The recognition method of thunder based on a noise-estimation algorithm for highly non-stationary environments

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***Abstract*—A recognition method of the thunder signal based on the end-point detection method with a noise-estimation algorithm for highly non-stationary environments is proposed. To determine the parameter of the algorithm and verify the effectiveness and accuracy of the method we analyze the acoustic signals obtained from two microphone arrays installed at the top platform on a seven-floor building in Wuhan. In this paper, we have chosen two acoustic signals to test the endpoint detection method. It is revealed from the recognition result that the method can find out the accurate beginning and ending time of the thunder signal from the acoustic signals.**

Keywords-thunder; the recognition method; end-point detection method; noise-estimation algorithm;

I. Introduction

Thunder is the acoustic radiation associated with lightning. It is divided into two categories: audible thunder that can be heard by humans and infrasonic thunder below the frequency that the human ear can't detect, generally a few tens of hertz [1-2]. Audible thunder is produced by the gas dynamic expansion of various portions of the rapidly heated lightning channel. Therefore, it is possible to reconstruct the geometry of the lightning channel from a detailed analysis of thunder recordings which has been researched over the past few decades [3-5]. The recognition of thunder signals must be a key problem if the technique of this lightning location method will be applied on actually engineering project.

Audible thunder research has mainly focused on understanding the nature of thunder generation mechanisms [6-7], inferring lightning energetics and their correlations with the measured acoustic output and other observations of the lightning channel [8]. In the past few years, some researchers also concentrate on reconstructing of lightning channel geometry by localizing thunder sources in which the distance of the thunder sources calculated from the time difference of arrival between the electrical electromagnetic signal and the thunder signal and the direction of the thunder signal calculated from the time difference of arrival between the thunder signals to different microphones. There is still no specific characteristic about the acoustic wave because the thunder signal is a superposition of multiple pulses from multiple leaders and strokes and also convolves the pulses from the numerous tortuous channel segments and branches. Research results only show that the domain frequency of the observed thunder spectrum is mostly below 1200 Hz which is closely related to the distance of the lightning [9]. Recently, the wavelet analysis method has been utilized to extract spatial distribution characteristics of the wavelet sub bands of thunder [10-11]. However, it hardly settled the question of identification thunder signals. Therefore, the beginning and ending of the thunder signal was always determined manually until now which is labor-intensive and time-consuming, the scientific research on this lightning location method could not be translated into the production system.

In this paper, a recognition method of the thunder signal based on the end-point detection method with a noise-estimation algorithm for highly non-stationary environments is proposed and tested by the acoustic signals from a microphone array which is installed on the roof of a building in Wuhan, China. It is shown that the recognition method can obtain the occurrence time of the thunder signal accurately.

II. Methodology

The original acoustic signal is pre-processed by the low pass filter, the mean removing and normalized algorithm. Then the processed signal will be split into several discrete sequence signals with proper frame. Each frame signal will be transferred into frequency domain signal by Fourier transform which is analyzed by a noise-estimation algorithm to recognize the effective thunder signal.

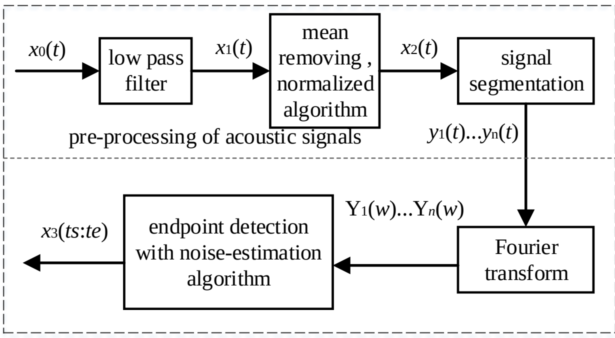

Figure 1. Principle of thunder signal recognition method

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A. The Pre-processing of Acoustic Signals

1) The major energy of thunder should be in the low frequency almost below 2000 Hz. Therefore, a low pass filter with upper cutoff frequency 5000 Hz is utilized to remove the noise signals of high frequency.

