

## Research Article

# Application of Boundary Local Feature Scale Adaptive Matching Extension EMD Endpoint Effect Suppression Method in Blasting Seismic Wave Signal Processing

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The intrinsic endpoint effect of empirical mode decomposition (EMD) will lead to serious divergence of the intrinsic mode function (IMF) at the endpoint, which will lead to the distortion of IMF and affect the decomposition accuracy of EMD. In view of this phenomenon, an EMD endpoint effect suppression method based on boundary local feature scale adaptive matching extension was proposed. This method can consider both the change trend of the signal at the endpoint and the change rule of the signal inside. The simulation results showed that the proposed method had better suppression effect on the intrinsic endpoint effect of EMD than the traditional EMD endpoint effect suppression method and achieved high-precision IMF. The endpoint effect suppression method of EMD based on boundary local feature scale adaptive matching extension was used to process the actual blasting seismic signal. The decomposition results showed that the method can effectively suppress the endpoint effect of EMD of blasting seismic signal and are helpful to extract the detailed characteristic parameters of blasting seismic signal.

## 1. Introduction

The endpoint effect is an unavoidable problem in most signal-processing methods. Empirical mode decomposition (EMD) [1] has been widely used as an adaptive algorithm that decomposes according to the characteristics of the data itself, so it is extremely important to solve the problem of endpoint effect of EMD [2–4].

Some methods have been put forward to solve the problem of endpoint effect of EMD, such as extremum extension method [5] and polynomial fitting extension method [6], which focus on the local change trend of signal endpoint but ignore the global signal feature. There are also a few methods that consider the global signal feature but ignore the change trend of signal endpoint [7].

In view of the above research status, an EMD endpoint effect suppression method based on boundary local feature scale adaptive matching extension is proposed, which can

combine the local change trend of the signal endpoint with the feature of the original global signal itself. Compared with the traditional methods, this method has better effect and higher signal decomposition accuracy after it is processed by this method. Through the analysis of the simulation signal and the actual signal, it is proved that this method can not only effectively suppress the endpoint effect but also accurately extract signal feature parameters [8–11].

## 2. The Principle of Endpoint Effect

The intrinsic mode function (IMF) [12, 13] of the signal obtained by EMD needs to be screened many times. The essence of screening is to calculate the local mean value of the signal according to the upper envelope determined by all maximum points of the signal and the lower envelope determined by all minimum points of signal [14, 15]. However, the endpoint of the signal cannot be at the maximum or

minimum at the same time, and it is not necessarily the extreme point. Therefore, the upper and lower envelope may diverge at the endpoint, which distorts the EMD result [16, 17].

### 3. The Principle of Boundary Local Feature Scale Adaptive Matching Extension EMD Endpoint Effect Suppression Method

The boundary local feature scale adaptive matching extension EMD endpoint effect suppression method consists of two parts. The first part is boundary local feature scale extension (BLFSE), which considering the variation trend of the signal endpoint amplitude and the internal relationship between the global time of the signal and the interval relationship between the global time of the signal and the time interval the endpoint. The second part is adaptive matching, finding the time series with the highest matching degree in the global signal according to the extended local feature scale.

Taking the ‘‘boundary local feature scale’’ as the reference, a time series with the highest matching degree with ‘‘boundary local feature scale’’ will be found in the global signal, which is the result of the ‘‘boundary local feature scale adaptive matching extension EMD endpoint effect suppression method.’’ Figure 1 shows the specific operation flow of the EMD endpoint effect suppression method based on the boundary local feature scale adaptive matching extension.

**3.1. The Principle of Boundary Local Feature Scale Extension.** The change trend of the signal is not only reflected at the endpoints but also reflected inside the signal [18, 19]. Therefore, there is an inherent connection between the global time of the signal and the interval time of the endpoints. According to this connection, time parameters corresponding to a maximum value point and a minimum value point can be calculated at the left and right endpoint of the signal. By importing the time parameters into the polynomial established by the maximum (minimum) value point of the endpoint, the amplitude parameters corresponding to the maximum (minimum) value point can be obtained.

**3.1.1. The Time Parameter of the Boundary Local Feature Scale Extension.** Take the left endpoint of the signal as an example, find the occurrence time of all the maximum points of the signal, and record them as  $t_{\max 1}, t_{\max 2}, \dots, t_{\max i}$  ( $i = 1, 2, 3, \dots, M$ ). In the same way, find the occurrence time of all the minimum points of the signal and record them as  $t_{\min 1}, t_{\min 2}, \dots, t_{\min i}$  ( $i = 1, 2, 3, \dots, N$ ). The maximum and minimum points which need to be extended are recorded as  $t_{\max 0}$  and  $t_{\min 0}$ , respectively. The calculation of  $t_{\max 0}$  and  $t_{\min 0}$  are divided into the following four cases.

