim_{\varepsilon \to 0} \frac{\ln K_q(\varepsilon)}{\ln \varepsilon} \quad (8)$$

When $q=0$, $q=1$, $q=2$, the generalized dimension are known as the capacity, information, and correlation dimension, respectively.

### 2.3 Generalized dimension based on MC method

Similar to the BC method, we can define a distribution function $u_i(\varepsilon)$ reflects the partial metric by MC method:

$$u_i(\varepsilon) = \frac{f \oplus \varepsilon g(n) - f \Theta \varepsilon g(n)}{\sum_{n=1}^{N(\varepsilon)} [f \oplus \varepsilon g(n) - f \Theta \varepsilon g(n)]} \quad (9)$$

Obviously, the formula $f \oplus g(n)-f \Theta g(n)$ expresses the difference between the dilation results and erosion results of the signal. The inhomogeneity of the signal on each scale can be characterized by the singularity of the high-order moment of the distribution function. Thus, the $q$-order measurement of the signal on scale $\varepsilon$ can be defined as

$$K_q(\varepsilon) = \alpha \cdot \frac{\ln \sum_{i=1}^{N} [u_i(\varepsilon)]^q}{(1-q)} \quad (10)$$

The parameter $\alpha$ can be defined as

$$\alpha = \frac{\log[A_q(\varepsilon)/\varepsilon^2]}{\log[N(\varepsilon)]} \quad (11)$$

Here the $A_g(\varepsilon)$ is the morphological covering area and the $N(\varepsilon)$ is the length of the signal. As a multifractal metric, the exponential relationship between $K_q(\varepsilon)$ and $\varepsilon$ must be satisfied as follows:

$$K_q(\varepsilon) \propto \varepsilon^{-\alpha_q}, \quad -\infty < q < +\infty \quad (12)$$

Then the generalized dimension can be calculated by

$$D_q = \lim_{\varepsilon \to 0} \frac{\ln K_q(\varepsilon)}{\ln \varepsilon} \quad (13)$$

In actual calculation, we can obtain the estimation of the generalized dimension by the least square linear fitting of $\ln K_q(\varepsilon)$ versus $\ln(\varepsilon)$. It can be proved that, when $q=0$, the generalized dimension degenerates into a single fractal dimension based on mathematical morphology.

### 3. Application to blasting vibration signal processing

#### 3.1 Experiment systems of blasting vibration

The blasting vibration signals processed in this article were measured from the extensive engineering of Tian Wang nuclear power station. The geological condition of the experimental field was slightly weathered rock. The blasting parameters are shown in Table 1. Four measuring points were placed in a straight line. The distance between the measuring points is fixed and the change value of the distance
between blasting sources and measuring points is small. The data of the blasting vibration signals measured by the four seismic sensors is demonstrated in Table 2. Among them, \( d \) represents the distance between the blasting sources and the measuring points, \( V \) represents the peak vibration speed and \( f \) represents the dominant frequency.

| Blasting parameters | Method or value |
|---------------------|----------------|
| Blasting method     | Single hole    |
| Hole diameter       | 90mm           |
| Charge diameter     | 70mm           |
| Hole depth          | 10m            |
| Charge length       | 6.5m           |
| Filling length      | 3.5m           |

Table 1: Blasting parameters

3.2 Generalized dimension of blasting vibration signal

In this section, the generalized dimension based on MC method is used to characterize the non-linear features of blasting vibration signals. Take the signal picked up by No.1 measuring point in the first test as an example to illustrate the calculation process of the generalized dimension based on MC method.

When we analyze the signal, only the record during effective vibration has been calculated. Take into account that the curves of blasting vibration signals have certain envelope characteristics and the universal rules of the blasting vibration records in this experiment, if the maximum amplitude of a signal is \( A \), then we define the blasting vibration duration of the signal as: from record value first reach 0.05\( A \) to finally reduce to 0.05\( A \). The time domain waveform of the original signal and the effective vibration range are shown in Fig.1.

It should be mentioned that there is no criterion to select the analysis scales. In this paper, in order to reflect the periodic characteristic of the blasting vibration signal, the maximum analysing scale should not exceed half length of the main shock cycle of the signal. We set the sizes of \( \varepsilon \) to be [1, 2, 4, 6, 2: 64]. The parameter \( q \) is set to be [0:2:20]. The dilation and the erosion of the signal using flat structure elements (SE) with different size (16 and 48) are shown in Fig.2. The red line in the figure is the result of dilation and erosion by the SE with size 16. The upper line is the dilation result and the below line is the erosion result. The black line is the result of covering by SE with size 48. And the area between the upper line and the below line is the coverage area \( A_g(\varepsilon) \).

