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An Improved Automatic Picking Method for Arrival Time of Acoustic Emission Signals

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ABSTRACT In this paper, an improved automatic method for picking arrival times of acoustic emission (AE) signals, has been proposed to overcome the interference of spike noise and channel crosstalk. First, median filter is applied to eliminate spike noise presented in signals. Second, the preliminary arrival time is obtained by the AIC picker. Then a judgment whether the signal is disturbed by channel crosstalk is conducted. If the signal is triggered normally, the preliminary arrival time is regarded as the final arrival time of the AE signal. If the signal is triggered in advance, the signal series is selected from the preliminary arrival time to the time corresponding to the maximum of absolute values of signal series. At last the AIC picker is used again to pick the arrival time of selected series and the second AIC arrival time is interpreted as the final arrival time. To validate the performance of the improved automatic method, AIC picker, AIC picker applied after the median filter (MF-AIC) are also used simultaneously to pick the arrival times of AE signals and perform event location. The results show that the improved automatic method has better waveform adaptability and location accuracies than other two methods.

INDEX TERMS Median filter, AIC picker, event location, waveform adaptability, acoustic emission (AE) signal.

I. INTRODUCTION

An accurate detection for arrival times of acoustic emission (AE), micro-seismic or seismic waves is an elementary and important step toward the analysis of acoustic data [1]–[5]. In the past, the measurement task of arrival time first is implemented by picking algorithm and then human operators adjust them manually by inspections [6]. However, when large amounts of acoustic data need to be processed, the manual picking is very time-consuming and the picking accuracy is affected by personal opinion or experience. Therefore, it is of great significance to develop an appropriate automatic picking algorithm after which any review from experts is not required.

At present, there are numerous automatic picking algorithms that have been proposed ©and presented in many literatures [7]–[9], among which the short-term-average to long-term-average ratio (STA/LTA) [10] and Akaike information criterion (AIC) [11] techniques are applied most widely. Based on the STA/LTA technique, arrival times of acoustic signals can be obtained when the ratio between the STA and LTA of this characteristic function exceeds a predefined or dynamically specified threshold value. This algorithm can identify the amplitude variation, but the detection accuracy relies on the moving interval and threshold settings to a large extent [6]. On the contrary, the AIC technique developed by Maeda [12] does not require the sliding interval and the point where the AIC function is minimized is regarded as the arrival time. This method assumes that the windows before and after arrival time are two different stationary time series and the variance changes will occur at the arrival time. With an appropriate time window, the AIC technique can pick arrival time accurately.

Along with the technological progress, filter or de-noising and time frequency transformation techniques have also been introduced to identification for the arrival times of noisy signals. Zhang et al [13] applied wavelet transform and threshold de-noising to obtain the de-noised time series at different scales. Then the AIC picker is used to determine the arrival times of different scale components.

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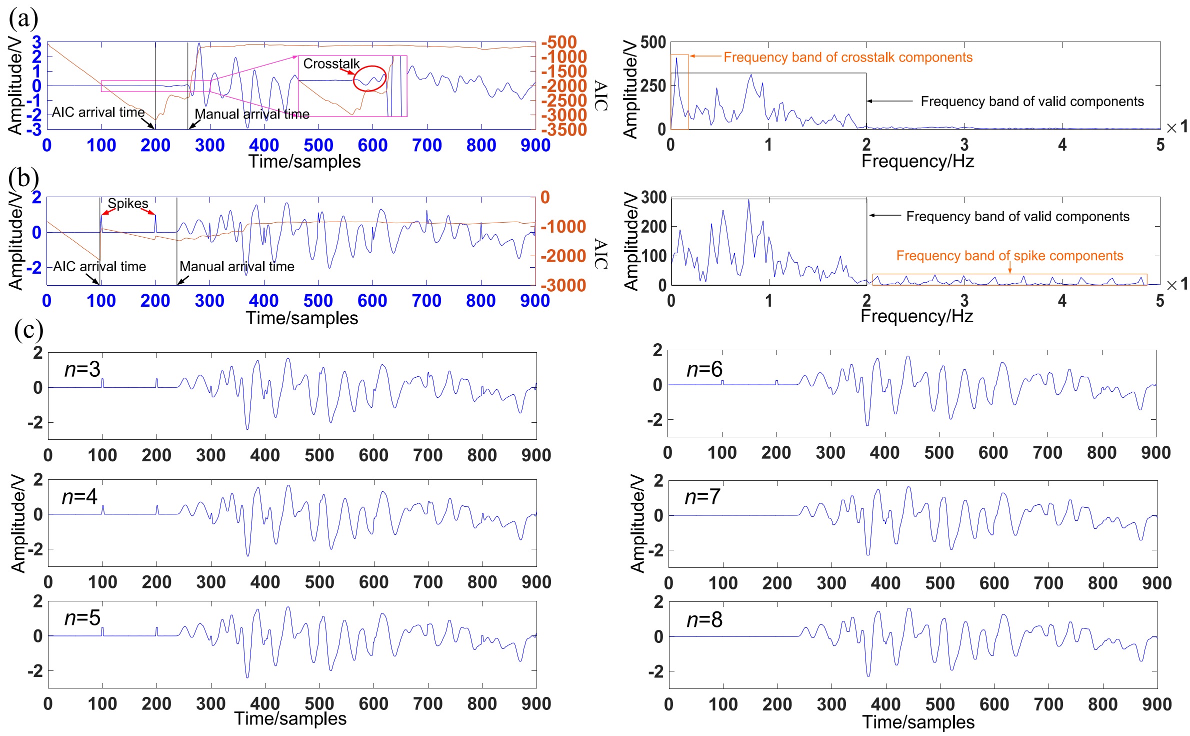

