STUDY AND MIMICKING THE TIME DELAY MAGNIFICATION OF THE FLY EAR

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The fly Ormia ochracea has an extraordinary localization ability because of a special mechanical coupling between its ears, which enhances differences of the two received signals. We investigate the time delay magnification of the coupling mechanism through the traditional general cross-correlation method. Inspired by the time delay magnification, we design a four-microphone array for sound source localization in 3-D space. It consists of a four-element microphone array and two coupling filters that execute the biologically inspired coupling and magnify the output time delay of microphones. Experimentally we compare localization results for the coupled and un-coupled arrays with the same size demonstrating the advantage of the coupled microphone array on improving the localization ability. The coupled microphone array can be used in various applications where space is limited.
Keywords: microphone array, time delay magnification

1. Introduction

Accurate sound source localization plays an important role in hearing animals facilitating prey, defense, and communication [1, 2]. The main directional cues such as interaural intensity difference (IID) and interaural time difference (ITD) are directly determined by the interaural distance [1, 3, 4]. There may exist a challenge for small animals, especially insects since the differences are extremely small. However, many small animals demonstrate acute sound source localization ability [5-7]. The parasitic fly Ormia ochracea is such an insect.

In order to propagate, the female Ormia must deposit her larvae on a live field cricket, the specific host for the parasite, relying on the cricket's mating call. Although the interaural distance separating the fly's hearing organs (about 500μm) does not match with the wavelength of the 4.8 kHz calling song (about 7 cm), the fly can accurately localize the cricket with a directional resolution of ±2°. Unlike most ears, the fly has a mechanical coupling between its ears. Previous researches show that the coupling mechanism magnifies the small interaural intensity and time differences between the two tympanal responses and subsequently improves the localization accuracy. However, the fly can only pinpoint the source within a certain incident angle range, otherwise the fly can only determine whether the source is on the left or right [8-11].

In this paper, we first investigate the time delay magnification property of the coupled ear through the traditional general cross-correlation (GCC) method. Inspired by the coupled mechanism, we then present a miniature four-microphone array for sound source localization in 3-D space. It consists of a four-element microphone array and two coupling filters. The filter executes the biologically inspired coupling and magnifies the output time delay of microphones. Coupling parameters of the filter can be adjusted easily to the frequency of the sound source to achieve high array performance. Finally, in the experiment, we compare localization results for the coupled and uncoupled arrays with the same size to demonstrate the advantage of the coupled microphone array on improving the localization ability.

2. Time delay magnification of the fly ear

In this section, the mechanical model of the Ormia ochracea's coupled ear used in [8] is described. Then, to investigate the effect of the coupling on time delay magnification, output time delays of the coupled and uncoupled systems are estimated through the GCC method.

2.1 Mechanical model

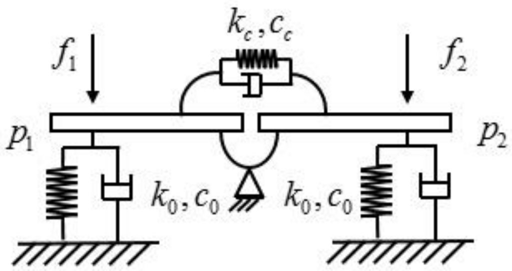

Figure 1: Mechanical model of the coupled ears of the Ormia ochracea [8].

The mechanical model of the Ormia ochracea's coupled ears is shown in Fig. 1. It consists of two spring-mass-damper systems (mass: m, stiffness: k_0, damping: c_0). They are connected at the pivot point through a coupling spring k_c and dash-pot c_c. The mechanical model has two inputs, f_1 and f_2, and two outputs, p_1 and p_2. They respectively represent the forces caused by the sound pressure and the vibration displacements of each tympanal membrane. Since the interaural distance is tiny, the two input signals have the same amplitude and a small time delay. For a pure tone stimulus, they can be assumed as

$$\begin{aligned} f_1 &= F\sin(\omega t + \omega\tau_{in}/2), \\ f_2 &= F\sin(\omega t - \omega\tau_{in}/2), \end{aligned} \tag{1}$$

where F is the amplitude of the force, ω is the sound frequency, and τ_{in} is the time delay between the two input signals. Then, output signals are [8]

$$\begin{aligned} p_1 &= A_2\sin(\omega t + \phi_2) + A_1\cos(\omega t + \phi_1), \\ p_2 &= A_2\sin(\omega t + \phi_2) - A_1\cos(\omega t + \phi_1), \end{aligned} \tag{2}$$