Case 1:  $t_{\max 1} < t_{\min 1} \cap t_{\max M} < t_{\min N}$ ,  $M = N$ ;  $t_{\min 0}$  and  $t_{\max 0}$  are solved with equations (1) and (2), respectively:

$$t_{\min 0} = \frac{\sum_{i=1}^{N-1} (t_{\max i+1} - t_{\min i})}{N-1} - t_{\max 1}, \quad (1)$$

$$t_{\max 0} = \frac{\sum_{i=1}^N (t_{\min i} - t_{\max i})}{N} + t_{\min 0}. \quad (2)$$

Case 2:  $t_{\max 1} < t_{\min 1} \cap t_{\max M} > t_{\min N}$ ,  $M = N + 1$ ;  $t_{\max 0}$  is solved with the same equation (2) and  $t_{\min 0}$  is solved with

$$t_{\min 0} = \frac{\sum_{i=1}^N (t_{\max i+1} - t_{\min i})}{N} - t_{\max 1}. \quad (3)$$

Case 3:  $t_{\max 1} > t_{\min 1} \cap t_{\max M} > t_{\min N}$ ,  $M = N$ ;  $t_{\min 0}$  and  $t_{\max 0}$  are solved with equation (4) and equation (5), respectively:

$$t_{\min 0} = \frac{\sum_{i=1}^N (t_{\max i} - t_{\min i})}{N} + t_{\max 0}, \quad (4)$$

$$t_{\max 0} = \frac{\sum_{i=1}^{N-1} (t_{\min i+1} - t_{\max i})}{N-1} - t_{\min 1}. \quad (5)$$

Case 4:  $t_{\max 1} > t_{\min 1} \cap t_{\max M} < t_{\min N}$ ,  $M = N - 1$ ;  $t_{\max 0}$  is solved with the same equation (5), and  $t_{\min 0}$  is solved with

$$t_{\min 0} = \frac{\sum_{i=1}^{N-1} (t_{\max i} - t_{\min i})}{N-1} + t_{\max 0}. \quad (6)$$

**3.1.2. The Amplitude Parameter of the Boundary Local Feature Scale Extension.** Take the left endpoint of the signal as an example, find all the amplitudes corresponding to the occurrence time of the maximum value points of the signal, and record them as  $x_{\max 1}, x_{\max 2}, \dots, x_{\max i}$  ( $i = 1, 2, 3, \dots, M$ ). In the same way, find all the amplitudes corresponding to the occurrence time of the minimum value points of the signal and record them as  $x_{\min 1}, x_{\min 2}, \dots, x_{\min i}$  ( $i = 1, 2, 3, \dots, N$ ). According to the amplitude variation trend near the endpoint, a maximum value point and a minimum value point near the left endpoint are extended.

The specific steps of the boundary local feature scale extension are as follows:

Step 1: take maximum points closest to the left endpoint of the signal, i.e.,  $x_{\max 1}, x_{\max 2}, \dots, x_{\max a}$ . The value of  $a$  is related to the sample size.

Step 2: polynomial fit is  $x_{\max 1}, x_{\max 2}, \dots, x_{\max a}$ . Then,  $(t_{\max 0}, x_{\max 0})$  can be obtained by taking  $t_{\max 0}$  obtained in Section 3.1.1 into the fitting formula in ‘‘Step 1.’’

Similarly,  $(t_{\min 0}, x_{\min 0})$  can be obtained.

**3.2. The Principle of Adaptive Matching.** The trend of the signal is reflected in the endpoint and in the whole signal. Therefore, it is possible to find a curve within the signal that has the highest matching degree with the ‘‘boundary local feature scale extension’’ obtained in Section 3.1.

Specific steps of adaptive matching are as follows:

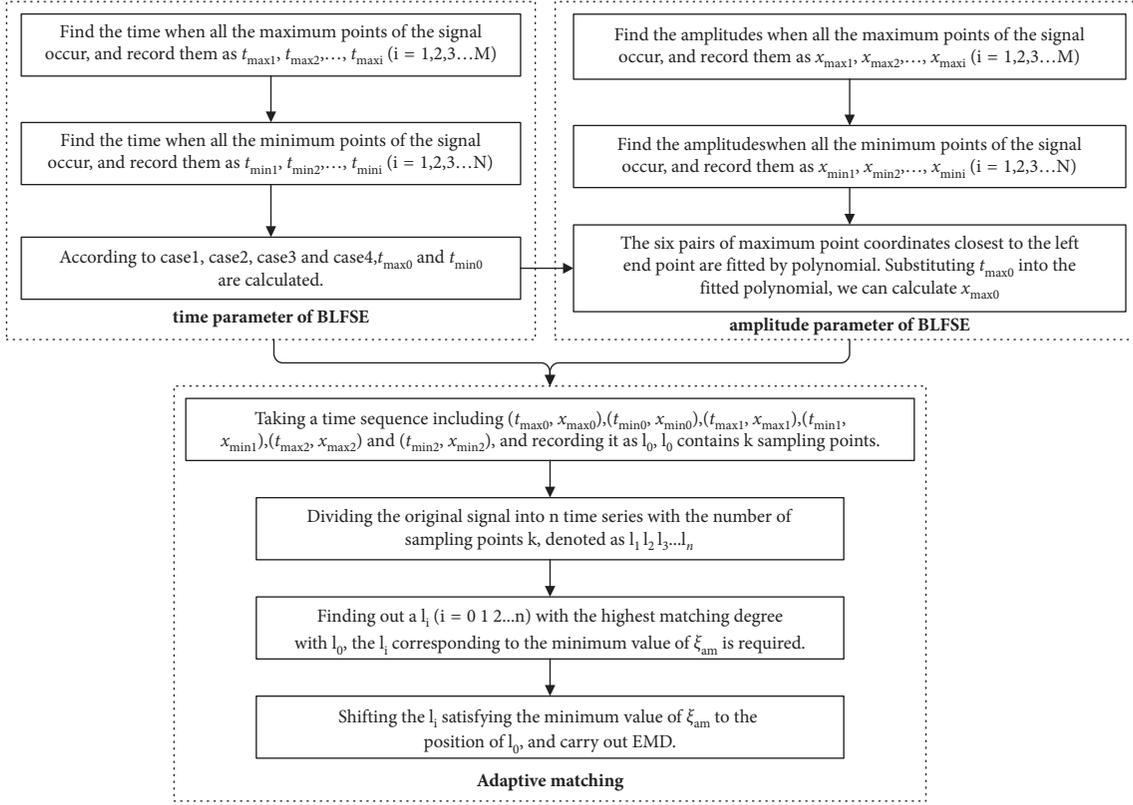


FIGURE 1: Boundary local feature scale adaptive matching extension EMD endpoint effect suppression method operation flow.

Step 1: take a time series that includes 6 extreme points, which contains the left point continuation results  $(t_{\max0}, x_{\max0})$  and  $(t_{\min0}, x_{\min0})$  and the two closest maximum and minimum value points  $(t_{\max1}, x_{\max1})$ ,  $(t_{\min1}, x_{\min1})$ ,  $(t_{\max2}, x_{\max2})$ , and  $(t_{\min2}, x_{\min2})$ . Record this time series as  $l_0$ , which contains  $k$  sampling points.

Step 2: divide the original signal into  $n$  time series with the number of sampling points  $k$  and record them as  $l_1, l_2, l_3, \dots, l_i \dots l_n$  ( $i = 0, 1, 2, \dots, n$ ).

Step 3: calculate the adaptive matching coefficient (adaptive matching,  $\xi_{am}$ ) [7] and find out  $l_i$  ( $i = 0 1 2 \dots n$ ) with the highest matching degree with  $l_0$ . The adaptive matching coefficient is calculated in equation (7), where  $A = \max \{x_{\max0}, x_{\max1}, x_{\max2}\}$  and  $B = \max \{x_{\min0}, x_{\min1}, x_{\min2}\}$ . Find the minimum value of the adaptive matching coefficient,  $\xi_{ammin} = \min \{\xi_{am1}, \xi_{am2}, \xi_{am3}, \dots, \xi_{amn}\}$ ; the corresponding  $l_i$  is the desired time series, which has the highest matching degree with  $l_0$ :

$$\xi_{am} = \frac{\sqrt{\sum_{j=1}^k (l_0 - l_j)^2 / k}}{A - B} \quad (7)$$

Step 4: shifting  $l_i$  satisfying the minimum value of  $\xi_{am}$  to the position of  $l_0$ , then carry out EMD.

In summary, the boundary local feature scale adaptive matching extension EMD endpoint effect suppression method can be realized by completing the above four steps.

#### 4. Comparative Study of Multiple EMD Endpoint Effect Suppression Methods for Simulated Signals

The simulation signal is used to conduct a comparative study of multiple EMD endpoint effect suppression methods, and the correlation coefficient and standard deviation of error between the IMF and the original signal are analyzed to evaluate the EMD endpoint effect suppression.

Simulation signal  $S(t)$  is composed of three sinusoidal signals with frequencies of 10 Hz, 30 Hz, and 60 Hz, that is,  $S(t) = x_1(t) + x_2(t) + x_3(t)$ , where  $x_1(t) = \sin(2 \times \pi \times 10 \times t)$ ,  $x_2(t) = \sin(2 \times \pi \times 30 \times t)$ , and  $x_3(t) = \sin(2 \times \pi \times 60 \times t)$ . Sampling point  $N = 200$ , sampling time  $t$  is  $0, \pi/100, 2\pi/100, 3\pi/100, \dots, 2\pi$ , that is, on  $[0, 2\pi]$ , the middle point is taken with an interval of  $\pi/100$ .