FIGURE 1. Two AE signals and their median filtering results by different interval lengths. (a) The AE signal triggered in advance and its frequency spectrum, (b) the AE signal with spike noise and its frequency spectrum, (c) the filtered series of the AE signal shown in Fig. 1(b) by different interval lengths.

This method achieves good results even for noisy seismograms. Karamzadeh et al [14] constructed a characteristic function by the application of the stack of the Continuous Wavelet Transform (CWT) coefficients that cover the frequency content of desired P phases. Karamzadeh et al. [15] used Maximal Overlap Discrete Wavelet Transform (MODWT) to obtain wavelet details for the detection of P phase arrival. Gaci [16] used discrete wavelet transform (DWT) with STA/LTA method to obtain the accurate arrival times at very low signal-to-noise ratio (SNR) condition. Álvarez et al [1] applied an adaptive multiband processing and noise reduction techniques to pick the computer-generated and real seismic signals respectively. The results showed that the picking accuracies had the great enhancement than that of STA/LTA. Shang et al [17] combined the empirical mode decomposition (EMD) and AIC picker to pick arrivals of 1938 micro-seismic signals, the results showed that the performance of this method is better than that of DWT-AIC.

Unlike the poor environment in the field, the background noise is seldom strong during the laboratory acoustic emission (AE) test. But channel crosstalk and unstable voltage are often encountered in this environment. The channel crosstalk is defined that when one signal channel is triggered by the emerging event, other channels not prepared to receive this event are triggered falsely in advance, which results in the picked arrival times are earlier than the real arrival times of signals at the interfered channels (Fig. 1(a)). It is worse that the frequency band of early triggered waveform is overlapped with that of valid signal heavily, causing that the interference cannot be eliminated by the filter or de-noising technique. In addition, spike noise could be induced by the unstable voltage in the records, which will lead to that the arrival times are picked to the vicinity of the spike by error (Fig. 1(b)).

To deal with the above issue, an improved automatic method has been proposed in this paper. The method is based on the median filter technique and AIC picker. First, median filter is applied to eliminate the spike noise. Then an automatic judgment whether the received signal is disturbed by other channels is performed. If the signal is not affected by other channels, the AIC picker is applied to obtain the arrival time. Otherwise, the time series between first AIC arrival time and the point corresponding to the maximum of absolute values of signal series is chosen. At last the AIC picker is applied again to pick the arrival time of the selected time series. And the second AIC arrival time is interpreted as the final arrival time. To evaluate the performance of the improved method, AIC picker, AIC picker applied after median filter (MF-AIC) are also utilized to pick arrival time simultaneously.

II. THE IMPROVED AUTOMATIC ALGORITHM

A. AIC AND MEDIAN FILTER PRINCIPLES

The AIC method depends on the concept that the intervals before and after the onset time of a waveform are two different stationary time series, where each interval is treated as an

