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Research on the vibration prediction model of bench blasting based on the volterraSeries

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Abstract. The nonlinear mechanical behavior of the rock mass between the explosion source and the testing point is described by using the Volterra nonlinear functional series in the nonlinear functional theory. A nonlinear vibration prediction model for bench blasting based on the Volterra functional series is established. The method of identifying the kernel function of the Volterra functional series by using multiple independent blasting tests is presented. An algorithm for predicting the vibration waveform by using nonlinear model is developed. Thevibration of the hole-by-hole millisecond delay blasting tests with two holes, three holes, and four holes isrespectively predicted by using the nonlinear modelbased on the Volterra Series. As validated by the comparison with the measured results, this prediction model is of high accuracy, strict theory and good applicability.

Key words. Volterraseries, bench blasting, nonlinear model, vibration prediction.

1. Introduction

If there are buildings near the bench blasting operation site, the strong impact load generated by the bench blasting on the surface or to the underground near the buildings would produce seismic wave propagating in the rock medium between the shock source and the structure foundation. When the seismic wave reaches the structure foundation, the structure would reflect to the impact load and vibrate. When the impact load energy generated by blasting is quite large, the buildings would be damaged or even destroyed, resulting in accidents, like casualties and property losses. Therefore, seeking for a prediction method of structure vibration

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under bench blasting load is essential for structure protection, and it would be of great application value and practical significance.

Anderson, etc.[1-5]put forward the integrated prediction method of blasting vibration based on the field measurement, and applied it to the open-pit bench blasting. The vibration waveform of the multi-row millisecond-delay blasting was simulated by the superstition of the single hole blasting waveform, supposing that under the constant blasting parameter, the single hole blasting could reappear in the given place, that each borehole of the multi-row millisecond blasting had the same source function, and that the space distribution of boreholes did not affect the transmission route of the seismic wave. Hinzen[6]comprehensively analyzed the change patterns of the spectral value and the phase of the superimposed signal by applying the advantage of the superstition of the single-hole blasting vibration signals in the time domain, and optimized the delay time of the multi-hole blasting accordingly. Ghosh, etc.[7] believed the energy of Rayleigh wave was dominant at acertain distance from the impact source, and therefore put forward the vibration prediction method by the superstition of Rayleigh wave. In addition, Aldas[8] and Svinkin[9] used a similar waveform superposition method to predict the vibration effect by the explosion impact load. To overcome the limitations of the linear superposition method, Blair [10] presented two nonlinear models, one based on the charge amount, and the other on the rock damage degree, but it is difficult to reflect the difference in vibration effect of different charge weights by his methods, and the numerical calculation is required. The above methods based on the time-domain waveform superstition assume that the vibration of the medium is linear under the impact load. When the impact energy is small, the predicted results agree well with the measured results, but when the impact energy is large, the difference between the predicted results and the measured results is significant. Although the model takes into account the medium's nonlinear vibration effect under the impact load, the correction method does not consider the factor of distance, and the known load chosen in the correction formula has certain one-sidedness.

To sum up, researches on the prediction of the blasting vibration effect are mostly based on the statistical analysis and the field measurement analysis, and the blasting vibration monitoring is a post-operation behavior, which cannot predict beforehand the potential vibration effect caused by the blasting impact load. The parameters of the numerical analysis method are difficult to determine, so it is not convenient for engineering application. The statistical analysis method has high requirements on the identity and invariance of the site, and a large number of vibration tests are needed. The linear prediction models put forward by current scholars do not consider the nonlinear characteristics of the disturbance propagation of the rock between the shock source and the structure foundation and that of the vibration effect of the structure, so the difference between the prediction result and the measured result is quite large. This paper, based on the nonlinear theory, presents a convenient nonlinear prediction model (NLM) which combines the vibration test with the theoretical model in the bench blasting field. It can predict and evaluate the vibration effect of the structure under the impact load of bench blasting and reflect the nonlinear characteristics of the vibration response of the rock mass between the shock source and the structure, breaking the limitations of the numerical method, the statistical analysis method and the linear prediction model. Its prediction result is quite close to the measured result.

