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Acoustic Source Localization Based on Generalized Cross-correlation Time-delay Estimation

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Abstract

In the existing acoustic emission (AE) localization methods, the estimation localization method based on the time difference of arrival (TDOA) has less computation and higher accuracy of positioning and is easy to implement the real-time systems and thus it becomes a commonly used method in the acoustic source localization methods. In this method, the most important thing is time delay estimation (TDE) that directly affects the accuracy of positioning. In this paper, we analyze the performance of several weighting functions in the generalized cross-correlation time-delay estimation algorithm and give the simulation results. By comparison, PHAT weighting is characterized by small fluctuations, sharp peak and strong anti-jamming ability and it is the best choice for acoustic source localization in the generalized cross-correlation time-delay estimation algorithm.

Keywords: Acoustic emission(AE); Time-Delay Estimation; acoustic source localization

1. Principles of acoustic emission technique

AE is the phenomenon of transient elastic-wave generation due to a rapid release of local energy in a material and it is also known as stress-wave emission [1-3]. AE is a common physical phenomenon. There is AE occurring when most materials undergo deformation and fracture. If the energy released is large

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enough, audible sound will be generated. When most metallic materials undergo plastic deformation and fracture, there is also the phenomenon of AE [4].

AE wave has a wide range of frequency from infrasonic frequency, acoustic frequency until ultrasonic frequency, which may include several Hz to several MHz; from the microscopic dislocation motion to the massive macroscopic fracture, its amplitude changes to a large range and may include several μV to hundreds of mV by the sensor output. Elastic waves emitted by the AE source spread to the surface of the objects under test through the media and cause the surface mechanical vibration. The surface transient displacement is converted into electrical signals by the AE sensor. AE signals are then amplified and processed to form the characteristic parameters that will be recorded and displayed. Finally, the characteristics of the AE source will be assessed through data interpretation.

2. Acoustic source localization algorithm based on TDE

TDE is the first and also most important step in the acoustic source localization algorithm. Subsequently, mathematical methods are used for data processing to estimate the relative time delay of signal arrival to each sensor. Finally, the time-delay estimate is used to calculate the acoustic source location. The location is actually an estimate and there are some errors, but it is permitted in practice. There are many time-delay estimation algorithms, but the generalized cross-correlation function is more widely used in practice and relatively simple. The basic principle of the generalized cross-correlation function is: obtain the cross-power spectrum between two groups of signals, then give different weighted operations in the frequency domain and finally inverse transform to the time domain and obtain the cross-correlation function between the two groups of signals, the corresponding time of the extreme of the cross-correlation function is the time delay between the two groups of signals. See Figure 1 for the flow of the generalized cross-correlation time-delay estimation algorithm.

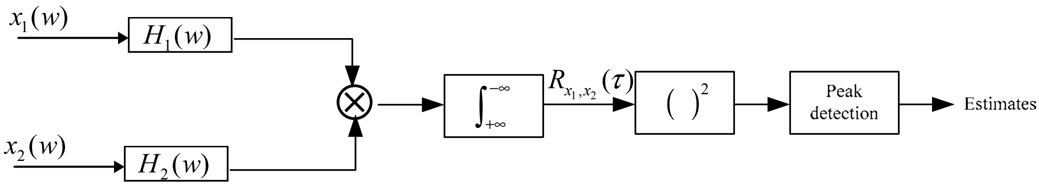

Fig. 1. Flow of generalized cross-correlation time-delay estimation

The two-dimensional localization only needs two independent time-delay estimates with each corresponding to a binary quadratic equation. The coordinates of the sound source can be acquired by solving the equations. So the second step of the time-delay estimation algorithm is some simple mathematical calculations based on the experimental estimates calculated in the first step. In general, the acoustic source localization algorithm based on TDE is superior to other localization algorithms in computation and can achieve low cost in practice.