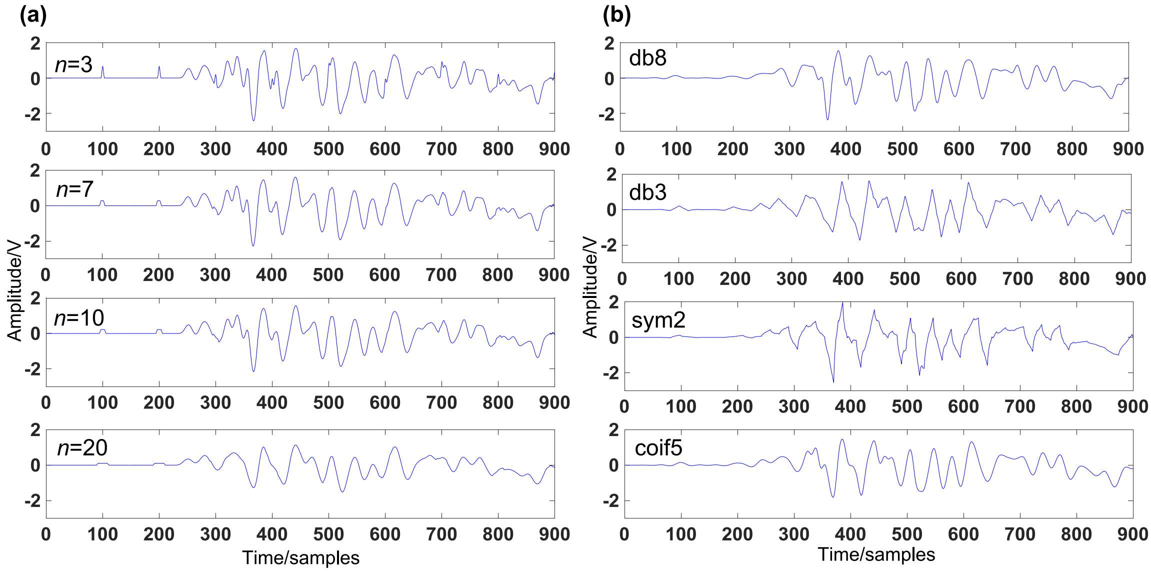

FIGURE 2. **The filtered series of the AE signal shown in Fig. 1(b) by, (a) Moving average filter, (b) Wavelet filter.**

autoregressive process. The AIC value of k^{th} sample of an acoustic emission signal $x(t)$ $(t = 1, 2, , N)$ is represented as:

$$AIC(k)=(k-M)\log(\sigma^2_{1,\max})+(N-M-k)\log(\sigma^2_{2,\max})+C \quad (1)$$

In order to obtain the AIC values, the coefficient C and the order M must be calculated, which have a high degree of computational complexity. Developing from the original AIC picker, Maeda [37] computes the AIC directly from the time series without using the autoregressive model coefficients. In this case, AIC is represented as:

$$AIC(k) = k\log(\text{var}\{x(1, k)\}) + (N - k - 1)\log(\text{var}\{x(k + 1, N)\}) \quad (2)$$

where $\text{var}\{x(1, k)\}$ is the variance of time series before the sliding sample k, and $\text{var}\{x(k + 1, N)\}$ is the variance of time series after the sliding sample k. The sample of onset time conforms to the global minimum of AIC series. In this paper, the latter is chosen considering its computational efficiency.

Due to the AIC picker is sensitive to the jump point of time series, when signal is disturbed by spike noise or triggered in advance, the arrival time could be picked by error near spike or the early triggered position. As shown in Fig. 1(a) and (b), when the AE signal is triggered in advance, the arrival time picked by AIC picker is located at the early-triggered position. When the AE signal is disturbed by the spike noise, the arrival time picked by AIC picker is the position of spike. Therefore, there is a great need to remove spike and judge whether the signal is triggered in advance.

To eliminate the spike presented in the AE signal, the median filter is introduced in the following. The median filter depends on that the value of each signal sample is set into the median value of all samples in an interval centered on that sample. When the interval length is odd, the median filtering value can be written by

$$y(k) = Med\,\{x(k - (n - 1)/2), \ldots, x(k + (n - 1)/2)\} \quad (3)$$

where $y(k)$ is the median filtering value of k^{th} sample in signal series, Med is the median symbol, n is the interval length, x is the original time series. When the interval length is even, the median filtering value can be written by

$$y(k) = Med\,\{x(k - n/2), \ldots x(k + n/2 - 1)\} \quad (4)$$

When the interval is partial overlapped with the time series, for instance the interval is centered on the start sample, the function considers that the un-overlapped parts in interval are set to 0. From Eqs. (3) and (4), the filtering performance is based on the interval length. The larger the interval length n is, the smoother the filtered result becomes. Meanwhile, the details of the original sequence are lost more. Hence, the interval length n should be reduced as far as possible on the premise of guaranteeing filtering effect. Fig. 1(c) shows the filtered results of the AE signal with spike (Fig. 1(b)) by different interval lengths. The results show the spike noise can be eliminated when the interval length is larger than 7. Thus $n = 7$ is selected for the median filter in this paper.