2. Vibration prediction model for bench blasting based on the Volterra functional series

As shown in Fig. 1, the rock medium between the explosive source and the measuring point is considered as a non-linear system, and the Volterra functional seriesis applied to describe the system. That is

$$y\left(t\right)=\sum_{n=1}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\cdots\int_{-\infty}^{\infty}h_{n}\left(\tau_{1},\tau_{2},\cdots,\tau_{n}\right)\bullet\prod_{i=1}^{n}\left[x_{i}\left(t-\tau_{i}\right)d\tau_{i}\right] \tag{1}$$

in which, $y\left(t\right)$ is the system output waveform, that is, the vibration waveform at the measuring point, $x\left(t\right)$ is the input waveform, h is the kernel function of the Volterra nonlinear functional series, and τ is the integral variable.

In order to predict the vibration waveform of the measuring point, firstly, the parameters of the Volterra nonlinear system should be identified, and then the vibration response of the measuring points of the multi-hole blasting is predicted based on the identified Volterra nonlinear functional series.

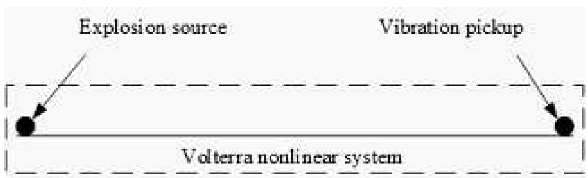


Fig. 1. Volterranonlienear system between the explosion source and the measuring point

In order to identify the $n$order kernel of Volterra functional series, n times of independent single hole blasting tests are conducted at the site of the explosion source. The so-called independence refers to the non-influence of the vibration caused by the blasting test, which means that the time interval between two blasting tests is long enough. At the same time, the vibration signal is monitored at the location of the measuring point,and the explosion impact load in the explosion test is simplified as the pulse signal taking the charging weigh as its amplitude, and the pulse signal is taken as the input of the nonlinear system,which is $a_1\delta\left(t\right)$,$a_2\delta\left(t\right)$,..., $a_n\delta\left(t\right)$, in which $a_1, a_2, ..., a_n$ are the charging weights of the n-times single-hole blasting tests. $a_1\delta\left(t\right)$,$a_2\delta\left(t\right)$,..., $a_n\delta\left(t\right)$,are taken as system input $x\left(t\right)$and brought into (1), and the result is

$$\begin{cases} a_1 h_1(t) + a_1^2 h_2(t,t) + \cdots + a_1^n h_n(t,t,\cdots,t) = y_1(t) \\ a_2 h_1(t) + a_2^2 h_2(t,t) + \cdots + a_2^n h_n(t,t,\cdots,t) = y_2(t) \\ \vdots \\ a_n h_1(t) + a_n^2 h_2(t,t) + \cdots + a_n^n h_n(t,t,\cdots,t) = y_n(t) \end{cases} \tag{2}$$

Carry out Fourier Transform to (2), and the result is

$$\begin{cases} a_1 H_1(f) + a_1^2 H_2(f,t) + \cdots + a_1^n H_n(f,t,\cdots,t) = Y_1(f) \\ a_2 H_1(t) + a_2^2 H_2(f,t) + \cdots + a_2^n H_n(f,t,\cdots,t) = Y_2(f) \\ \vdots \\ a_n H_1(f) + a_n^2 H_2(f,t) + \cdots + a_n^n H_n(f,t,\cdots,t) = Y_n(f) \end{cases} \tag{3}$$

Rewrite (3) into the matrix

$$\begin{bmatrix} a_1 & a_1^2 & \cdots & a_1^n \\ a_2 & a_2^2 & \ldots & a_2^n \\ \vdots & \vdots & \vdots & \vdots \\ a_n & a_n^2 & \cdots & a_n^n \end{bmatrix} \begin{bmatrix} H_1(f) \\ H_2(f,t) \\ \vdots \\ H_n(f,t,\cdots,t) \end{bmatrix} = \begin{bmatrix} Y_1(f) \\ Y_2(f) \\ \vdots \\ Y_n(f) \end{bmatrix} \tag{4}$$

