

Research Article

Identifying Delay Time of Detonator for a Millisecond Blasting

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Received 10 February 2021; Accepted 18 May 2021; Published 25 May 2021

Academic Editor: Hao Wu

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Based on wavelet transform, the blasting vibration signals are analyzed here. For millisecond blasting, the blasting effect is mostly affected by the actual delay time. Local characteristics of the analyzed signals could be highlighted by the wavelet transform. The simultaneous initiation of large explosive quantity could be avoided by the use of multistage detonators, while the vibration resistance effect could be better. For the same level of detonator segment, the larger the arranged time interval, the less the possibility of initiation at the same time, which is not conducive to the vibration resistance. Therefore, it is suggested to use high-level detonators with detonating cord or high-precision digital electronic detonators to minimize the initiation error. Furthermore, by identifying the delay time using wavelet transform, the interval delay time of different detonator segments could be obtained. Moreover, the nominal delay time, actual delay time, and interval delay time are further compared and analyzed. It is suggested that the millisecond delay series of detonators should be selected in the whole section blasting, and the segment should be jumped as much as possible, so as to increase the secondary breakage time. Detonators with longer interval delay time should be avoided to the full.

1. Introduction

Millisecond blasting is a kind of blasting technology, which is initiated in a certain sequence at millisecond intervals. This technology has been widely used in reducing seismic effect, rationally utilizing explosive energy, reducing explosive unit consumption, and improving blasting fragmentation [1–3]. To determine the reasonable delay time is the key to the successful implementation of millisecond blasting. And the delay initiation of different charges is mainly realized by ordinary delay detonators in engineering. It is well known that a vital problem of accuracy initiation has existed for the common detonators; that is, the delay of each detonator has a positive or negative error. Even if the high-precision detonator, it also has reached the error of ± 10 ms. The intuitive phenomenon is that sometimes the front section detonator will initiate later than the latter section detonator; that is, the jumping of detonator section has appeared [4–9].

Particularly, reliable electronic detonator has reached the level of practicality, and the delay control error of electronic

detonator could be up to microsecond or even zero error. However, the cost of electronic detonator is always 10 times higher than that of ordinary detonator, which makes it still have a long time to be applied in engineering [10, 11]. Therefore, even if the reasonable millisecond time of a certain blasting can be calculated accurately, the actual millisecond time cannot be controlled exactly because of the error of detonator itself.

Therefore, it is very important to select an appropriate detonator and identify the accurate delay time. Furthermore, the appropriate detonator section and delay time should be selected based on the cross section of the tunnel, the layout of blasting boreholes and geological conditions, and so on [12–20]. Most importantly, it plays a vital role in the improvement of blasting footage and the control of vibration. The principle and feasibility of the wavelet analysis method in the identification of delay time have been demonstrated here. Moreover, combining with the specific blasting vibration signal, the initiation time and delay interval time of each detonator are identified separately. The following is a description of the mentioned method.

2. Principle of Time and Energy Density Analysis Based on Wavelet Transform

2.1. Wavelet Transform. Let $\psi(t) \in L^2(R)$, in which $L^2(R)$ is a signal space with limited energy, and its Fourier transform could be expressed as $\hat{\psi}(w)$. When $\hat{\psi}(w)$ is satisfied, one has the following condition [21, 22]:

$$C_\psi = \int_R \frac{|\hat{\psi}(w)|^2}{|w|} dw < \infty, \quad (1)$$

where $\psi(t)$ could be called the basic wavelet. Through scaling and shifting of the basic wavelet, the wavelet sequence is obtained here:

$$\psi_{a,b}(t) = \frac{1}{|a|} \psi\left(\frac{t-b}{a}\right), \quad (2)$$

where a and b are scaling factor and shifting factor, respectively.