EMD is performed on  $S(t)$  directly, and the IMF is obtained as shown in Figure 2(a). It can be found that the two ends of IMF1, IMF2, and IMF3 have different degrees of divergence. With the decomposition, the divergence of IMF3 is the most serious and tends to develop into the data. The decomposition results obtained by boundary local feature scale adaptive matching extension EMD endpoint effect suppression method, extremum extension method, and polynomial fitting method are shown in Figures 2(b)–2(d), respectively. The correlation coefficient ( $r_{xy}$ ) [14] and standard deviation of error ( $D_{sde}$ ) [20] between IMF component and corresponding sinusoidal signal are calculated one by one. The equations of correlation coefficient and

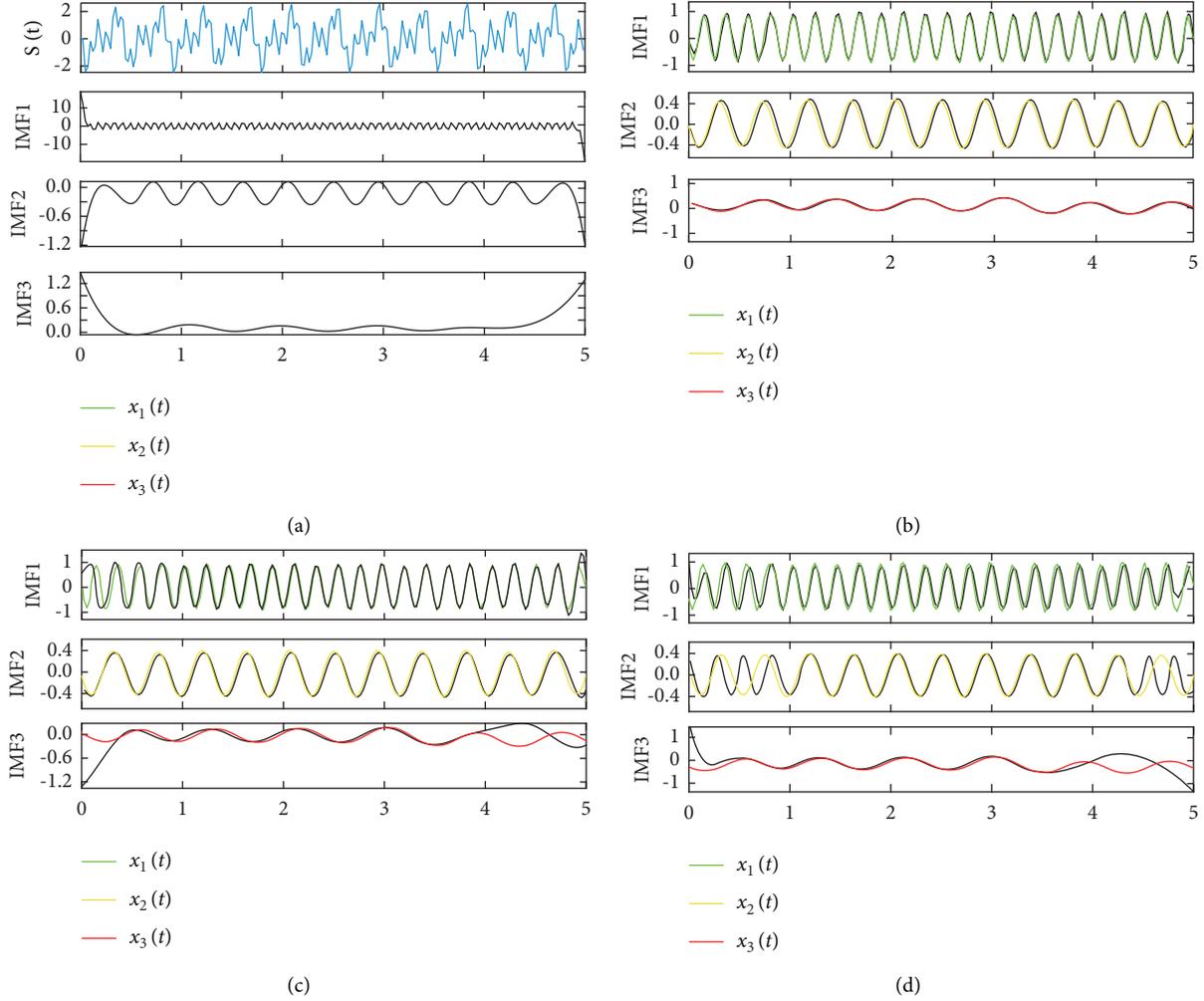


FIGURE 2: Simulation signal decomposition results.

standard deviation of error are shown in equations (8) and (9), respectively, where  $N$  is the number of sampling points,  $x$  corresponds to  $x_1(t)$ ,  $x_2(t)$ , and  $x_3(t)$ , and  $y$  corresponds to IMF1, IMF2, and IMF3. The calculation results are shown in Table 1.