2) The mean of the acoustic signal is equivalent to a direct current component which will be removed to prevent the frequency spectrum curve impacted by the spectrum peak of the zero frequency while estimating the signal power spectrum in the following step. The mean of the signal $x(t)$ with length N will be expressed by:

$$\bar{\mu}_x = \frac{1}{N}\sum_{n=0}^{N-1} x_N(n) \tag{1}$$

Then the signals will be normalized to obtain a signal with unified length range and amplitude range for analysis more conveniently.

3) The received signals should be divided into numerous small pieces with the same length N which must comply with certain conditions:

$$N \geq \frac{1}{\Delta f} \tag{2}$$

where Δf represents the frequency resolution of the signal.

B. Endpoint Detection with Noise-estimation Algorithm

The purpose of endpoint detection method is to distinguish the thunder signal and other noise signals in complex application environment for determining the beginning and ending of the thunder signal. Effective endpoint detection method can not only eliminate noise interference but also shorten the processing time of acoustic signals. However, it is very difficult to determine the appropriate endpoint values in more realistic environments where the spectral characteristics of the noise might be changing constantly. Therefore, a noise-estimation algorithm will be proposed for highly non-stationary noise environments in which the noise estimate is updated by averaging the noisy speech power spectrum using time and frequency dependent smoothing factors.

Let the noisy speech signal in the time domain be denoted as:

$$y(n) = x(n) + d(n) \tag{3}$$

where $x(n)$ is the clean speech and $d(n)$ is the additive noise. The smoothed power spectrum of noisy speech is computed using the following first-order recursive equation:

$$P(\lambda,k) = \eta P(\lambda-1,k) + (1-\eta)\left|Y(\lambda,k)\right|^2 \tag{4}$$

where $P(\lambda,k)$ is the smoothed power spectrum, λ is the frame index, k is the frequency index, $|Y(\lambda,k)|^2$ is the short-time power spectrum of noisy speech and η is a smoothing constant. The proposed algorithm is summarized in the flow chart diagram as shown in Fig. 2. Next, we describe each of the individual blocks of the algorithm.

1) A non-linear rule is used in our method for tracking the minimum of the noisy speech by continuously averaging past spectral values [12].

$$\begin{aligned}
&\text{If } P_{min}(\lambda-1,k) < P(\lambda,k) \text{ then} \\
&\quad P_{min}(\lambda,k) = \gamma P_{min}(\lambda-1,k) \\
&\qquad + \frac{1-\gamma}{1-\beta}\left(P(\lambda,k) - \beta P(\lambda-1,k)\right) \\
&\text{else} \\
&\quad P_{min}(\lambda,k) = P(\lambda,k) \\
&\text{end}
\end{aligned} \tag{5}$$

where $P_{min}(\lambda-1,k)$ is the local minimum of the noisy speech power spectrum. The constants β and γ are determined experimentally.

2) Let the ratio of noisy speech power spectrum and its local minimum be defined as:

$$S_r(\lambda,k) = P(\lambda,k) / P_{min}(\lambda,k) \tag{6}$$

This ratio is compared with a frequency dependent threshold, and if the ratio is found to be greater than the threshold, it is taken as a speech-present frequency bin else it is taken as a speech-absent frequency bin. The speech-presence decision can be summarized as follows:

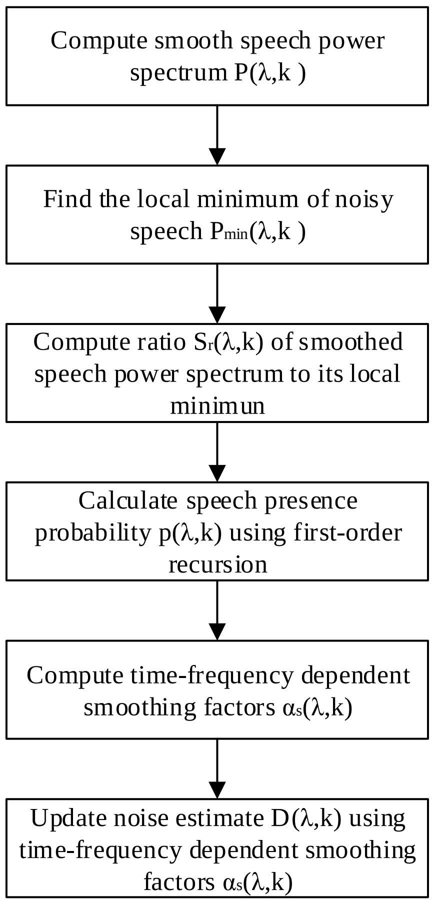

Figure 2. Flow diagram of proposed noise-estimation algorithm

$$
\begin{aligned}
&\text{If } S_r(\lambda,k) > \delta(k) \\
&\quad I(\lambda,k)=1 \quad \text{speech present} \\
&\text{else} \\
&\quad I(\lambda,k)=0 \quad \text{speech absent} \\
&\text{end}
\end{aligned} \tag{7}
$$

where $\delta(k)$ is the frequency-dependent threshold determined experimentally [13]. From the above rule, the speech-presence probability, $p(\lambda,k)$ is updated using the following first-order recursion:

$$p(\lambda,k) = a_p p(\lambda-1,k) + (1-a_p) I(\lambda,k) \tag{8}$$

where a_p is a smoothing constant.

3) Using the above speech-presence probability estimate, we compute the time–frequency dependent smoothing factor as follows:

$$a_s(\lambda,k) = a_d + (1-a_d) p(\lambda,k) \tag{9}$$

where a_d is a constant. Note that $a_s(\lambda,k)$ takes values in the range of $a_d \leqslant a_s(\lambda,k) \leqslant 1$.

4) Finally, after computing the frequency-dependent smoothing factor $a_s(\lambda,k)$ using (7), the noise spectrum estimate is updated as:

$$D(\lambda,k) = a_s(\lambda,k) D(\lambda-1,k) + (1-a_s(\lambda,k)) \left|Y(\lambda,k)\right|^2 \tag{10}$$

where $D(\lambda,k)$ is the estimate of the noise power spectrum. Hence, the overall algorithm can be summarized as follows. After classifying the frequency bins into speech present/absent using (5), we update the speech-presence probability using (6) and then use this probability to update the time–frequency dependent smoothing factor in (7). Then, the noise spectrum estimate is updated according to (8) using the time–frequency dependent smoothing factor. Finally the upper and lower threshold amp1 and amp2 of the endpoint detection method as shown in Fig. 3 will be determined based on the noise spectrum estimate results.

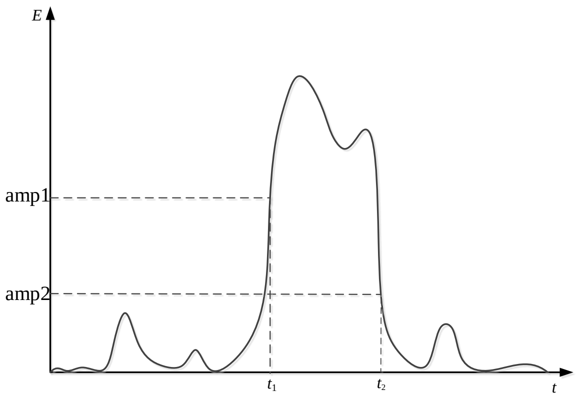

Figure 3. Schematic diagram of the endpoint detection method

III. EXPERIMENTAL RESULTS

During the summer from 2011 to 2015 two microphone arrays were set up at the top platform on a 7-floor building in Wuhan, China to observe the nature lightning and plenty of good experimental audible thunder data was obtained. The microphones had a frequency response of 20 Hz–100 kHz and a dynamic range of > 122 dB which could detect both thunder and electromagnetic signals. The central logger namely NI PXIe-4492 and PXIe-4497 were connected with shielded cable to the microphones, with sampling rate at 50 KS/s and duration of 30 s. In the following section, we chose 2 acoustic signals to test the proposed recognition method.