Making$\mathbf{A} = \begin{bmatrix} a_1 & a_1^2 & \cdots & a_1^n \\ a_2 & a_2^2 & \ldots & a_2^n \\ \vdots & \vdots & \vdots & \vdots \\ a_n & a_n^2 & \cdots & a_n^n \end{bmatrix}$, then (**??**) becomes

$$\begin{bmatrix} H_1(f) \\ H_2(f,t) \\ \vdots \\ H_n(f,t,\cdots,t) \end{bmatrix} = \mathbf{A}^{-1} \begin{bmatrix} Y_1(f) \\ Y_2(f) \\ \vdots \\ Y_n(f) \end{bmatrix} \tag{5}$$

Taking the inverse Fourier Transform of the two parts of (**??**), the time domain kernel of each order kernel would be got

$$\begin{bmatrix} h_1(t) \\ h_2(t,t) \\ \vdots \\ h_n(t,t,\cdots,t) \end{bmatrix} = \begin{bmatrix} F^{-1}(H_1(f)) \\ F^{-1}(H_2(f,t)) \\ \vdots \\ F^{-1}(H_n(f,t,\cdots,t)) \end{bmatrix} \tag{6}$$

After the time domain kernel is got, the system identification is finished. Then construct the pulse sequence function of the multi-hole blasting and take it as the input of the nonlinear system, which is

$$x(t) = \sum_{i=1}^{m} b_i \delta(t - t_i) \tag{7}$$

in which, $b_i$is the charge weight of the No. $i$borehole in the multi-hole blasting. Take (7) into (1), and its convolution function is

$$y(t) = h_1(t)*x(t)+h_2(t,t)*x(t)*x(t)+\cdots+h_n(t,t,\cdots,t)*x(t)*x(t)*\cdots*x(t) \tag{8}$$

(8) is the expression of the vibration waveform at the measuring point predicted by the Volterra nonlinear system.

3. Calculation design of using the nonlinear model to predict the vibration waveform

The Volterra functional series model algorithm is programmed and the calculation program is developed in C language. The program's flow diagram is shown in Fig. 2.

3.1. Identification of the nonlinear model

The nonlinear mechanical characteristics of the non-soil medium between the explosion source and the measuring point are described by the third-order nonlinear Volterra functional series. The identification of the model is through three independent single hole blasting tests, and Point 6# is chosen as the test point. Nine single hole blasting tests are made, and the vertical waveforms of three tests of them are chosen and identified by the model, which are Borehole 3#, Borehole 4# and Borehole 7#. Their vertical waveforms and their frequency spectrums are shown Fig. 4, and the blasting parameters are in Table 2. The nonlinear system between the explosion source and the measuring point is identified, and the three kernel functions by the Volterra functional series are shown in Fig. 5. After the recognition of the nonlinear system between the explosion source and the measuring point, the vibration effect of a given blasting scheme can be predicted.

Table 1 The blasting test parameters

Type	Two holes	Three holes	Four holes
Borehole No.	11,12	25,29,33	37,38,41,42
Charge weight(kg)	10??10	10,10,10	10,10,10,10
Delay time(ms)	25	25	25

Table 2 Parameters of the three independent blasting tests for identifying the nonlinear system