$$r_{xy} = \frac{\sum_{i=1}^N \sum_{k=1}^3 (x_k^i(t) - \overline{x(t)})(y_k^i(t) - \overline{y(t)})}{\sqrt{\sum_{i=1}^N \sum_{k=1}^3 (x_k^i(t) - \overline{x(t)})^2 (y_k^i(t) - \overline{y(t)})^2}}, \quad (8)$$

$$D_{sde} = \sqrt{\frac{\sum_{i=1}^N [\sum_{k=1}^3 (x_k^i(t) - y_k^i(t))]^2}{N}}. \quad (9)$$

The following conclusions can be drawn from Figure 2 and Table 1:

- (1) The three IMF components obtained by the boundary local feature scale adaptive matching extension EMD endpoint effect suppression method reflects the three sinusoidal signals contained in  $S(t)$

and has high correlation and small error with the corresponding sinusoidal signals

- (2) The IMF obtained by the boundary local feature scale adaptive matching extension EMD endpoint effect suppression method has the highest accuracy
- (3) The effect of extremum extension method is slightly better than polynomial fitting method, especially, for the suppression of low frequency components

By further analysis, the IMF obtained in Figures 2(b)–2(d) are transformed by Hilbert transform, and the marginal spectrum-based boundary local feature scale adaptive matching extension EMD endpoint effect suppression method, extremum extension method, and polynomial fitting method are obtained, respectively, as shown in Figures 3(b)–3(d). Figure 3(a) is the marginal spectrum obtained by direct Hilbert transform of  $x_1(t)$ ,  $x_2(t)$ , and  $x_3(t)$ . In Figure 3, the energy spectral density (ESD) is the ordinate.

It can be seen from Figures 3(b)–3(d) that the marginal spectral frequencies obtained by the boundary local feature scale adaptive matching extension EMD endpoint effect suppression method are 10.15 Hz, 30.11 Hz, and 60.12 Hz,

TABLE 1: Evaluation index of the endpoint effect suppression method.

Evaluating indicator	Boundary local feature scale adaptive matching extension method	Extremum extension method	Polynomial fitting method
$r_{xy}$	IMF1	0.9981	0.8969
	IMF2	0.9979	0.9384
	IMF3	0.9926	0.6837
$D_{sde}$	IMF1	0.0081	0.2095
	IMF2	0.0078	0.1563
	IMF3	0.0091	0.3319