In order to verify the endpoint detection method, two thunder signals were analyzed in the following section. The first thunder signal was recorded in a thunderstorm on March 22, 2012 as shown in Fig. 4(a) from which we could find out that there were five electromagnetic signals and the thunder signal lasted about 4 second. The distance of the lightning was close to the observation point which was about 850 m estimated by the time delay of the electromagnetic signal and the thunder signal. Therefore, the thunder signal was strong enough to be discovered from the time domain waveform and frequency domain waveform as shown in Fig. 4(a). The power spectrum energy of the acoustic and the noise signal was calculated by the noise-estimation algorithm as shown in Fig. 4(b), and then the beginning and ending time of the thunder signal was obtained by the proposed end-point detection method as shown in Fig. 4(c) which was from 5.17 s to 8.82 s in good agreement with the actual situation what we heard.

Meanwhile, we chose another thunder signal with low signal-to-noise ratio observed on June 19, 2013 in which there was rumbling thunder to verify the accuracy of endpoint monitoring method further. The amplitude of the thunder signal was small as shown in Fig. 5(a) because this lightning might be far away from the microphone array or intro-cloud lightning. It was very difficult to find out the thunder signal according to the time domain waveform and frequency domain waveform. However, the beginning and ending times of the thunder signal could be determined by the noise-estimation results as shown in Fig. 5(b). The detection results were shown in Fig. 5(c) which were also consistent with the situation what we heard.

IV. CONCLUSIONS

This paper provided a recognition method of the thunder signal based on the end-point detection method with a noise-estimation algorithm for highly non-stationary environments. The appropriate parameters in the algorithm were determined by analyzing the acoustic signals from the microphone array. And finally the two thunder signals were analyzed by the proposed method and we obtained the accurate beginning time and ending time of the thunder signal which verified the efficiency and accuracy of the proposed method. Accordingly, this method could provide the arrival time of the thunder signals automatically in real time making the research results on acoustic reconstruction of lighting channels to be applied in practical engineering.