For any function $f(t)$ with limited energy, the definition of continuous wavelet transform concerning $\psi(t)$ is as follows:

$$W_f(a, b) = \langle f, \psi_{a,b} \rangle = \frac{1}{|a|} \int_R f(t) \overline{\psi\left(\frac{t-b}{a}\right)} dt. \quad (3)$$

2.2. Time and Energy Density Analysis. According to the inner product theorem, that is, Moyal theory [23], the following formula could be

$$\frac{1}{C_\psi} \int_R \frac{da}{a^2} \int_R |W_f(a, b)|^2 db = \int_R |f(t)|^2 dt. \quad (4)$$

Formula (4) shows that the integral of the square of the wavelet amplitude is proportional to the signal energy to be analyzed. It is well known that, in the study of nonstationary random signal, due to the limitation of the Heisenberg uncertainty principle, the instantaneous energy density of a point in time-frequency space cannot be determined; that is, the energy at a certain frequency at a certain time is conceptually nonexistent. However, in equation (4), $1/a^2 C_\psi |W_f(a, b)|^2$ can be regarded as the energy density function on the (a, b) plane. Therefore, $1/a^2 C_\psi |W_f(a, b)|^2 \Delta a \Delta b$ can be considered as the energy centered on scale a and time b , with scale interval Δa as well as time interval Δb . According to the concept of energy density, formula (4) can be expressed as follows:

$$\int_R |f(t)|^2 dt = \int_R E(b) db. \quad (5)$$

Here,

$$E(b) = \frac{1}{C_\psi} \int_R \frac{1}{a^2} |W_f(a, b)|^2 da. \quad (6)$$

For the wavelet transform, the so-called scale a corresponds to frequency w in a sense, so the energy distribution of all frequency bands of signal with time b has been given in formula (6), which could be termed time energy density function. In practical application, the upper and lower bounds of integration can be changed so that the integration interval falls within a certain frequency range of the signal to be analyzed. Therefore, the distribution characteristics of energy density of the signal in the frequency band with time could be obtained.

2.3. Actual Delay Time of Millisecond Blasting Judged by Time and Energy Density Method. If a certain blasting could be considered as a system, the initiation of each detonator is the process of input energy to the system. In the meantime, a sudden change in the energy density of the system would be inevitably caused by each initiation [24]. Therefore, the energy density of blasting vibration in the main frequency band can be calculated according to formula (6) by choosing the appropriate upper and lower bounds of integration, and the time and energy density map could be drawn. Based on the peak position in the map, the actual initiation time of each detonator could be obtained, and the actual millisecond delay time in blasting would be further determined.

3. Wavelet Transform in Delay Recognition of Blasting

3.1. Blasting Vibration Signal. Figure 1 shows the blasting holes' layout in this section. In Figure 1, six holes are evenly distributed around the empty hole, that is, No. 1. The full-face blasting excavation method is adopted here. Meanwhile, the millisecond detonators are used, that is, MS1, MS3, MS5, MS7, MS8, MS9, MS10, MS11, MS13, MS15, and MS19, respectively. The emulsion explosive is used and the weight of each roll is 300 g. The charge quantity and other blasting parameters are shown in Table 1. Meanwhile, the blasting footage is 2 m.

Blasting vibration waveform can be analyzed intuitively by blasting vibration instrument system. Therefore, the vibration amplitude, main frequency, and duration could be obtained. The intuitive analysis method of blasting vibration signal is to directly analyze the measured waveform and determine the characteristic quantity of blasting vibration from the waveform diagram itself.

A typical blasting vibration signal is selected here to analyze the representative characteristics, as shown in Figure 2. Furthermore, the initiation time and delay time of this blasting are identified and recognized separately.