In addition to the median filter, the performances of moving average filter and Wavelet filter on dealing with the spike noise are also evaluated in the paper. Similar to the median filter, it is vital for moving average filter to determine the interval length n. Fig. 2(a) shows the filtered results of the AE signal with spike noise (Fig. 1(b)) by different interval lengths. It can be seen that when the interval length is 20, the obvious change of the signal waveform occurs compared

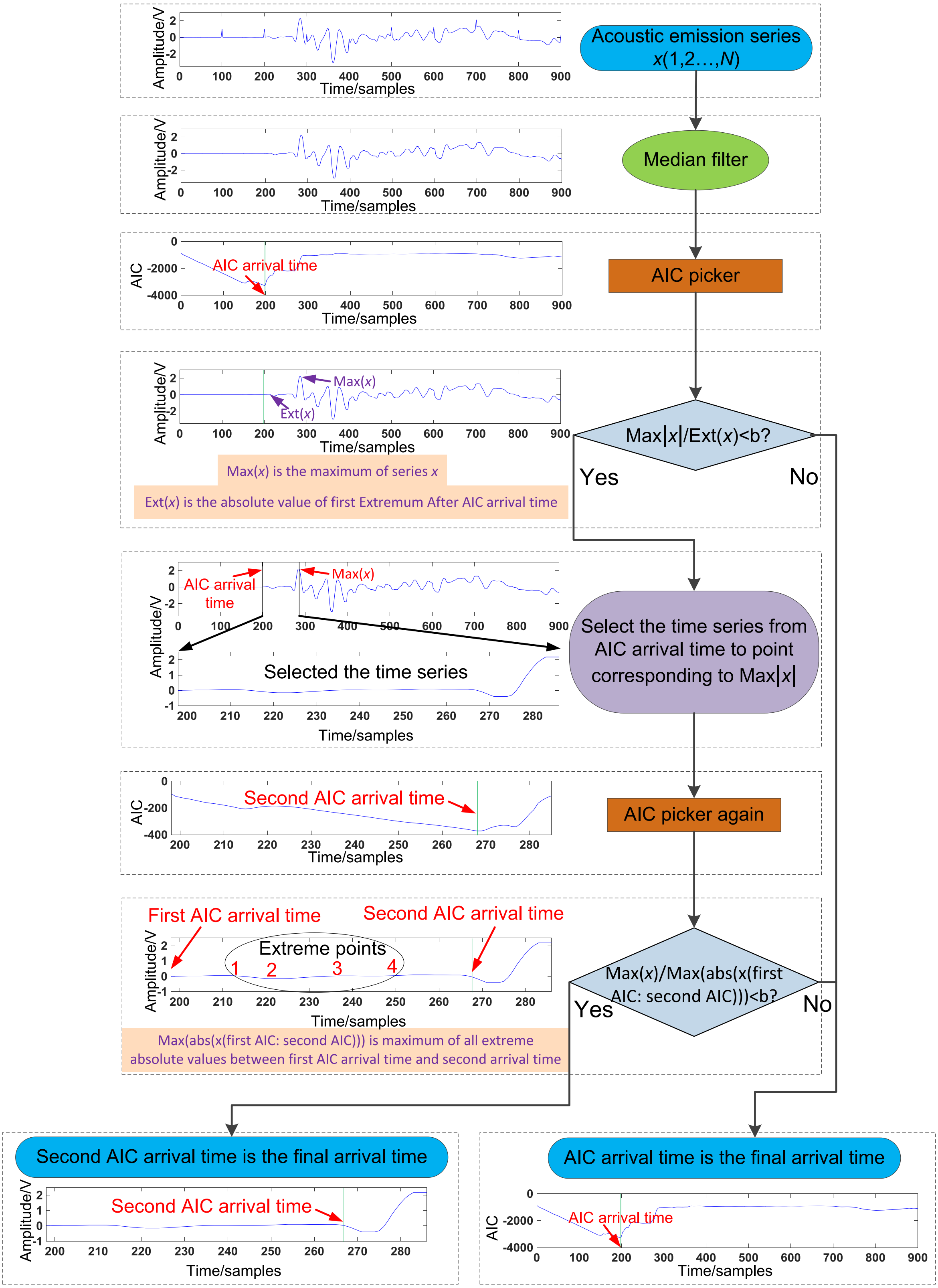

FIGURE 3. **The picking process of arrival time by the improved automatic method for AE signal (Note: the sampling frequency of signal is 3 MHz).**

to the original signal (Fig. 1(b)), which denotes that the interval length cannot be greater than 20. However, even if interval length is increased to 20, the spike noise is not eliminated well yet. For Wavelet filter, it is important to determine the appropriate mother wavelet. Fig. 2(b) shows the filtered results of the AE signal with spike noise (Fig. 1(b)) by different mother wavelets. It can be seen that when 'db3' and 'sym2' mother wavelets are used, the obvious signal distortions are encountered, which indicates that these two mother wavelets are not feasible for Wavelet filter to remove the spike noise. Meanwhile, when 'db8' and 'coif5' mother wavelets are used, the spike noise is not removed well. Through the above analysis, the median filter is better on dealing with the spike noise than moving average filter and Wavelet filter.

