A biomimetic coupled circuit based microphone array for sound source localization

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Abstract: An equivalent analog circuit is designed to mimic the coupled ears of the fly *Ormia ochracea* for sound source localization. This coupled circuit receives two signals with tiny phase difference from a space closed two-microphone array, and produces two signals with obvious intensity difference. The response sensitivity can be adjusted through the coupled circuit parameters. The directional characteristics of the coupled circuit have been demonstrated in the experiment. The miniature microphone array can localize the sound source with low computational burden by using the intensity difference. This system has significant advantages in various applications where the array size is limited.

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1. Introduction

Sound source localization is one of the most important functions of the auditory system in any hearing animals. The main acoustic directional cues available for them are interaural time differences (ITDs) and interaural intensity differences (IIDs). They are generated by the distance between ears and the significant diffractive effect due to the head, respectively. Because larger ITDs and IIDs are available for animals with big body size, they have an inherent advantage over those with a small size.[1] However, the *Ormia ochracea*, for instance, is able to determine the direction of sound source even though the interaural distance is extremely small. Studies have shown that this remarkable ability owes to its special auditory structure. Unlike the isolated ears of large animals, the fly is revealed that its ears are coupled by a flexible cuticular lever. This structure makes both ITDs and IIDs available for the *Ormia ochracea* fly.[2]

The *Ormia ochracea*'s auditory system has inspired the design of the microphone array. Traditionally, a microphone array consists of at least two individual probes and the ITD is the only available directional cue which is proportional to the distance of them. As a result, it has to keep enough separation to ensure reliable measurement of phase information. Besides, the time-difference of arrival estimation techniques based on cross-correlation of the signals require high oversampling ratios for estimating small time delays.[3] However, the *Ormia ochracea*'s coupled ears give a biological solution to miniaturize the traditional microphone array. A number of researchers have reported the construction of transducers based on microelectromechanical systems (MEMS) guided by a two-degree-of-freedom model. For example, Miles *et al.* describe a low-noise differential microphone using IID response of the coupled ears. Their experiment shows that it is much quieter than the uncoupled microphone with the same separation.[4,5] Liu *et al.* investigated the ITD response and introduced a method to optimize its performance.[6] Kuntzman and Hall introduced a rotational capacitive micromachined ultrasonic transducer.[7] Besides, the theory of a coupled system has been well applied in the field of antenna array. Inspired by the directional hearing in small animals, an electrically small antenna array is designed using the ITD response.[8] Akcakaya *et al.* implemented a multi-input/multi-output filter

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on a uniform linear antenna array output inspired by the biological coupling. They show that the model of coupled ears greatly improves the localization performance by an analysis of the Cramér-Rao lower bound.[9]

In this letter, we employ the mechanical principles of the coupled ears on the analog circuit in a miniature two-microphone array. The equivalent circuit of the coupled ears is exploited to detect the tiny difference of two signal outputs from the array. The outputs of the circuit have an intensity difference which serves as a directional cue for sound source localization. Besides, the monotonic intensity difference response is optimized to get the best sensitivity to the incident angle of sound. The utilization of the coupled circuit can reduce the computational burden in the miniature microphone array.

2. The coupled circuit

The two-microphone array we have designed is shown in Fig. 1(a). The coupled circuit in Fig. 1(a) acts as a two-input and two-output system. It takes signals from a space closed two-microphone array as its inputs. The two microphones are separated by a distance of d which is far smaller than the wavelength of objective sound. When the sound wave is incident at some angle relative to the microphones' longitudinal axis, the output signals of microphones will have a very small phase difference and almost equal amplitude due to the short distance. If the incident angle is θ, the phase difference of the outputs is $\varphi = (2\pi d/\lambda)\sin(\theta)$, where λ is the wavelength of incident sound and $d \ll \lambda$. Therefore, the two output signals can be assumed as $u_1 = Ae^{i\varphi/2}$ and $u_2 = Ae^{-i\varphi/2}$, where A is amplitude, u_1 comes from the microphone close to the sound source, and u_2 comes from the other one. These voltage signals are then output to the coupled circuit. The circuit responds to their phase difference and its two outputs have a greatly enhanced phase difference and intensity difference which is also unique for each θ. In our design, the intensity difference is chosen as the directional cue for investigation.