where

$$\begin{aligned} &A_1 = \frac{F\sqrt{2/m}\sin(\omega\tau_{in}/2)}{\sqrt{(\omega_1^2-\omega^2)^2+(2\omega_1\xi_1\omega)^2}}, \quad A_2 = \frac{F\sqrt{2/m}\cos(\omega\tau_{in}/2)}{\sqrt{(\omega_2^2-\omega^2)^2+(2\omega_2\xi_2\omega)^2}}, \\ &\phi_1 = -\arctan(\frac{2\omega_1\xi_1\omega}{\omega_1^2-\omega^2}), \quad \phi_2 = -\arctan(\frac{2\omega_2\xi_2\omega}{\omega_2^2-\omega^2}), \end{aligned} \tag{3}$$

where

$$\begin{aligned} &\omega_1 = \sqrt{k_0/m}, \quad \omega_2 = \sqrt{(k_0+2k_c)/m}, \\ &\xi_1 = c_0/(2\omega_1 m), \quad \xi_2 = \left(c_0+2c_c\right)/(2\omega_2 m). \end{aligned} \tag{4}$$

2.2 GCC time delay estimation

The GCC method is one of the basic methods of time delay estimation. By searching for the maximum of the cross-correlation function, the point where signals are best aligned in time can be achieved. Thus, the output time delay can be obtained.

For two discrete-time signals $p_1(n\Delta)$ and $p_2(n\Delta)$ ($n = 1, 2, \cdots, N$), where Δ is the sampling period, the general cross-correlation function of the two signals can be expressed as

$$R_{12}(\tau)=\int \psi_{12}P_1(\omega)P_2^*(\omega)e^{-j\omega\tau}d\omega, \tag{5}$$

where $P_1(\omega)$ and $P_2(\omega)$ are the Fourier transform of $p_1(n\Delta)$ and $p_2(n\Delta)$, and $\psi_{12}=1$ is the weighted function. By searching for the maximum of the general cross-correlation function, the estimate of output time delay can be obtained as $\hat{\tau}_{out}=D_{out}\Delta$, where D_{out} is the number of sampling periods one signal behind the other. Since the time delay estimation is an integer multiple of the sampling period, the estimation error is on $[-\Delta/2,\Delta/2]$. Note that, $f_1(n\Delta)$ and $f_2(n\Delta)$ are output signals of the un-coupled system.

As the incident angle changes from 0° to 90°, time delay estimations of the coupled and uncoupled systems are shown in Fig. 2. In this case, the sampling period is $\Delta=3.9\times10^{-7}$ s, and the sampling number is $N=819200$. Coupling parameters [4] are shown in Table 1. For the uncoupled system, since the interaural distance is so small, the maximum output time delay is no more than 5 sampling periods. The sampling period has a great effect on the time delay estimation. While for the coupled system, the output time delay is significantly magnified due to the coupling mechanism. The sensitivity of the output time delay to the incident angle (measured from the normal direction) is enhanced. Therefore, the localization accuracy is improved. In Fig. 2, we observe that the sensitivity decreases as the incident angle increases. As to the Ormia ochracea, it can pinpoint the source in a certain range when its head front.

Table 1: Coupling parameters.

Coupling parameter	Data	Unit
Mass m	2.88×10^{-10}	kg
Stiffness k_0	0.576	N/m
Stiffness k_c	5.18	N/m
Damping c_0	1.15×10^{-5}	$N\,s/m$
Damping c_c	2.88×10^{-5}	$N\,s/m$

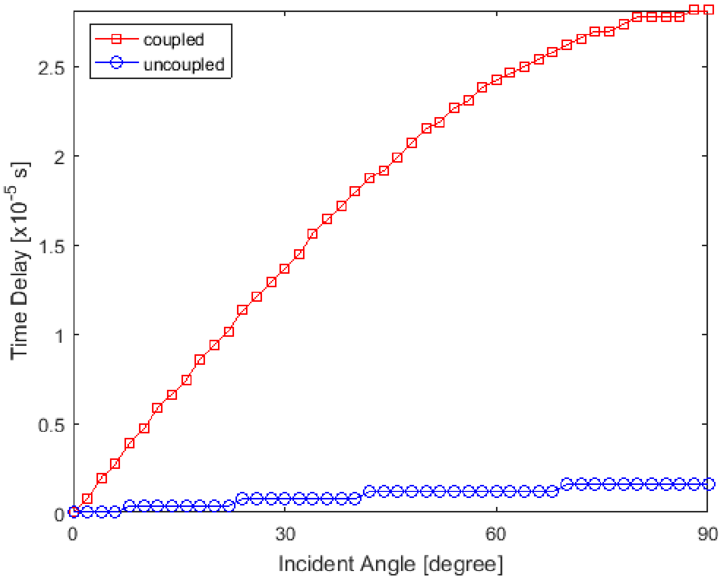

Figure 2: The time delays versus incident angles for the standard and the coupled microphone arrays.