3.2. Wavelet Transform Using for Delay Time Identification. From the definition of wavelet transform, the time-frequency window of wavelet transform has its uniqueness. It means that only the window position on the time axis of the phase plane is affected by the shifting factor b , while not only the window position on the frequency axis but also the window shape is influenced by the scaling factor a . Therefore, the sampling step of wavelet transform in time domain

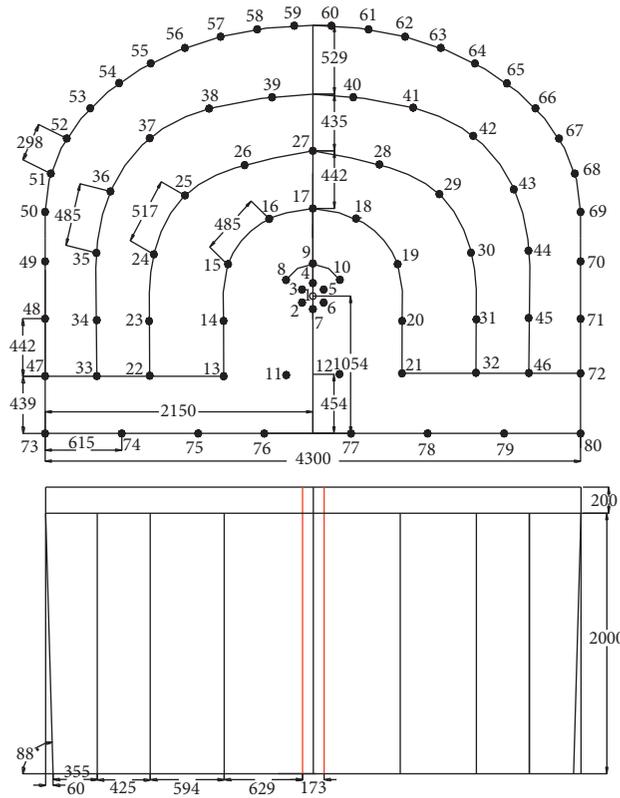


FIGURE 1: Layout of blasting holes (mm).

TABLE 1: Blasting parameters.

Hole name	Hole no.	Number of holes	Charge quantity		Detonator order
			Each hole	Total weight (kg)	
Empty hole	1	1	0	0.0	
Cutting hole	2-7	6	5	9.0	1
Auxiliary hole	8-10	3	5	4.5	3
Auxiliary hole	11-12	2	5	3.0	5
Auxiliary hole	13-18	6	4.5	8.1	7
Auxiliary hole	19-21	3	4	3.6	8
Auxiliary hole	22-27	6	3	5.4	9
Auxiliary hole	28-32	5	3	4.5	10
Auxiliary hole	33-38	6	2.5	4.5	11
Auxiliary hole	39-46	8	2.5	6	13
Peripheral hole	47-54	8	2	4.8	15
Peripheral hole	55-72	18	1.5	8.1	19
Bottom hole	74-79	6	3	5.4	15
Bottom hole	73-80	2	3	1.8	19
Total	—	80	—	68.7	

is adjustable for different frequencies, that is, the time resolution is poor at low frequencies, while the frequency resolution is high, and the time resolution is high at high frequencies, while the frequency resolution is low. Considering the filter point, the wavelet transform makes the signal pass through a series of band-pass filters, respectively. The center frequency and bandwidth of the band-pass filter are proportional to the scaling factor a . That is to say, the ability of wavelet transform to highlight the local characteristics of the signal is different under different value.

Millisecond blasting is often applied in engineering blasting, and the number of millisecond detonator sections depends on the specific blasting conditions and purposes. If a certain blasting is considered as a system, the initiation of each detonator is the process of input energy to the system, and the initiation of each detonator will inevitably cause a sudden change of energy in the system. Therefore, the monitored blasting vibration signal could be transformed using the wavelet transform method, and the time of signal mutation can be

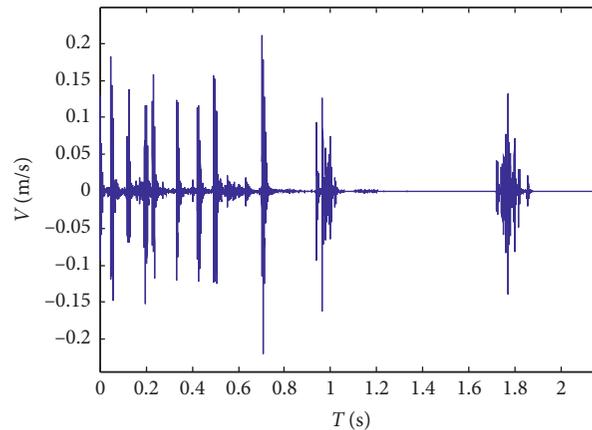


FIGURE 2: Blasting vibration waveform.