B. THE DETAILS OF THE IMPROVED AUTOMATIC METHOD

The AIC method is easy to be interfered by spike and channel crosstalk. Although the spike noise can be removed by the median filter, the problem of channel crosstalk has not been solved yet. Moreover, data records include not only the signals triggered in advance but also the normal triggered signals. Hence, a judgment whether the input signal belongs to the early triggered signal is necessary. According to these issues, an improved automatic picking algorithm is proposed. The specific implement procedures are depicted in Fig. 3 and the details are elaborated as follows:

Step 1: Import an original AE signal $x(t)$ $(t = 1, 2, \ldots, N)$

Step 2: Eliminate the spike noise presented in the AE signal based on the median filter technique. It is vital to select an appropriate interval length for the median filter. In this paper, the interval length is equal to 7. The details are interpreted in section II (A).

Step 3: Pick up the arrival time of filtered series using the AIC method.

Step 4: Judge whether the ratio between the maximum of absolute values of filtered time series and the first extremum behind AIC arrival time is less than b or not. If the ratio is not less than b, the time series is considered to be a normal triggered signal. Otherwise, the time series is preliminarily considered to be an early triggered signal. Therefore, the determination of b value is a critical factor for the picked arrival time. To determine the b value, 100 AE signals containing 50 normal triggered signals and 50 early triggered signals are picked by the improved automatic method using different b values. The results indicate that the best accuracies can be obtained when b is equal to 10 (Fig. 4(a)). To the early-triggered signal, when b is larger than 10, the crosstalk problem is not overcome yet (Fig. 4 (b)). To the normally-triggered signal, when b is equal to 5, the normal signal is considered to be the early-triggered signal by error (Fig. 4 (c)). Hence, the b is set to 10 in this paper.

Step 5: Decide whether the AIC arrive time is the final arrival time or not. For the normal triggered signal judged by step 4, the AIC arrival time is determined as the final arrival

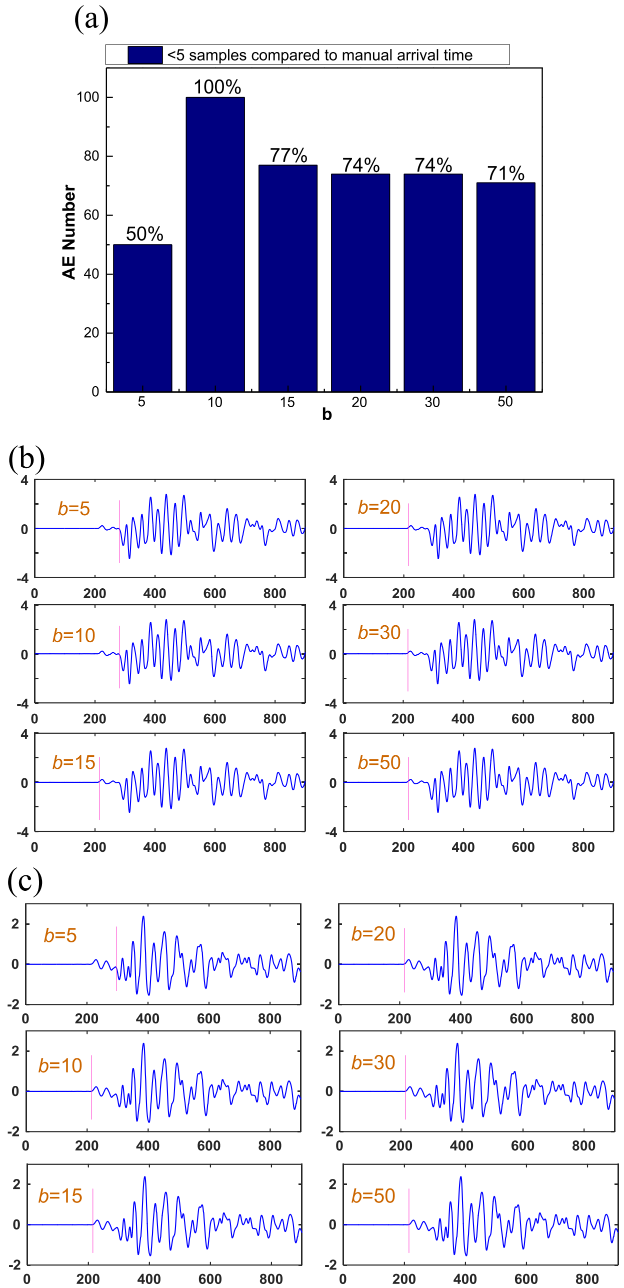

FIGURE 4. The picking results by the improved automatic method using different b values. (a) The picking percentages less than 5 samples compared manual arrival time at different b values, (b) the picking result of arrival time for an early triggered signal using differ ent b values, (c) the picking result of arrival time for a normal triggered signal using different b values.

time. For the early triggered signal judged preliminarily by step 4, the time series between AIC arrival time and the point corresponding to the maximum of absolute values of the whole signal series is selected.