The coupled circuit in Fig. 1(a) is an equivalent analog circuit of a mechanical coupled system, the detail of which is shown in Fig. 1(b). It contains independent voltage sources u_1 and u_2 and impedances Z and Z_c. Here, u_1 and u_2 represent the voltage signals from the microphones as mentioned above. Z is the impendence of a RLC series resonant circuit. The circuits are coupled by Z_c which is the impendence of the series of a capacitor C_c and a damping R_c. Then, we have

$$Z = R + j\omega L + \frac{1}{j\omega C},\ Z_c = R_c + \frac{1}{j\omega C_c}\,. \tag{1}$$

In this circuit, u_1 and u_2 act on each other after being filtered by the impedances Z and Z_c. The outputs of the coupled circuit are the mesh currents labeled as i_1 and i_2.

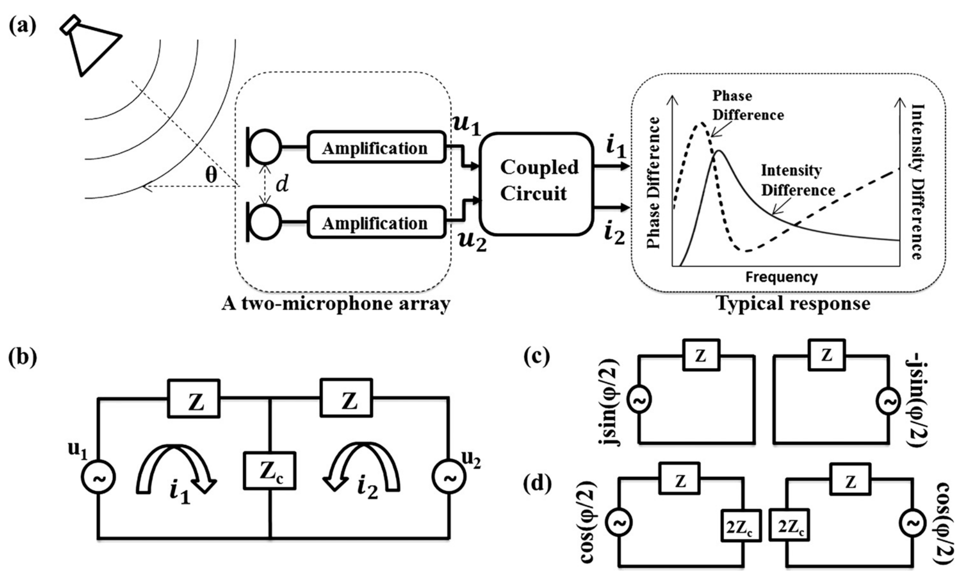

Fig. 1. (a) Schematic of the coupled circuit based two-microphone array and its typical response as directional cues. The response includes the intensity difference and the enhanced phase difference which strongly depend on the sound incident angle θ, and (b) the equivalent coupled circuit of the ears of *Ormia ochracea*. It consists of two natural modes: the differential mode and the common mode; (c) the circuit of differential mode; (d) the circuit of common mode.

For our later analysis, it is convenient to take the clockwise of i_1 and the counterclockwise of i_2 as their positive direction. Then, i_1 and i_2 can be solved by the well-known method of network analysis[10]

$$i_1 = A\frac{u_1(Z+Z_c)-u_2Z_c}{Z(Z+2Z_c)}\,,\ i_2 = A\frac{u_2(Z+Z_c)-u_1Z_c}{Z(Z+2Z_c)}\,. \tag{2}$$