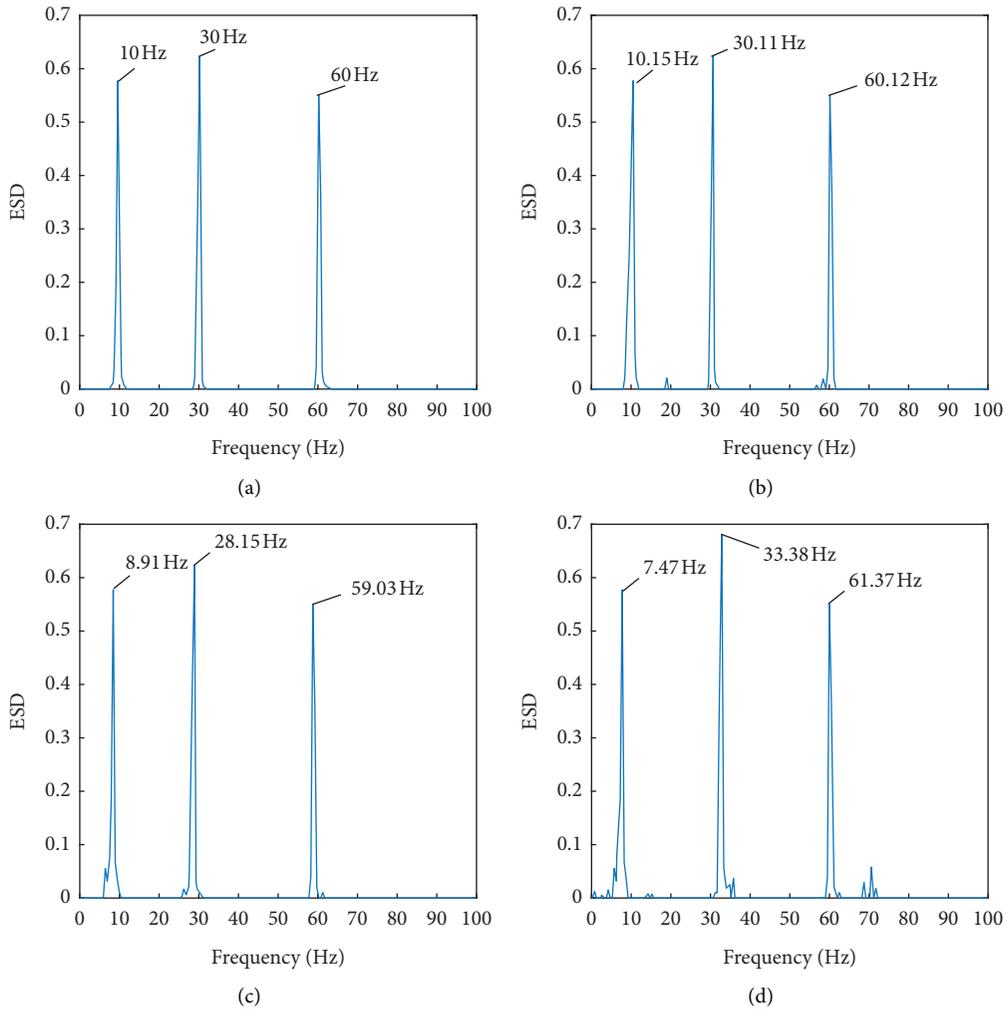


FIGURE 3: Marginal spectrum.

respectively; the marginal spectral frequencies obtained by the extremum extension method are 8.91 Hz, 28.15 Hz, and 59.03 Hz, respectively; the marginal spectral frequencies obtained by the polynomial fitting method are 7.47 Hz, 33.38 Hz, and 60.12 Hz, respectively. The marginal spectrum shows the frequency of simple harmonic wave contained in IMF by different endpoint effect suppression methods. The error between the marginal spectrum obtained by the boundary local feature scale adaptive matching extension

EMD endpoint effect suppression method and the marginal spectrum obtained by  $x_1(t)$ ,  $x_2(t)$ , and  $x_3(t)$  direct Hilbert transform is the smallest, which indicates that the boundary local feature scale adaptive matching extension EMD endpoint effect suppression method can accurately detect the characteristic frequency contained in  $S(t)$ . The results are consistent with those in Figure 2 and Table 1, which further shows that the boundary local feature scale adaptive matching extension EMD endpoint effect suppression

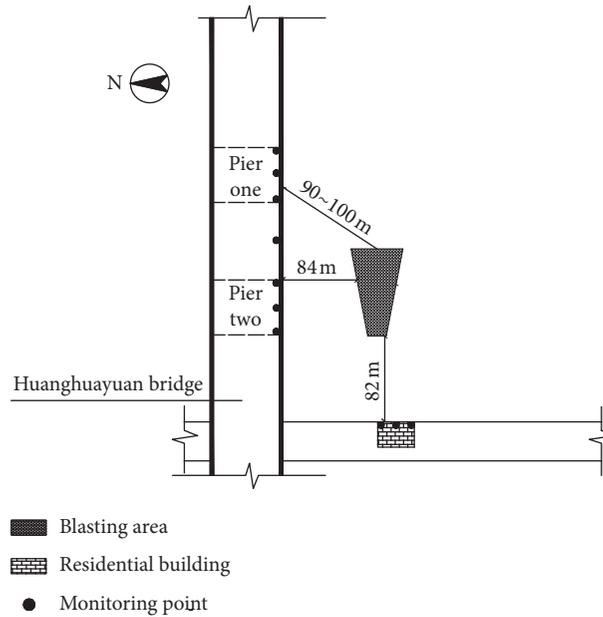


FIGURE 4: Blasting construction environment diagram.

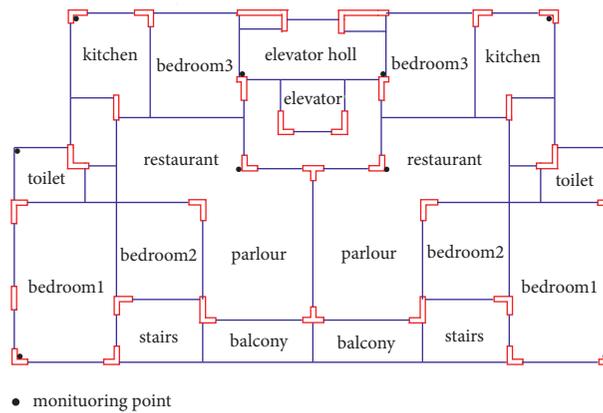


FIGURE 5: Layout of measuring points of houses.

method can effectively suppress the EMD endpoint effect, realize the extraction of the original signal detail feature parameters, and obtain high-precision IMF.

## 5. Application of Boundary Local Feature Scale Adaptive Matching Extension EMD Endpoint Effect Suppression Method of Blasting Seismic Wave Signal

The development of engineering blasting has greatly improved work efficiency and brought great convenience to the country's infrastructure construction. However, the impact of its seismic effects and air shock waves on the surrounding environment has become increasingly prominent. The main manifestations are destruction and cracking of existing buildings, slope instability and collapse, and fear of humans and animals. Among them, blasting seismic effect is considered to be the primary hazard of engineering blasting [21].