effectively identified by the modulus maxima of the wavelet transform. That is to say, the initiation time of each detonator in millisecond blasting can be precisely determined by the means mentioned above, and the actual millisecond delay time in blasting could be further confirmed.

For the signal processed by wavelet analysis, how to select an optimal wavelet base is much more important, because results could be various even for the same problem by different wavelet bases. Furthermore, the function with fast attenuation and good similarity between the waveform and the analyzed signal should be chosen as the wavelet basis function. Therefore, the selection of the wavelet basis is closely related to the properties and characteristics of the analyzed signal. Four common waveforms of wavelet basis functions are listed in the following, as shown in Figure 3.

When choosing a wavelet basis, besides the requirement of compact support, that is, the speed at which the function converges from a finite value to zero, and regularity, which has a great influence on the smoothing effect of signal reconstruction, the curve shape of the wavelet basis is also required to be similar to that of the analyzed signal.

The waveforms of the four main wavelet bases are similar to those of the analyzed signals. However, there is much more information contained in the sym7 and db8 waveforms and the waveforms of the analyzed signals could be matched better with them. That is, the information of the analyzed waveforms reflected by the two waveforms is more accurate.

Furthermore, the waveform of db8 is more consistent with the analyzed signal than that of sym7, and the fluctuation trend of db8 is more similar to that of the analyzed signal. Among these common series of wavelet functions, Daubechies wavelet series have good compactness, smoothness, and approximate symmetry and have been successfully applied to the analysis of nonstationary signal problems, such as blasting.

Therefore, db8 is chosen as the basis function of wavelet analysis for the blasting vibration signal. The original signal is modeled by continuous wavelet transform on scaling factor $a = 16$. The singularity of energy contained in blasting

vibration is identified by the modulus maximum point. The transformed modulus diagram is shown in Figure 4.

Through continuous wavelet transform using db8 wavelet method (scaling factor $a = 16$), several local singularities appear obviously in Figure 4. Time of local singularities is 0.00075, 0.04462, 0.1276, 0.2021, 0.233, 0.3347, 0.4249, 0.4984, 0.7084, 0.9645, and 1.771, respectively. It is clear that the millisecond blasting vibration signal shown in Figure 4 is formed by the superposition of 11 blasting vibration waveforms.

The delay time interval of millisecond blasting can be defined as the time interval between the initiation time of two adjacent detonators. Here, for the identified convenience, the time position of the first local singularity point is determined as the initiation time of the lowest detonator segment (MS1). The actual initiation delay interval of each detonator obtained by this method is 43.87 ms, 82.98 ms, 74.5 ms, 30.9 ms, 101.7 ms, 90.2 ms, 73.5 ms, 210 ms, 256.1 ms, and 806.5 ms, respectively, as shown in Table 2. It should be noticed that the data in Table 2 is obtained from the blasting test through wavelet analysis, while the blasting parameters are from Table 1.

4. Discussion

Wavelet packet analysis can provide a more precise method for signal analysis. Wavelet packet analysis divides the time-frequency plane more carefully, and its resolution to the high-frequency part of the signal is higher than other wavelets. Moreover, it introduces the concept of optimal basis selection on the basis of wavelet analysis theory. According to the characteristics of the signal to be analyzed, dividing the frequency band into several levels, the best basis function is adaptively selected to match the signal, to improve the signal analysis ability.