Step 6: Pick up the arrival time of selected time series in step 5 using the AIC picker again.

Step 7: Search the maximum of all extreme absolute values between the first AIC arrival time and the second AIC arrival time. Judge whether the ratio between maximum

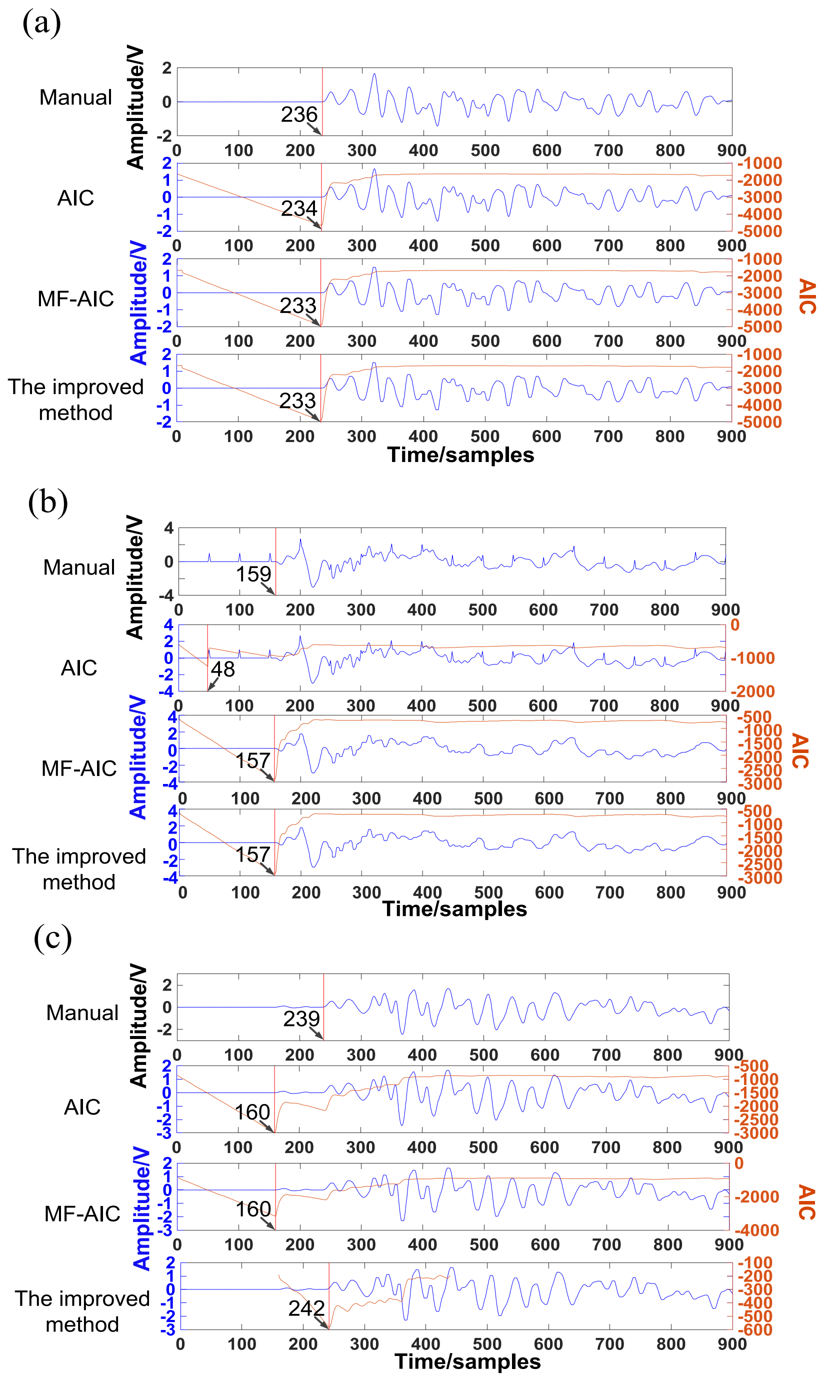

FIGURE 5. The arrival times of three typical AE signals picked by AIC, MF-AIC and the improved automatic methods. (a) The normally triggered signal, (b) the signal with spike noise, (c) the early triggered signal.

of absolute values of filtered time series and the maximum of all extreme absolute values is less than b. If this ratio is less than b, the whole signal is determined to be the final early-triggered signal and the second AIC arrival time is regarded as the final arrival time. Otherwise, the first AIC arrival time is still interpreted to the final arrival time.