They have two maxima. One at the frequency for which Z is a minimum and the other one at the frequency for which $(Z+2Z_c)$ is a minimum. These correspond to two resonant modes: the first-order mode and the second-order mode, respectively. For a closer analysis, the rational function above can be further expanded into partial fractions. Then, the current response i_1 and i_2 can be written as following after Eq. (1) substituting into the partial fractions of Eq. (2):

$$i_1 = \frac{A\cos\left(\frac{\varphi}{2}\right)}{(R+2R_c)+j\omega L\left(1-\frac{{\omega_c}^2}{\omega^2}\right)} + j\frac{A\sin\left(\frac{\varphi}{2}\right)}{R+j\omega L\left(1-\frac{{\omega_d}^2}{\omega^2}\right)},$$

$$i_2 = \frac{A\cos\left(\frac{\varphi}{2}\right)}{(R+2R_c)+j\omega L\left(1-\frac{{\omega_c}^2}{\omega^2}\right)} - j\frac{A\sin\left(\frac{\varphi}{2}\right)}{R+j\omega L\left(1-\frac{{\omega_d}^2}{\omega^2}\right)}\,, \tag{3}$$

where

$$\omega_d = \sqrt{\frac{1}{LC}},\quad \omega_c = \sqrt{\frac{2C+C_c}{LCC_c}}. \tag{4}$$

In this equation, ω_d and ω_c are natural frequencies corresponding to the two resonant modes in the coupled circuit.

From Eq. (3), we can see that the response i_1 and i_2 are the sum and difference of two damped resonators, respectively. Actually, the coupled circuit shown in Fig. 1(b) can be decomposed into the resonant circuits shown in Figs. 1(c) and 1(d). For the first mode corresponding to the natural frequency ω_d which is shown in Fig. 1(c), i_1 and i_2 have the same amplitude but opposite directions. It responds only to the difference of the input signals and is usually described as "differential" mode. For the second mode corresponding to natural frequency ω_c, shown in Fig. 1(d), i_1 and i_2 have the same phase and amplitude. It responds only to the sum of the input signals and is usually described as "common" mode.[2] Each mode will gradually dominate the response as ω approaches to its own natural frequency. Then, the current response is the combination of these two modes. At certain frequencies and angles, the amplitude of current in the side close to sound source will be the add of the two mode's amplitude, but the amplitude of the other side will be canceled because the direction of two modes' current is opposite. Hence, the coupled circuit has intensity difference response which is sensitive to the input phase difference.

3. Parametric study

The intensity difference of the outputs of the coupled circuit is a function of frequency ω and input phase difference φ. It can be defined in a logarithmic scale

$$20\log_{10}\left|\frac{i_1}{i_2}\right|. \tag{5}$$

After substituting Eq. (3) directly into Eq. (5), the response of the coupled system can be obtained, which has been demonstrated in previous research.[11] It shows that the intensity difference response depends on the parameters of the coupled system in a rather complicated way. Therefore, we further explore how these parameters influence the property of it.

The intensity difference response has been revealed in a mechanical model to be caused by the combination of the two modes, which makes the amplitudes add on the side close to the source and cancel on the other side.[12] The proportion of the two modes in the response could be used to determine the intensity difference response of the coupled circuit. We assume

$$a = \frac{\cos\left(\frac{\varphi}{2}\right)}{(R + 2R_c) + j\omega L\left(1 - \frac{{\omega_c}^2}{\omega^2}\right)}, \; b = j\frac{\sin\left(\frac{\varphi}{2}\right)}{R + j\omega L\left(1 - \frac{{\omega_d}^2}{\omega^2}\right)}, \tag{6}$$

where a represents the common mode shown in Fig. 1(d) and b represents the differential mode shown in Fig. 1(c), respectively.

The intensity difference is determined by the ratio of i_1 and i_2. The complex variable i_1/i_2 can be mapped onto b/a through a bilinear transformation