Especially, in the construction urban blasting engineering, the impact of blasting seismic effects on surrounding buildings is more prominent. Based on the blasting excavation project of the water intake tank of Huanghuayuan Bridge in Chongqing, the length of the water intake tank is 135 m, the upper and bottom width is 69 m, and the lower and lower width is 24 m. The layout plan of the blasting site is shown in Figure 4. It can be seen in Figure 4 that there is a residential building 82 meters away from the water intake tank. The residential building is the key monitoring object of this blasting construction, with 7 floors above the ground. The TC-4850 intelligent blasting vibration instrument is used to monitor the building. The layout of the measuring points is shown in Figure 5. Only the layout of the measuring points of the first floor is shown here, and the other floors are the same as the first floor.

The impact of the blasting seismic effect on surrounding buildings is studied through the EMD method. The boundary local feature scale adaptive matching extension

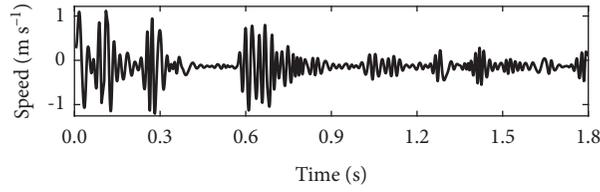


FIGURE 6: Seismic wave monitoring signal.

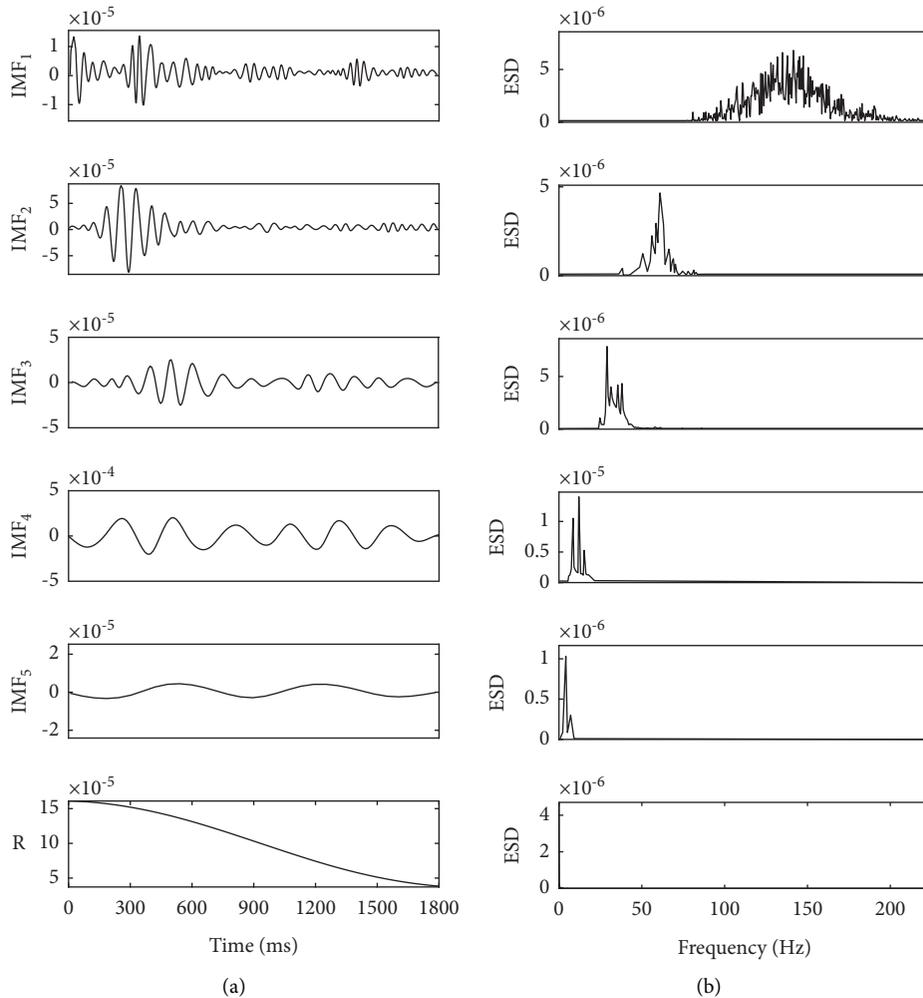


FIGURE 7: Seismic wave-monitoring signal decomposition diagram.

method is studied to suppress the EMD endpoint effect of the blasting seismic wave signal.

In the monitoring results, a typical seismic wave signal is selected as the research object, as shown in Figure 6. The sampling frequency of the signal is 4000 sps. According to the Nyquist sampling theorem [22], the Nyquist frequency of the measured blasting seismic wave signal is 2000 Hz, including 4096 sampling points.