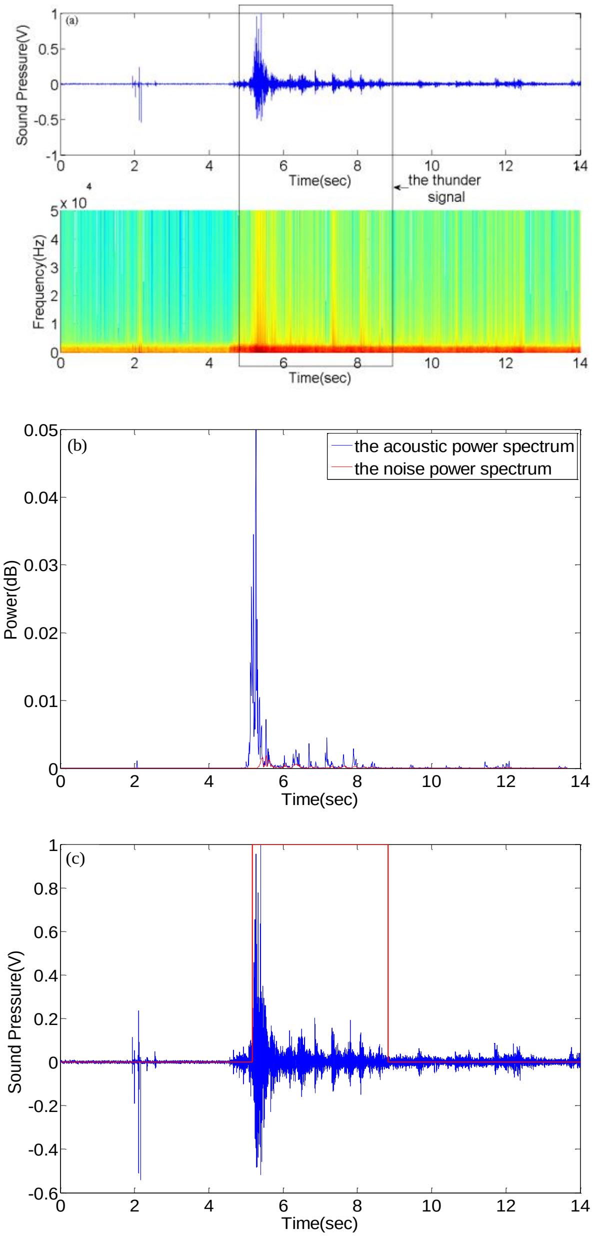

Figure 4. (a) the acoustic signal of the first lightning ; (b) the noise spectrum estimate results of the first acoustic signal; (c) the recognition result of the first lightning

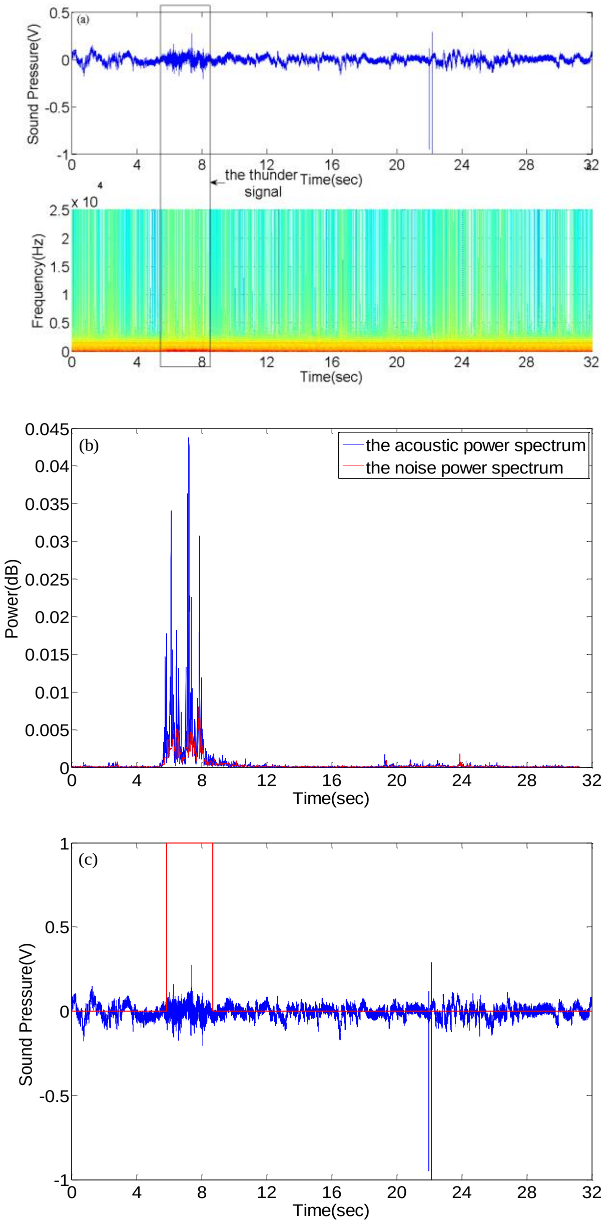

Figure 5. (a) the acoustic signal of the second lightning ; (b) the noise spectrum estimate results of the second acoustic signal; (c) the recognition result of the second lightning

However, some noise signals such as bird, whistle and so on might be mistaken as the thunder signal by the proposed method. Future work will be devoted to optimization of the recognition method by analyzing the energy distribution of kinds of acoustic signals. Meanwhile, we would carry on with accumulating the acoustic data and expanding the thunder and noise database.

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