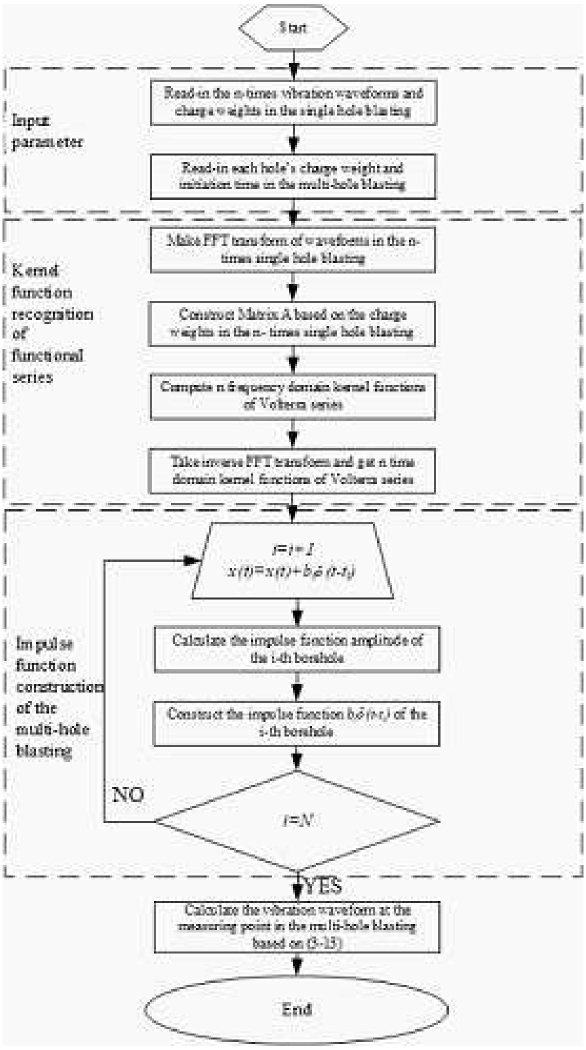


Fig. 2. Flow chart of Volterra functional series model program

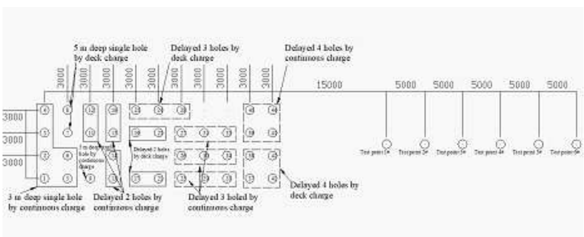
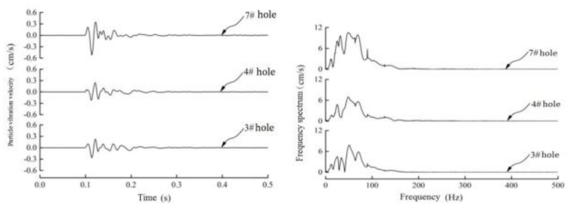


Fig. 3. Schematic diagram of the experimental site

Borehole No.	Charge weight(kg)	Test point No.	Distance from the explosion source to the test point(m)
3#	5	6#	69.2
4#	2.5	6#	69.5
7#	13.5	6#	66.2



(a) time-domain waveform (b) spectrum

Fig. 4. Waveform and frequency spectrumofthe three single hole blasting tests (4#, 3#, 7#) in the vertical direction of the measuring point 6#

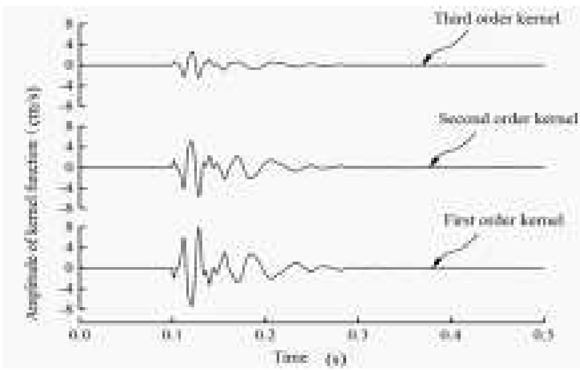


Fig. 5. 5Kernel functionsbyVolterra functional seriesidentified by using the three single hole blasting tests (3#, 4#, 7#).

3.2. Prediction results of the two-hole millisecond delay blasting

Fig. 6 is the comparison of the predicted and measured time domain waveforms and spectrums in the two-hole millisecond delay blasting. The delay time between the two holes is 25 ms, the charge weight is 10 kg, and the distance from the explosion source to the test point is 64 m.