III. PERFORMANCE TEST OF THE IMPROVED AUTOMATIC METHOD

Before the performance test of the improved method is conducted, acoustic emission signals of broken-lead experiments are collected using the AE monitoring system DS5-16C with 3 MHz sampling frequency and RS-15A sensors with the frequency band of 40-150KHz. After connecting the equipment with the rock specimen, the stability of acquisition system is first test by knocking the rock surface. When the acquisition system can stably obtain the acoustic signals with more than 60db amplitude stipulated by the manufacturer of DS5-16C, its stability can be guaranteed. In the process of broken-lead experiments, these sensors are tightly coupled at the surface of the rock specimen by the special coupling agent, which guarantees the accuracy and effectiveness of information acquisition. Meanwhile, the broken-lead experiments are conducted in the laboratory without other vibrations or acoustic sources, which ensures that the collected acoustic signals are related to broken-lead experiments. To obtain acoustic signals with spike noise, the electromagnetic interference equipment is placed near this acquisition equipment during the measurements. When the electromagnetic interference equipment is close to the acquisition mainframe, the unstable electric current of this acquisition device will be produced, resulting in spike noise at equal intervals presented in broken-lead signals, which ensures the effective acquisition of acoustic signals with spike noise. Moreover, the phenomenon of channel crosstalk often occurs in some channels during the signal acquisition due to the hardware drawback of the monitoring system itself. The crosstalk noise has a frequency band similar to the valid signal and the low amplitude arising at the front end of the valid signal. According to the aforementioned characteristic of channel crosstalk, the acoustic signals with crosstalk noise can be selected manually from the collected acoustic emission signals, which ensures the reliability of acoustic signals used in the subsequent performance test of the improved method.

A. WAVEFORM ADAPTABILITY

One way to test the picking performance of the improved automatic method is the waveform adaptability. There are three typical AE signals selected to test the waveform adaptability. The picking results of these three signals by AIC, MF-AIC and the improved automatic methods are shown in Fig. 5. To the normally triggered signal (Fig. 5(a)), the arrival times by AIC, MF-AIC and the improved automatic methods are the 234th, 233th and 233th samples, respectively. Compared to the manual arrival time, the picking results by these three methods all are accurate. For the AE signal with spike noise (Fig. 5(b)), the arrival times by AIC, MF-AIC and the improved automatic methods are the 48th, 157th and 157th samples, respectively. Compared to the manual arrival time, the picking result by AIC method is obviously affected by the spike noise. Meanwhile, the arrival times picked by MF-AIC and the improved automatic methods are still precise. To the early triggered signal (Fig. 5(c)), the arrival times by AIC, MF-AIC and the improved automatic methods are the 160th, 160th and 242th samples, respectively. Compared to the manual arrival time, the picking results by AIC and MF-AIC methods have been influenced severely due to the channel crosstalk. However, the arrival time picked by the improved automatic method still is close to the manual arrival time.

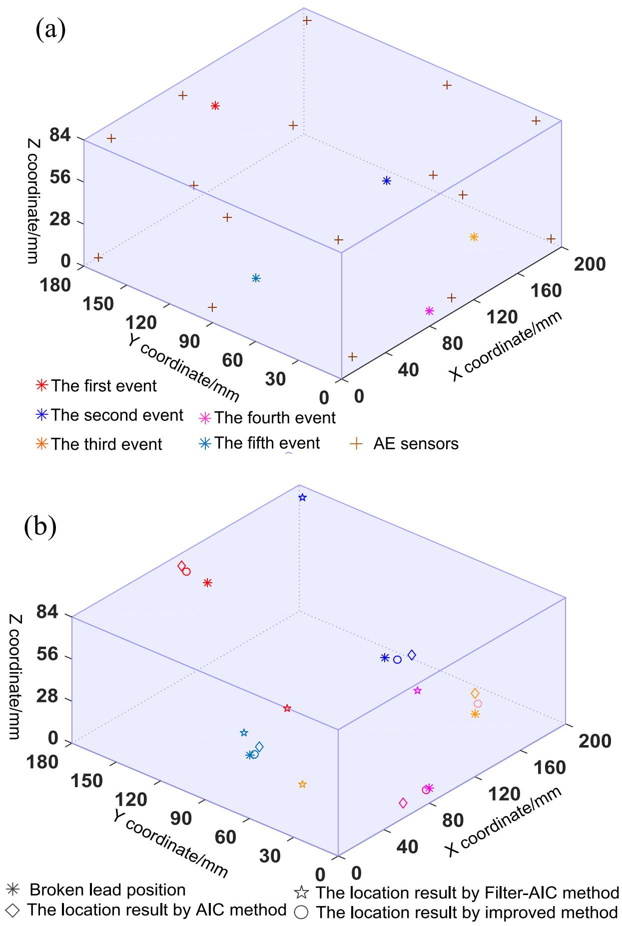

FIGURE 6. **The arrangement of acoustic emission sensors and the location results by three picking methods for arrival time. (a) The arrangement of acoustic emission sensors and the broken lead tests, (b) the location results by different picking methods for arrival time.**

Through the above analysis, the AIC method is easy to be disturbed by the spike and channel crosstalk. Although the MF-AIC method can overcome the spike interference, it is useless to pick the signal interfered by the channel crosstalk accurately. Meanwhile, the improved automatic method proposed in this paper can both pick the arrival times accurately for the signals disturbed by spike and channel crosstalk, which proves that this method has better waveform adaptability and robustness.