The signal in Figure 6 is decomposed by the boundary local feature scale adaptive matching extension EMD endpoint effect suppression method. The decomposition results are shown in Figure 7(a). It can be found from Figure 7(a) that there is only slight divergence at the right end of IMF4,

and the endpoint effect suppression of other components is well controlled. Further analysis is carried out to calculate the marginal spectrum of each IMF. The calculation results are shown in Figure 7(b). It can be found that each IMF carries a set of specific frequency signals of the blasting seismic wave signal, which once again shows that the boundary local feature scale adaptive matching extension EMD endpoint effect suppression method can realize the accurate extraction of signal feature parameters. The total marginal spectrum of the signal, as shown in Figure 8, is further obtained. Figure 8 shows that the energy of the underwater drilling blasting seismic wave is mainly concentrated in 0~50 Hz, which is consistent with the

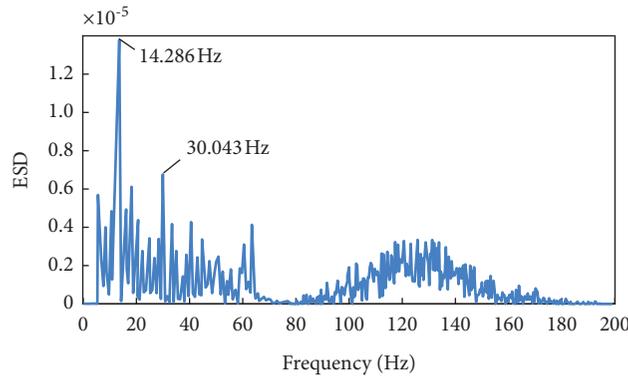


FIGURE 8: The total marginal spectrum of the signal.

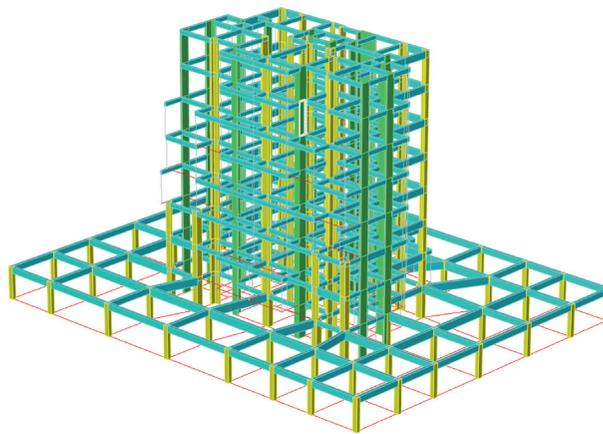


FIGURE 9: Three-dimensional model diagram of the residential building.

TABLE 2: The natural frequency corresponding to the first eight-order mode shape (unit: Hz).

Array	Natural frequency
1	8.234
2	13.806
3	18.806
4	25.023
5	29.920
6	32.156
7	42.714
8	44.976

conclusion drawn by [23]. The dominant frequency of the signal is the frequency corresponding to the maximum energy density [24], so the dominant frequency of this signal is 14.286 Hz. When the frequency of blasting seismic wave is the same as the natural frequency of the residential building, the amplitude of the structure will reach the maximum, thus inducing resonance harm.

Through the finite element analysis software of YJK, the three-dimensional model of the residential building is obtained, as shown in Figure 9, and the natural vibration frequency of the house is calculated. The natural vibration frequency of the first eight-order formation of the residential building is shown in Table 2. It can be found from the

analysis of Table 2 that the second-order formation of the residential building is 13.806 Hz, and the dominant frequency of this blasting is 14.286 Hz, which are very close to each other. Therefore, the seismic wave generated by the blasting is very likely to cause the resonance of the residential building.

Therefore, the corresponding control measures must be taken in the actual construction to ensure the safety of the residential building. The conclusion also shows that the method proposed in this paper is not only helpful to suppress the EMD endpoint effect and obtain higher precision IMF but also can accurately extract the frequency parameters contained in the blasting seismic wave, which is helpful to control blasting vibration and provide basis for formulating scientific antiseismic measures.

## 6. Conclusions

- (1) The boundary local feature scale adaptive matching extension method not only considers the local change trend of the signal at the endpoint but also retains the unique internal attributes of the signal through the global search ability of “adaptive matching,” so as to retain the authenticity of the original signal to the greatest extent

- (2) By comparing the decomposition results of simulation signals, it is found that the boundary local feature scale adaptive matching extension EMD endpoint effect suppression method can effectively suppress the EMD endpoint effect and obtain higher accuracy IMF
- (3) The frequency energy information contained in the blasting seismic wave can be effectively extracted from the marginal spectrum of the IMF obtained by the boundary local feature scale adaptive matching extension EMD endpoint effect suppression method, which is helpful to identify the characteristic parameters of blasting seismic wave signal and control blasting vibration

## Data Availability

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

## Conflicts of Interest

The authors declare no conflicts of interest.

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