The coupling mechanism is different from the interpolation methods. The coupling enhances the output time delay, which improves its sensitivity to the incident angle. As a result, the localization accuracy is improved.

3. Mimicking the time delay magnification of the fly ear

Inspired by the coupled ear of Ormia ochracea, we design a coupled four-microphone array in this section. The coupled array can magnify the time delay of received signals and locate the sound source in 3-D space.

The four-element biomimetic microphone array we designed is shown in Fig. 3. It consists of a four-microphone array and two two-input two-output filters. The filter implements the biologically inspired coupling and thus magnifies the time delay of outputs of microphones. The filter's outputs can be acquired by solving the differential equations which control the response of the mechanical model shown in Fig. 1.

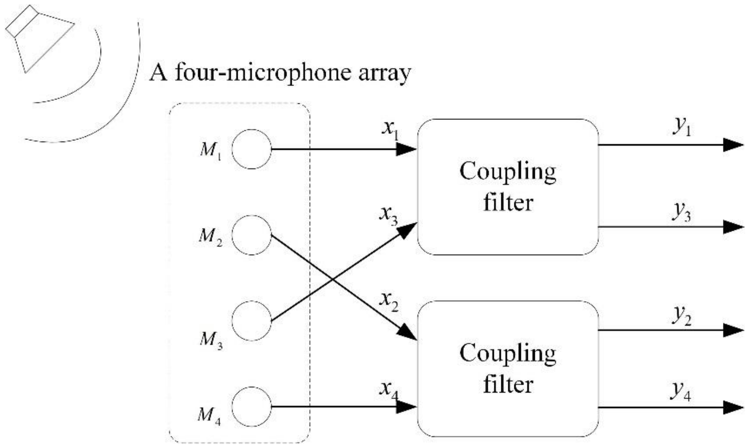

Figure 3: The four-element biomimetic microphone array.

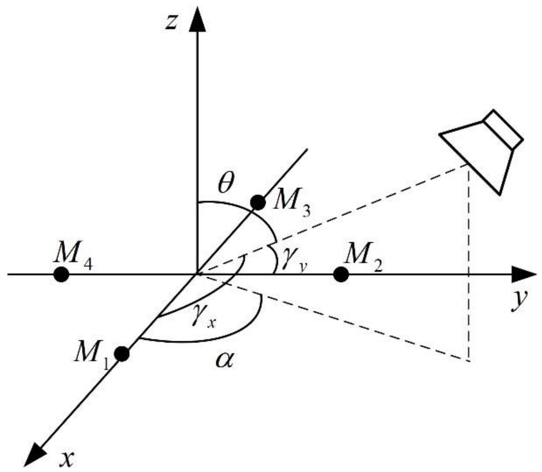

Figure 4: Geometric relationship between the sound source and four-microphone array.

The layout of the four microphones is shown in Fig. 4. A 3-D coordinate system is established with the origin at the centre of the microphone array. Two microphones (M_1 and M_3) are located on the x-axis, and the others (M_2 and M_4) are located on the y-axis. The distance between each microphone and the origin is *d*. The geometric relationship between the sound source and microphones is shown in Fig. 4. For the microphones on the x-axis, the incident angle is $90^\circ - \gamma_x$, where γ_x is the angle between the incident sound and the x-axis. While for the microphones on the y-axis, the incident angle is $90^\circ - \gamma_y$, where γ_y is the angle between the incident sound and the y-axis. By estimating the output time delay of each filter, angles γ_x and γ_y can be obtained through a mapping technique. Thus, the pitch angle θ and azimuth angle α can be calculated as

$$\theta = \arcsin\sqrt{\cos^2\gamma_x + \cos^2\gamma_y},$$
$$\alpha = \arctan\left(\frac{\cos\gamma_y}{\cos\gamma_x}\right). \quad (6)$$

Since the coupling filter enhances the sensitivity between its output time delay and the incident angle (γ_x and γ_y), the 3-D localization accuracy will be improved.