$$\frac{i_1/i_2 - 1}{i_1/i_2 + 1} = \frac{b}{a}. \tag{7}$$

When $|i_1/i_2| = 1$, there only exists the common mode. For this mode, the response has the same amplitude and phase, which means that $i_1/i_2 = 1 + j0$. So this point is mapped onto $|b/a| = 0$. If $|i_1/i_2|$ intends to infinity, it can be proved mathematically that $|b/a|$ intends to 1. In this case, the two modes equally contribute to the response, and the current of coupled circuit will experience a maximized cancellation in the side far from the sound source. Hence, $|i_1/i_2|$ with the range from 1 to infinity is mapped onto $|b/a|$ with the range from 0 to 1. In this range, $|b/a|$ increases with the increasing of $|i_1/i_2|$ monotonically. In fact, $|i_1/i_2|$ will reach finite maximum due to damping. If $|i_1/i_2|$ reaches its maximum, the incident wave angle may continue to increase which leads to the decrease of $|i_1/i_2|$. In this case, $|b/a| > 1$. As a consequence, $|b/a| \le 1$ guarantees the monotonic response of the intensity difference.

From the above analysis, the ratio of $|b|$ and $|a|$ is closely related with $|i_1/i_2|$ and can be employed to determine the property of the intensity difference response. It can be written as

$$\left|\frac{b}{a}\right| = \tan\left(\frac{\varphi}{2}\right)|G(\omega)|, \tag{8}$$

where

$$|G(\omega)| = \left|\frac{(R + 2R_c) + j\omega L\left(1 - \frac{{\omega_c}^2}{\omega^2}\right)}{R + j\omega L\left(1 - \frac{{\omega_d}^2}{\omega^2}\right)}\right|, \tag{9}$$

and $|G(\omega)|$ can be seen as a gain factor to the input phase difference which determines the sensitivity of the intensity difference $|i_1/i_2|$ to input phase difference φ.

There is a two-fold importance for using $|b/a|$ to determine the intensity difference. First, it helps to investigate the effects of input phase difference φ and frequency ω as single variable functions, separately. Hence, $|G(\omega)|$ can be seen as a frequency-dependent amplification coefficient to φ. In the precondition of $|b/a| \le 1$, the larger $|G(\omega)|$ means that the intensity difference is more sensitive to the incident wave angle. $|G(\omega)|$ is the key to design coupled circuit if the distance between microphones has been fixed. Second, compared with the expression of $|i_1/i_2|$, $|G(\omega)|$ is much simpler and the influence of parameters is more instructional. The purpose is clear that we need $|G(\omega)|$ that is larger but its peak value should not result in $|b/a| > 1$ to ensure the best sensitivity for monotonic intensity difference response. As a consequence, the maximum value that $|b/a|$ can reach should be larger but less than 1.

From Eq. (9), we can see that it has a maximum at the frequency ω_d. In the best-case scenario (sound source location is 90°), the value of $|b/a|$ reaches its maximum at ω_d. This can be written as

$$m = \left|\frac{b}{a}\right|_{\substack{\theta = 90^\circ \\ \omega = \omega_d}} = \tan\left(\frac{\pi d}{\lambda}\right)\left|1 + \frac{2R_c}{R} - j\frac{2}{RC_c\omega_d}\right|, \tag{10}$$

where m is the value of $|b/a|$ at ω_d. When this value is close to 1, the intensity difference response is optimal. Therefore, we can design the coupled circuit under the guidance of Eq. (10). In practice, the working frequency of the coupled system is near ω_d. So ω_d is determined by the characteristic frequency of sound source and it usually has been fixed first. The remaining parameters we can adjust freely are R, R_c, and C_c. In Fig. 2, for example, three designs with different m values by adjusting C_c are shown. The dashed line illustrates that $m = 1.29 > 1$. In this case, the intensity difference response to incident angle θ at most sensitive frequency is non-monotonic, which

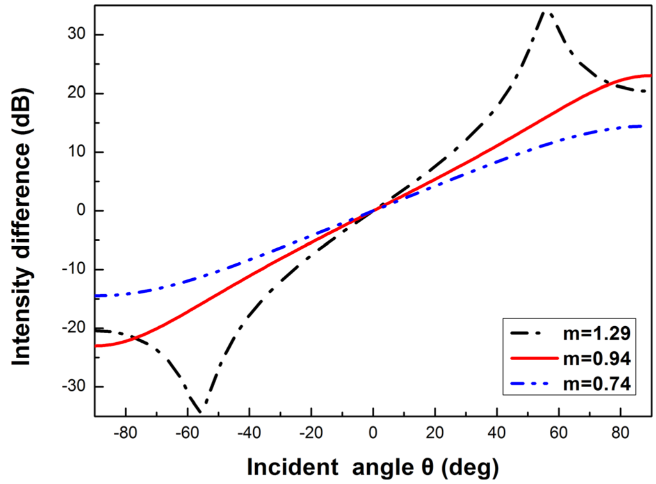

Fig. 2. (Color online) The intensity difference response relative to incident angle of sound for three values of m. It shows that the solid (red) line response is better than the other two.