Referring to the calibrated error intervals of different detonators provided by detonator manufacturers, the above analyzed time points correspond to the detonator segments 1, 3, 5, 7, 8, 9, 10, 11, 13, 15, and 19, respectively. The allowable errors of delay time of each detonator are ± 10 , ± 15 , ± 20 , ± 25 , ± 30 , ± 35 , ± 40 , ± 50 , ± 60 , and ± 130 , respectively. At

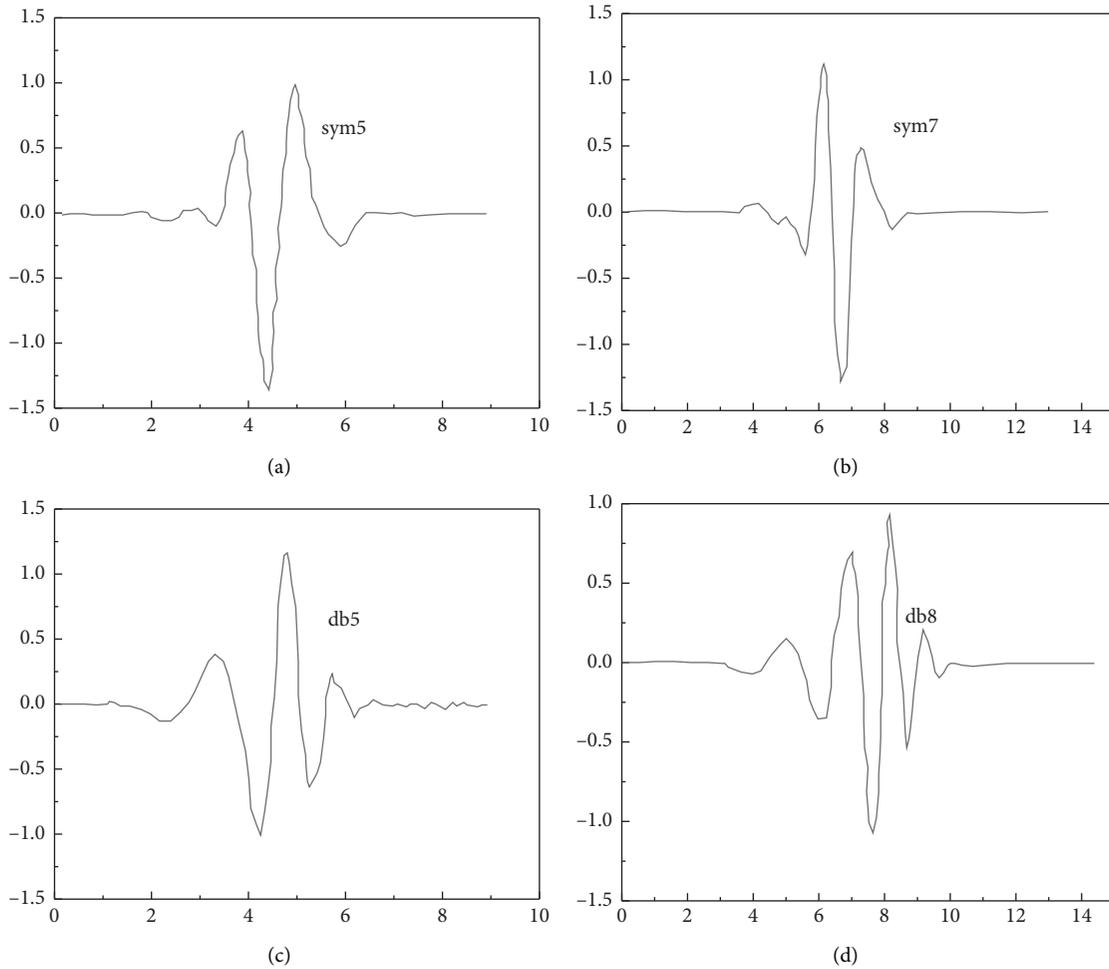


FIGURE 3: Several common series of wavelet functions.