4. Experiment

In this section, we verify the coupled four-microphone array by experimentation. Results of the coupled and uncoupled arrays are compared to demonstrate the effect of the coupling on improving the localization accuracy.

The experiment is completed in the anechoic chamber, and the measurement system is shown in Fig. 5. The receiving array is placed on a support frame which is vertical to the ground. The receiving array consists of four microphones (BSWA MPA416), and the layout of microphones is shown in Fig. 4. The distance between each microphone and the centre is 3 cm. The loudspeaker is placed in the far-field of the receiving array. The loudspeaker and centre of the array are in the same horizontal plane. Different incident angles of the sound source from the loudspeaker can be achieved by rotating two rotators, one is behind the support frame, and the other is under it. The pitch angle is controlled by rotator 1, which is rotated in the range 0° to 90°. The azimuth angle is controlled by rotator 2, which is also rotated in the range 0° to 90°.

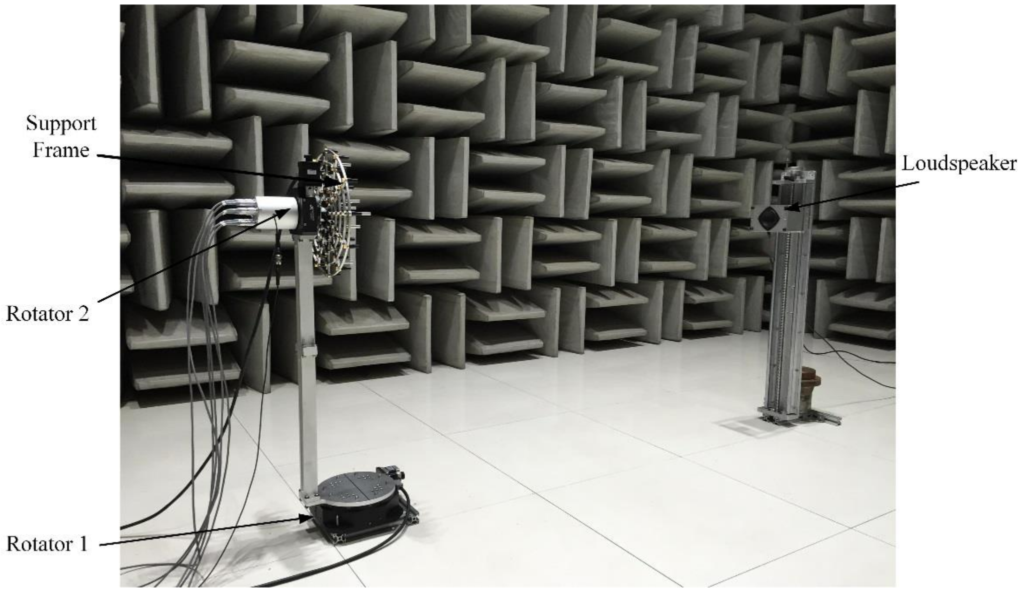

Figure 5: The measurement system in the anechoic chamber.

The loudspeaker is driven by a signal generator. It creates a 500 Hz acoustic signal. The microphones receive the signal and convert them into electrical signals. A data collector collects signals form the four-microphone array with a sampling frequency of 51200 Hz and sampling number of 16384. The data collector output the data to a computer to acquire the time domain response of the coupled microphone array through the Newmark method. The arithmetic is used to implement the biologically inspired coupling as a two-input two-output filter. The four microphones, data collector, and two filters compose the coupled microphone array. For the coupling is realized through an algorithm, the coupling parameters can be adjusted easily according to the frequency of the sound source. The ideal array performance can be achieved by choosing appropriate parameters. As a reference for comparison, the outputs of the data collector which are not being coupled are recorded as outputs of the standard microphone array.

In order to realize localization in 3-D space, we first estimate output time delays of the two filters of the coupled microphone array through the GCC method. Then we obtain the two angles γ_x and γ_y through a mapping technique, in which time delay estimations are compared to a theoretical map of calculated time delays. Finally, the pitch and azimuth angles of the sound source can be obtained through Eq. (6). In this experiment, the coupling parameters are shown in Table 2. The pitch angle is set to 20°, and the azimuth angle changes every 5 degrees in the range 7° to 57°. Localization results are shown in Fig. 6 and Fig. 7. For the pitch angle, experiment results of the coupled and uncoupled cases both agree well with theoretical values. While for the azimuth angle, estimation errors of the standard microphone array are significant at some angles. Due to the effect of the coupling filter, the coupled microphone array shows an improvement in the localization ability as observed from Fig.7. Under the same experimental conditions, the output time delay of the coupling filter is greatly magnified, and the estimation accuracy of angles γ_x and γ_y is enhanced, hence the localization accuracy is significantly improved compared to that of the standard array.