3. Cross-correlation time-delay estimation

Correlation analysis is the basic method to compare the similarity of time domain between two signals. Assuming the discrete event signal model of the signals received by two microphones is:

$$x_1(n) = s_1(n - \tau_1) + n_1(n) \tag{1}$$

$$x_2(n) = s_2(n - \tau_2) + n_2(n) \tag{2}$$

Wherein, $s(n)$ signifies the sound source signal, $n_1(n)$ and $n_2(n)$ signify uncorrelated Gaussian white noise. $s(n)$ and $n_1(n)$, $s(n)$ and $n_2(n)$ are also uncorrelated. τ_1 and τ_2 are the travel time of acoustic wave transmitted from the sound source to the sensor 1 and sensor 2, and $\tau_{12} = \tau_1 - \tau_2$ is the time delay between the two sensors [5].

The correlation function $R_{12}(\tau)$ of $x_1(n)$ and $x_2(n)$ can be expressed as:

$$R_{12}(\tau) = E[x_1(n)x_2(n-\tau)] \tag{3}$$

Putting the formulas (1) and (2) into the formula (3), we get that:

$$\begin{aligned} R_{12}(\tau) &= E[s(n-\tau_1)s(n-\tau_1-\tau) + E(s(n-\tau_1)n_2(n-\tau))] \\ &+ E(s(n-\tau_2-\tau)n_1(n)) + E[n_1(n)n_2(n-\tau)] \end{aligned} \tag{4}$$

Since $s(n)$, $n_1(n)$ and $n_2(n)$ are uncorrelated, we can get from the above formula:

$$R_{12}(\tau) = E[s(n-\tau_1)s(n-\tau_1-\tau)] = R_s(\tau - (\tau_1 - \tau_2)) \tag{5}$$

The properties of the autocorrelation function show that, when $\tau - (\tau_1 - \tau_2) = 0$, $R_{12}(*)$ is the maximum. Therefore, the corresponding τ of the $R_{12}(\tau)$ maximum value got is the time delay between the two sensors.

We can see from the above calculation that the most important feature of the cross-correlation time-delay estimation is simplicity, but its limitations are obvious. In the above derivation, it is considered by default that there is no correlation between signal and noise as well as between noise and noise [6], but it is not satisfactory in practice. Moreover, the correlation function defined in such a way is the statistical average or the mathematical average substituted by the infinite time average in the stationary ergodic process in the strict mathematical sense. In practice, this strict mathematical average and infinite time average is impossible, and we can only use the finite time average instead of the infinite average and we cannot ignore the impact of noise on the correlation function caused by this short-time approximation. Otherwise, the peak of $R_{12}(\tau)$ will be unobvious and the time-delay estimation accuracy will be reduced. For this reason, the generalized cross-correlation comes into being, which can weaken or eliminate the impact of noise on the time-delay estimation accuracy. See Figure 2 for the block diagram of the generalized cross-correlation time-delay estimation.

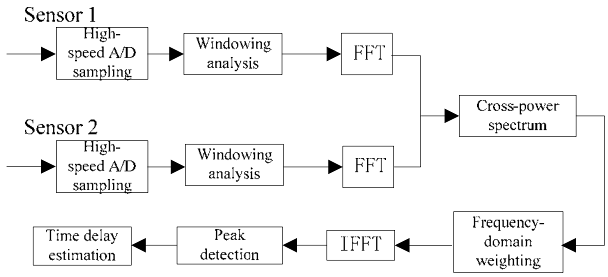

Fig. 2. Block diagram of generalized cross-correlation time-delay estimation

First, the sensors 1 and 2 acquire the voice signals and the A/D converter samples to obtain the AE signals to be processed. A movable finite-length window is used for framing to conduct the Fourier transformation of signals and then get the frame cross-power spectrum of two signals. After frequency-domain weighting to the cross-power spectrum according to a certain weight, the frame cross-correlation function is got through inverse Fourier transformation and the corresponding τ of the peak of the cross-correlation function is found through peak detection, which is the time delay between the two sensors τ_{12}.