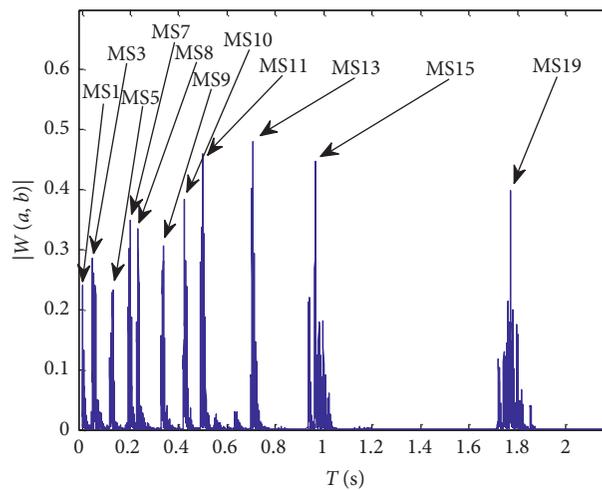


FIGURE 4: Modulus value map by db8 continuous wavelet transform ($a = 16$).

the same time, the higher the detonator segment is, the worse the precision is.

Through longitudinal comparison, simultaneous initiation with a large amount of explosive can be avoided using

different detonators with multisegments, which reduced the vibration effect better. However, as for a same one detonator segment, the larger the allowable error range of the detonator, the less possibility of simultaneous detonation would

TABLE 2: Initiation time and time interval of each detonator.

Detonator segment	Initiation time (s)	Detonator interval	Delay time interval (ms)
MS1	0.00075	—	—
MS3	0.04462	MS1~MS3	43.87
MS5	0.1276	MS3~MS5	82.98
MS7	0.2021	MS5~MS7	74.5
MS8	0.233	MS7~MS8	30.9
MS9	0.3347	MS8~MS9	101.7
MS10	0.4249	MS9~MS10	90.2
MS11	0.4984	MS10~MS11	73.5
MS13	0.7084	MS11~MS13	210
MS15	0.9645	MS13~MS15	256.1
MS19	1.771	MS15~MS19	806.5

TABLE 3: Detonator deferment stages, deferral times, and actual differential intervals.

Detonator segment	Initial time	Modulus maximum	Notional delay time (ms)	Error ratio of notional delay time	Arranged time interval (ms)	Monitored time interval (ms)	Whether early explosion or refusal
MS1	0.00075	0.2411	<13	—	0~13	0	No
MS3	0.04462	0.285	50 ± 10	0.2	0~50	43.87	No
MS5	0.1276	0.2324	110 ± 15	0.1364	35~85	82.98	No
MS7	0.2021	0.349	200 ± 20	0.1	55~125	74.5	No
MS8	0.233	0.335	250 ± 25	0.1	5~95	30.9	No
MS9	0.3347	0.3057	310 ± 30	0.0968	5~115	101.7	No
MS10	0.4249	0.3836	380 ± 35	0.0921	5~135	90.2	No
MS11	0.4984	0.4587	460 ± 40	0.0869	5~155	73.5	No
MS13	0.7084	0.4793	650 ± 50	0.0769	100~280	210	No
MS15	0.9645	0.4467	880 ± 60	0.0682	120~340	256.1	No
MS19	1.771	0.3984	1700 ± 130	0.0765	630~1010	806.5	No

naturally occur. That is to say, with the increase of detonator segment, the detonators in the same segment but high section are liable to produce interference and fail to achieve a good vibration reduction effect.

The detonator segment, delay time, and actual time interval of detonators in this test are shown in Table 3.

The relationship between nominal delay time and error ratio of the nominal delay time of detonators is shown in Figure 5. It can be seen that the error ratio of nominal delay time decreases gradually with the increase of detonator segments.

The relationship between the actual initiation time and the actual interval delay time of detonators is shown in Figure 6. It can be seen that although the error ratio of nominal delay time decreases gradually, the absolute error of delay time of high-level detonators increases. Particularly, the error of delay time of MS19 detonator reaches 130 ms, which is not conducive to blasting and shock absorption effect.