![Figure 1: Time domain waveform (a) original signal (b) effective vibration range](image_url)
Figure 2: Dilation and erosion results on the signal using SE with sizes 16 and 48

Table 2: The data of the blasting vibration signals measured by the four seismic sensors

| Test number | Charge/kg | No.1 Measuring point | No.2 Measuring point | No.3 Measuring point | No.4 Measuring point |
|-------------|-----------|-----------------------|----------------------|----------------------|----------------------|
|             |           | $d_1$/m | $V_1$/ (cm/s) | $f_1$/Hz | $d_2$/m | $V_2$/ (cm/s) | $f_2$/Hz | $d_3$/m | $V_3$/ (cm/s) | $f_3$/Hz | $d_4$/m | $V_4$/ (cm/s) | $f_4$/Hz |
| 1           | 24        | 60      | 1.882     | 47.6     | 90      | 1.124     | 70.2     | 130      | 0.675     | 37.2     | 180      | 0.197     | 60.2     |
| 2           | 20        | 58      | 1.633     | 62.5     | 88      | 0.958     | 60.5     | 128      | 0.473     | 50.3     | 178      | 0.096     | 75.8     |
| 3           | 17        | 58      | 1.455     | 56.3     | 88      | 0.798     | 66.3     | 128      | 0.329     | 40.8     | 178      | 0.044     | 88.3     |
| 4           | 20        | 53      | 1.893     | 53.9     | 83      | 1.215     | 78.3     | 123      | 0.748     | 45.9     | 173      | 0.216     | 69.5     |
| 5           | 17        | 53      | 1.703     | 70.1     | 83      | 1.019     | 59.8     | 123      | 0.598     | 52.9     | 173      | 0.128     | 70.4     |

Figure 3 gives the log-log plot of $K_q(\varepsilon)$ versus scale $\varepsilon$. It shows satisfactory linear property. So, the log-log points over all the scales are used to estimate the generalized dimension.

Figure 3: The log-log plot of $K_q(\varepsilon)$ versus scale $\varepsilon$

Figure 4 presents the generalized dimension estimation result of the signal. It can be observed that the generalized dimension $D_q$ of the signal is strictly decreasing with $q$. When $q=0$, the generalized dimension $D_q$ degenerates into a single fractal dimension based on mathematical morphology.
Then we employ this method to calculate the generalized dimension based on MC of all the signals measured from the four measuring points. The calculation results are illustrated in Figure 5. From Figure 5, we can find that the generalized dimension of the blasting vibration signals measured from the same measuring point is relatively close. It means that with the same location and similar blasting source, the features of the rock medium are alike which reflected by the generalized dimension of the blasting vibration signals. Furthermore, in the same test number, the generalized dimension of the signals measured from different measuring points decreases with the increase of the distance. It shows that the main influence factor of the generalized dimension is the field medium.

In the actual process of blasting, it is possible to control the parameters of blasting source. However, the influence factor of the propagation medium is often estimated by experience. Therefore, it is impossible to predict the damage effect of the blasting vibration signal accurately. The introduction of generalized dimension can solve the long-standing problem, which can be used as a new parameter to describe the blasting vibration signal. It provides a new research route for establishing the model of blasting vibration which is suitable for different filed structure.
4. Conclusion
This paper has first applied generalized dimension based on the morphological covering algorithm to characterize the blasting vibration signals. Experimental results have revealed that the fractal mechanism of blasting vibration signal is closely related to the features of the field and the generalized dimension based on MC method can reflect the characteristics of the field medium. Introduce the generalized dimension to the study of blasting vibration effect as a new dimensionless parameter to describe the blasting vibration signals can solve the problems that we cannot accurately understand the features of field medium and the formation or propagation mechanism of blasting vibration signals.

It should be noted that there is no criterion to select the analysing scales yet. Moreover, we have only demonstrated that the generalized dimension based on BC method can reflect the features of field medium. More works will be done about fractal theory to analyze the structure, spectrum and energy of the blasting vibration signals.

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