From the relationship between the cross-correlation function and cross-power spectrum, we can get:

$$R_{12}(\tau)=\int_0^{\pi} G_{12}(\omega)e^{j\omega\tau}d\omega \tag{6}$$

Wherein, $G_{12}(\omega)$ is the cross-power spectrum of the signals $x_1(n)$ and $x_2(n)$ received by the two sensors.

By first seeking the cross-power spectrum between the two signals and then giving a certain weight in the frequency domain, the generalized cross-correlation method [7-9] conducts whitening processing on the signals and noise so as to enhance frequency components with higher signal to noise ratio in the signals and inhibit the impact of noise, and finally it inverse transforms to the time domain to get the generalized cross-correlation function between the two signals, namely:

$$R_{12}^{g}(\tau)=\int_0^{\pi} \psi_{12}(\omega)G_{12}(\omega)e^{j\omega\tau}d\omega \tag{7}$$

Wherein, $\psi_{12}(\omega)$ signifies generalized cross-correlation weighting function. The selection of generalized cross-correlation weighting function is based on two aspects: noise and reflection condition. The purpose to choose weighting function in the light of specific conditions is to make $R_{12}(\tau)$ have a relatively sharp peak. The $R_{12}(\tau)$ peak is the time delay between the two sensors.

4. Performance analysis of cross-correlation time-delay estimation weighting functions

Because there is some correlation among the signals from the same sound source, we can estimate the TDOA value by calculating the correlation function between the signals received by different microphones [10]. However, in the real environment, due to the impact of noise and reverberation, the maximum peak of the correlation function will be weakened and sometimes there are multiple peaks, which have caused difficulties in the actual peak detection [11]. The GCC method is to weight signals in the power spectral domain to highlight the relevant signal components and suppress the components disturbed by noise so as to make the peak of relevant function at the time delay more prominent. However, due to the presence of reverberation, there are multiple echo components in the signals, so the cross-correlation function calculated will include the peaks formed by the direct wave and reflected wave that will make the time-delay estimation detection difficult under a low SNR. In order to make the time-delay estimation not affected by the characteristics of the signals themselves and to suppress reverberation and noise as much as possible, we need carry out special processing to the spectrum of the signals under observation and choose the weighting function $\psi_{12}(\omega)$. Table 1 lists several commonly used weighting functions, wherein $G_{11}(\omega)$ and $G_{22}(\omega)$ respectively signify the auto-spectral density of the signals received by the sensors 1 and 2 and $G_{12}(\omega)$ signifies the cross-spectral density of the signals received by the sensors 1 and 2.

Table 1. Several commonly used weighting functions

Weighting	Expression	Characteristics
CC	1	Sensitive to external noise and reflection.
ROTH	$\frac{1}{G_{11}(\omega)}$	Equivalent to the Wiener filtering, which can effectively suppress the big-noise band, but will broaden the peak of correlation function.
SCOT	$\frac{1}{(G_{11}(\omega)G_{22}(\omega))^{\frac{1}{2}}}$	Compared o the ROTH weighting, the SCOT weighting considers the impact of the two channels and will broaden the peak of cross-correlation function.
PHAT	$\frac{1}{\lvert G_{12}(\omega)\rvert}$	Denominator tends to zero under small signal energy, so it will increase the error. In some improved methods, it is considered to add a fixed constant in the denominator.

5. Experiment and conclusion

In the experiment of two-dimensional localization, the sound source is generated by a fracture lead and a SR series piezoelectric AE sensor is connected with a digital oscilloscope. The sound source is placed at (0.25, 0.35) and three sensors are respectively arranged at (0.50, 1.00), (0.00, 0.00) and (0.00, 1.00), and the signal propagation velocity measured in the marble slabs is 3483.670m/s. See Figure 3 and 4 for the time domain waveform and spectrum of the signal acquired by the three-channel sensor:

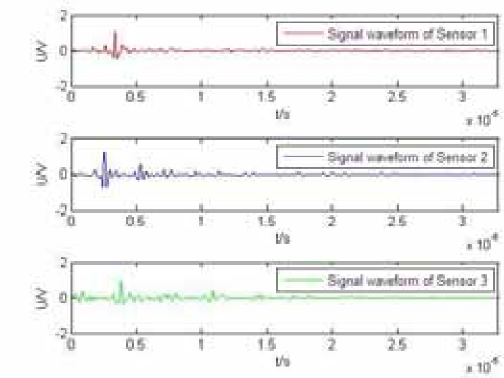

Fig. 3. Three-channel time-domain waveform

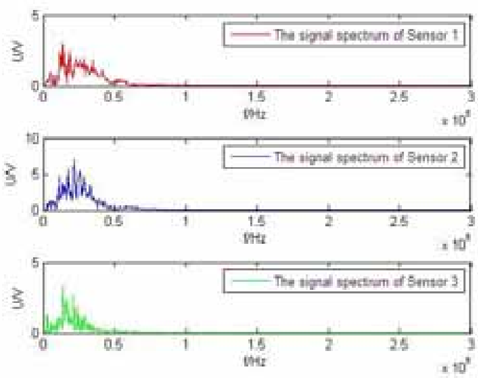

Fig. 4. Three-channel spectrum

Using the MATLAB software to conduct cross-correlation time-delay estimation on the signals acquired by the sensors 1 and 2 and the sensors 1 and 3 with the CC, ROTH, SCOT and PHAT weighting functions respectively, the results are shown in Figure 5.

Figure 5 shows that, for the PHAT weighting, there are the characteristics of small fluctuations, sharp peak and strong anti-jamming ability. The experimental value for time delay estimation of the sensors 1 and 2 is 7.523×10^{-5}S, the experimental value for time delay estimation of the sensors 3 and 2 is 10.686×10^{-5}S, the sound source location coordinates measured in the experiment are (0.2437, 0.3403), the absolute errors of the x-coordinate and y-coordinate are 0.0063m and 0.0097m respectively and the relative errors are: 0.0252 and 0.0277.

In the experiment, a total of 100 groups of experimental data are obtained. By statistics, the points with error of less than 0.2m account for 93% and the points with error of less than 0.1m account for 82%, indicating that the positioning accuracy can fully meet the positioning requirements of mechanical failure source.

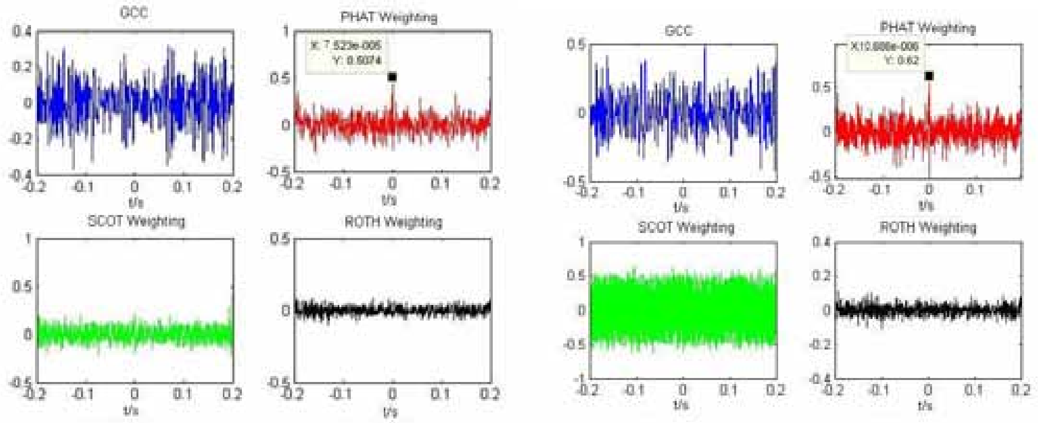

Fig. 5. Comparison of four weighting functions. (a) Comparison of Sensors 1 and 2. (b) Comparison of Sensors 3 and 2

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