Therefore, it is suggested to adopt a high-level detonator with detonating cord or a high-precision digital electronic detonator in peripheral holes to minimize the initiation error, in other words, to ensure the same detonator initiation at the same time, especially the high-level detonator segments.

Time intervals of kinds of detonator segments are shown in Figure 7, which illustrates the relationship between the

monitored time interval and the arranged time interval. It can be seen that interval delay times of each detonator are within the arranged interval delay times, which shows that the detonators of this blasting have given full play to their respective performances and the blasting is controlled accurately.

Furthermore, it can be seen from Table 3 that the jumping segment use of low-level detonators, for example, MS1~MS5, reduces the error of delay time to a certain extent, which is beneficial for blasting vibration reduction. Contrarily, using adjacent detonator segments will lead to the overlapping of specified errors and increase the scale range of errors in time. For example, MS8~MS11 detonator segments have been continuously used the lower limit of error range is 5 ms, and the upper limit is increased from 95 ms to 155 ms with an equal interval of 20 ms. Rock could not be broken sufficiently as the interval time is too short. Moreover, the explosion pile is not conducive to be discharged and transported. At the same time, it will increase the accident probability of early explosion and antiexplosion.

The interval time between MS15 and MS19 detonators is 806.5 ms, and the interval time is too long, which leads to a long vibration duration. While the vibration energy accumulation is easy to be produced, it should be avoided to reduce the blasting negative effect.

Therefore, it is suggested that the millisecond delay series of detonators should be selected in the whole section

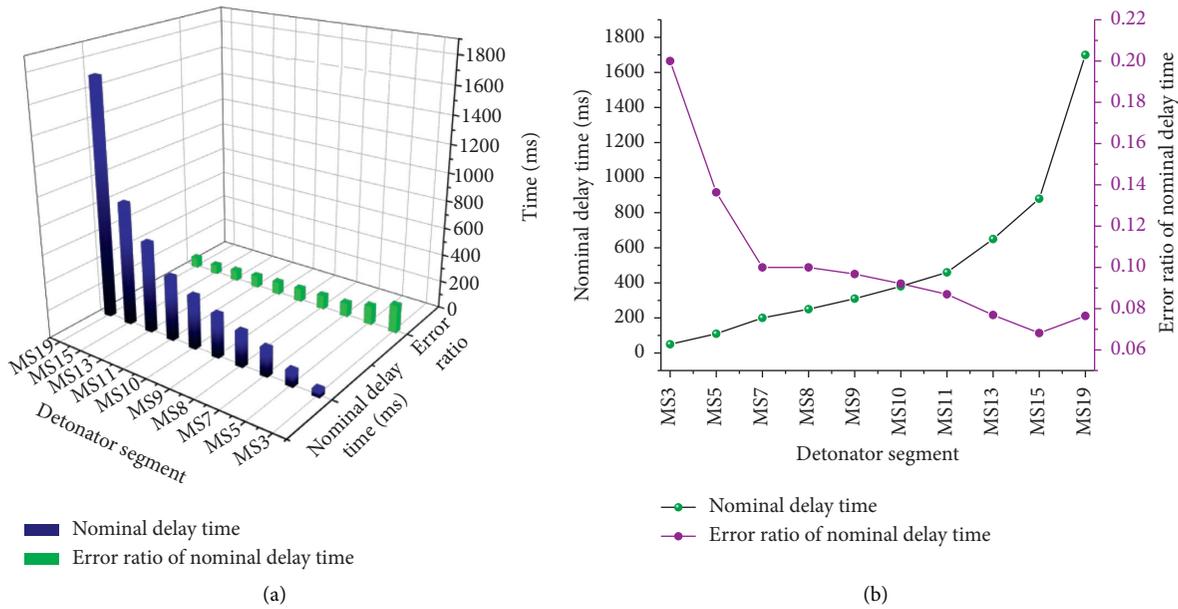


FIGURE 5: Nominal delay time and its error ratio.