B. THE DETAILS OF THE IMPROVED AUTOMATIC METHOD

The accurate arrival time is the fundamental step for event location. Hence, it is necessary to validate the picking performance of the improved automatic method through the event location test. To evaluate the performance of the improved automatic method, five broken-lead tests, monitored by AE machine with sixteen parallel channels, are done on 200 mm × 180 mm × 84 mm white sandstone. The coordinates of five broken-lead points are (80,150,84) mm, (80,30,84) mm, (0,60,42) mm, (120,0,42) mm and (80,0,10) mm, respectively. The arrangement of sixteen

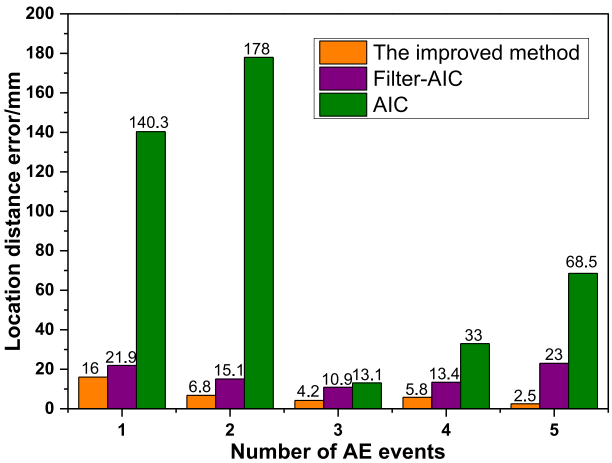

FIGURE 7. The location distance errors of five events based on arrival times picked by three methods.

acoustic emission sensors is shown in Fig. 6(a). At present, the conventional speed and time difference (STD) is still applied most widely at event location. This method is defined as follows:

$$Q(x0, y0, z0) = \min \sum_{i,j=1}^{n} (t_i - t_j - \frac{L_i - L_j}{c})^2 \tag{5}$$

where n is the number of sensors, t_i is the arrival time of i^{th} triggered sensor, t_j is the arrival time of the j^{th} triggered sensor, L_i is the distance between the event location and the i^{th} triggered sensor, L_j is the distance between the event location and the j^{th} triggered sensor, c is the constant propagation velocity, here $c = 5000$ m/s.

The AIC picker, MF-AIC picker and the improved automatic method have been applied to pick arrival times at different sensors for five broken-lead tests. Combined the conventional STD method with above three picking methods, the location results are displayed in Fig. 6(b) and the quantitative distance errors compared to the broken-lead positions are shown in Fig. 7. From Fig. 6(b) and Fig. 7, the location accuracies of five events by AIC picker are all worst among three picking methods. After the AE signals are filtered by the median filter, the location accuracies by MF-AIC picker have been enhanced greatly for these five events, which indicates that spike noises presented in AE signals have been eliminated. When the arrival times are picked by the improved automatic method, the location results are closest to the broken-lead positions. That is because this method not only overcomes the interference of spike noise but also gets rid of the problem that channels are triggered in advance.

IV. CONCLUSION

Based on the median filter and AIC picker, this paper has proposed an improved automatic method to pick the arrival time of acoustic emission events. The improved automatic method is compared to AIC and MF-AIC methods in terms of waveform adaptability and event location. The results demonstrate that the AIC method is easy to be disturbed by spike noise and channel crosstalk. Although the MF-AIC method overcomes the influence of spike noises for arrival times of AE signals, it cannot conquer the barrier of channel crosstalk yet. However, the improved automatic method can identify arrival times of AE signals accurately when signals are interfered by spike noise and channel crosstalk. To further validate the accuracies of arrival times picked by this improved automatic method, the event location for broken-lead test is also conducted. The results indicate that the five location results based on this improved automatic method all are closest to the broken-lead positions among these three picking methods. Through above analysis, the improved automatic method has better performance for picking arrival times of AE signals than AIC and MF-AIC.

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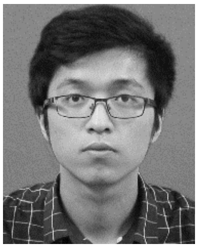

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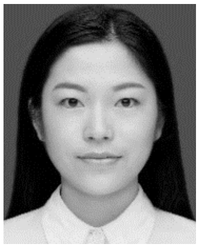

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