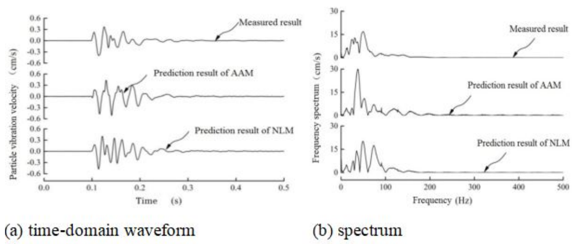


Fig. 6. Comparison between the predicted and measured results of the two-hole blasting test (11#, 12#) in the vertical direction of the measuring point 6#

3.3. Prediction results of the three-hole millisecond delay blasting

Fig. 7 is the comparison of the predicted and measured time domain waveforms and spectrums in the three-hole millisecond delay blasting. The delay time between the three holes is 25 ms, the charge amount is 10 kg, and the distance from the explosion source to the test point is 49 m.

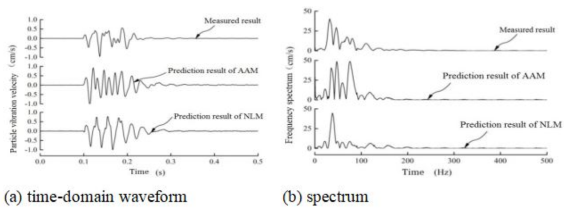


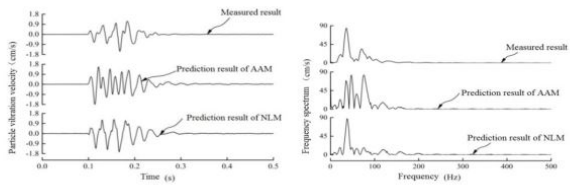
Fig. 7. Comparison between prediction and measured results of the three-hole blasting test (25#,29#,33#) in the vertical direction of the measuring point 6#

3.4. Prediction results of the four-hole millisecond delay blasting

Figure 8 is the comparison of the predicted and measured time domain waveforms and spectrums in the four-hole millisecond delay blasting. The delay time between the three holes is 25 ms, the charge amount is 10 kg, and the distance from the explosion source to the test point is 40 m.

3.5. Comparison analysis of the prediction results and the measured results

The prediction results and the measured results of the three blasting tests are respectively compared and analyzed, and the comparison index is the Peak Particle Velocity, the main frequency and its corresponding amplitude predicted by NLM and AAM. As shown in Table 3, the prediction error of PPV, the main frequency error and the main frequency spectrum error of NLM prediction method are all less than 20%. As for AAM's prediction results, the PPV error andthe main frequency error are about 30%, and partial of thecorresponding spectral value error of the



(a) time-domain waveform (b) spectrum

Fig. 8. Comparison between prediction and measured results of the four-hole blastingtest (37#,38#,41#,42#) in the vertical direction of the measuring point 6#

main frequency is up to 80%. Analysis results show that the prediction error of the proposedNLM based on the Volterrafunctional series is small, because it fully considers the nonlinear characteristics of the rock medium, and it could be accepted by the actual blasting engineering.The AAMis just modified in the seismic ratio coefficient, and it cannot fully reflect the complex non-linear characteristics of the rock medium, so its error is larger.

Table 3 Comparison between prediction and measured results of the three blasting tests

Index	Two holes			Three holes			Four holes		
	NLM	AAM	Measured	NLM	AAM	Measured	NLM	AAM	Measured
PPV(cm/s)	0.44	0.47	0.39	0.90	1.00	0.76	1.6	1.7	1.6
PPVerro(%)	14	23	0	18	31	0	0	6	0
Main frequency(Hz)	49	38	49	38	47	32	38	47	36
Spectrum of main frequency(cm/s)	20	31	17	44	48	40	88	83	84
Main frequency erro(%)	1	24	0	17	47	0	4	31	0
Spectrum of main frequency(cm/s)	20	83	0	11	21	0	4	2	0

4. Conclusion

In view of the field test, the proposed nonlinear system prediction method "NLM" based on the Volterra functional series and the advanced Anderson model (AAM)prediction method are applied to forecast the hole by hole millisecond delay blasting under the circumstance of two holes, three holes, and four holes, and the differences between the predicted. The measured results are analyzed in detail, and the errors of the predicted and the measured PPVs, main frequencies and corresponding spectrums are respectively calculated. Results show that compared with the improved Anderson model, the prediction method of nonlinear system based on Volterra functional series has the advantages of high accuracy and wide application range.

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