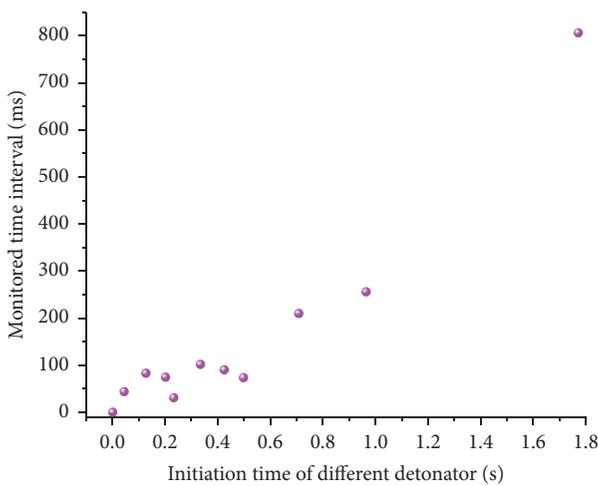


FIGURE 6: Initiation time and monitored time interval of detonators.

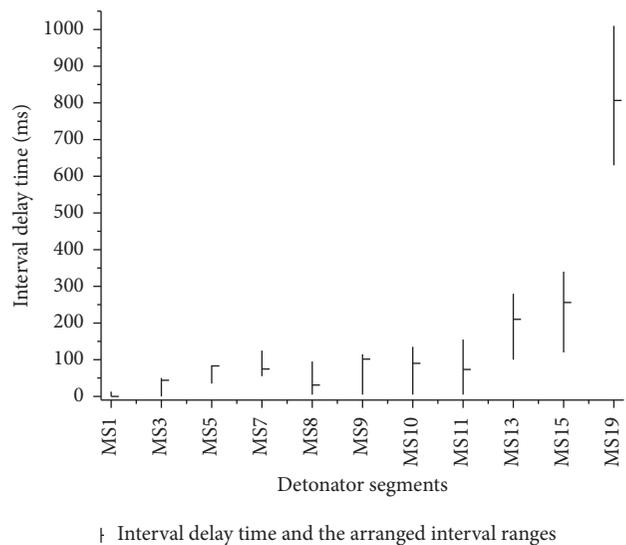


FIGURE 7: Interval delay time under kinds of detonator segments.

blasting, and the segment should be jumped as much as possible, so as to increase the secondary breakage time. Detonators with longer interval delay time should be avoided to the full.

5. Conclusions

For millisecond blasting, the blasting effect is mostly affected by the actual delay time. The blasting vibration signals are analyzed using the wavelet transform method to identify the actual delay time, and the following conclusions are obtained here:

- (1) Using the ability of wavelet transform to highlight the local characteristics of the analyzed signals, the initiation time of detonators can be effectively

identified by wavelet transform, and then the actual delay time could be determined.

- (2) Furthermore, the allowable error of different detonator segments is analyzed. It is considered that the simultaneous initiation of large explosive quantity can be avoided by the use of multistage detonators, and the vibration resistance effect could be better. However, for the same level of detonator segment, the larger the arranged time interval, the less the possibility of initiation at the same time, which is not conducive to the vibration resistance. Therefore, it is suggested to use high-level detonators with detonating cord or high-precision digital electronic detonators to minimize the

initiation error, that is, to ensure that the same detonator segment initiates at the same time.

- (3) By identifying the delay time, the interval delay time of different detonator segments is obtained. The nominal delay time, actual delay time, and interval delay time are further compared and analyzed. It is suggested that the millisecond delay series of detonators should be selected in the whole section blasting, and the segment should be jumped as much as possible, so as to increase the secondary breakage time. And detonators with longer interval delay time should be avoided fully.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grants nos. 51522903 and 51774184), Excellent project Fund in North China University of Technology (Grant no. 216051360020XN199/006), and Scientific Research Fund in North China University of Technology (Grant no. 110051360002).

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