Table 2: Coupling parameters of the coupled four-microphone array.

Coupling parameter	Data	Unit
Mass m	1	kg
Stiffness k_0	5.98×10^7	N/m
Stiffness k_c	9.99×10^7	N/m
Damping c_0	3.87×10^3	$N\,s/m$
Damping c_c	7.74×10^3	$N\,s/m$

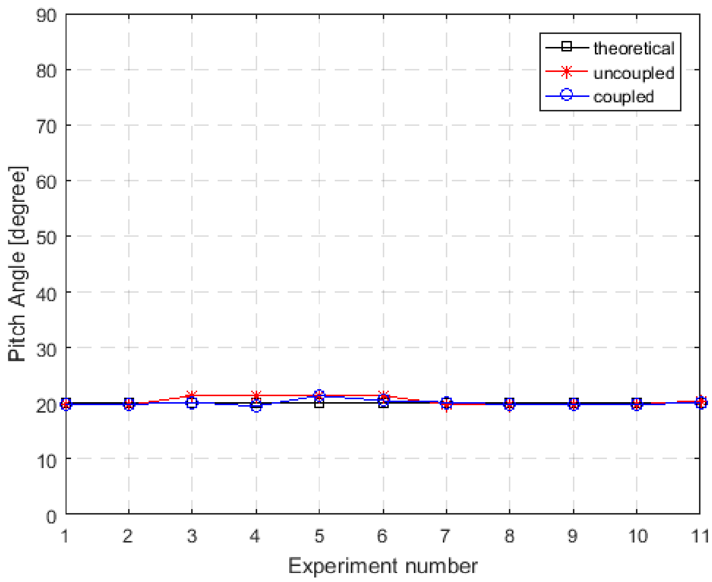

Figure 6: Localization results for the coupled and the uncoupled microphone arrays (pitch angle).

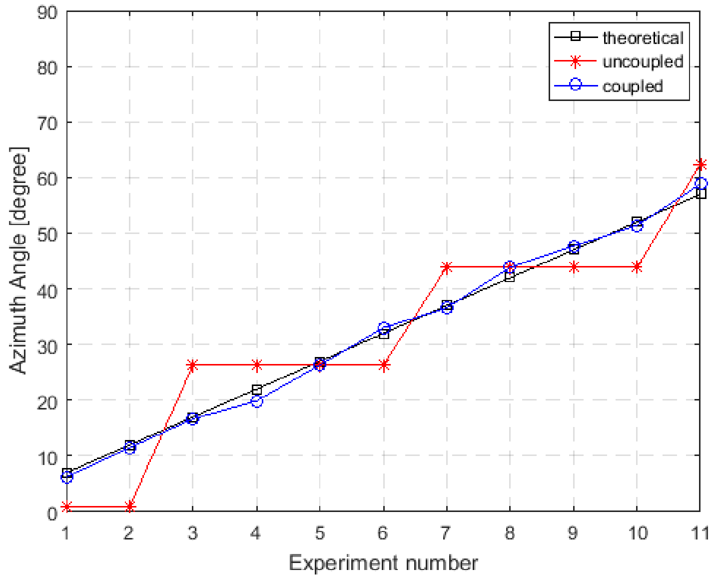

Figure 7: Localization results for the coupled and the uncoupled microphone arrays (azimuth angle).

5. Conclusion

We analyzed the output time delay of the Ormia ochracea' coupled ears through the GCC method. It was demonstrated that the time delay magnification decreases the estimation error of time delays and improves the localization performance of the ear. We designed a coupled four-microphone array that mimic the coupled ears of the Ormia ochracea. The coupling filter implements the biologically inspired coupling and magnifies the output time delay of the microphone array. Based on the coupled four-microphone array, a 3-D localization method is presented. Experimentally we verified the coupled four-microphone array and influence of the coupling filter on improving the localization performance of the array. The biologically inspired coupled array has significant advantages in various applications requiring miniature acoustic arrays such as portable devices. It can also lead to promising solutions with improved performance and reduced size for underwater sound source localization devices.

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