should be avoided. The dashed-dotted line shows that the intensity difference is monotonic when $m = 0.74$. But its sensitivity can be further improved. The solid line represents the optimal response because it is monotonic and more sensitive than the former. In this case, $m = 0.94$ and it is closer to 1.

4. Experiment

The experiment schematic is shown in Fig. 1(a). Two electret microphones with a distance of 7 mm are used as a two-microphone array. The two output signals with phase difference generated due to the incident azimuth θ are output to the coupled circuit after amplification. Besides, we use two transformers to transform the coupled circuit's current outputs to voltage outputs. Both microphones and transformers work well at the frequency with the range from 20 Hz to 20 kHz. The voltage outputs of the coupled circuit are collected for power spectrum analysis. The intensity difference is achieved by subtraction of the power spectrum of the two signals in a logarithmic scale. The parameters of the coupled circuit are: $L = 500\,\text{mH}$; $C = 21\,\text{nF}$; $Cc = 3.3\,\text{nF}$; $R = 7000\,\Omega$; $R_c = 4500\,\Omega$. The inductances are completely offered by the transformers in the coupled circuit. The natural frequencies are $f_d = 1.6\ \text{kHz}$, $f_c = 5.8\ \text{kHz}$, respectively. The value of m is 0.92 which is optimal as discussed above. It is worth mentioning that the value of m is 0.95 for the *Ormia ochracea* fly which is calculated based on the given parameters.[2]

We test the performance of the coupled microphone array with respect to frequency and wave incident angle. In frequency domain, sound source is placed on 40° to microphone array and the frequency response is shown in Fig. 3(a). We can see that the intensity difference reaches its peak at 1.6 kHz which corresponds to f_d. This response is very sensitive to the incident angle around the natural frequency. Then, we test the response at 2 kHz with the change of θ. The changing of θ is realized by turning the two-microphone array from 0° to 90°. The result is shown in Fig. 3(b). The

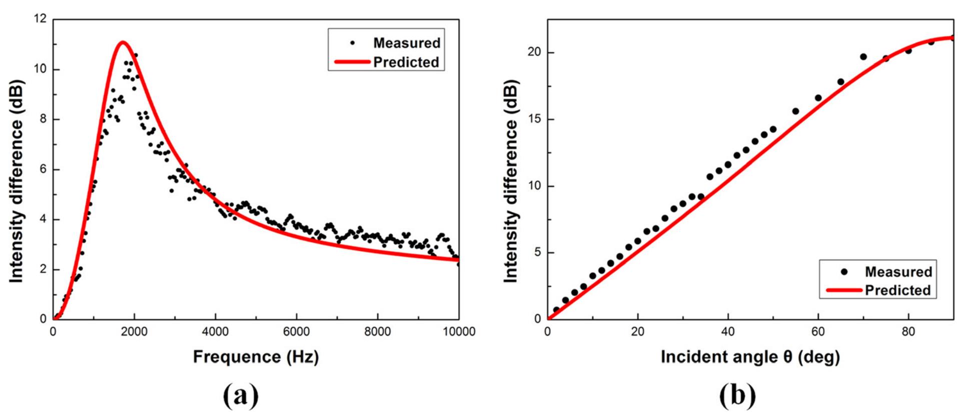

Fig. 3. (Color online) Measured (black dots) and predicted (red solid line) intensity difference response of the coupled circuit based microphone array. (a) The frequency response for $\theta = 40°$; (b) the response relative to the incident angle at 2 kHz. The experiment data was calibrated by the response at 0° angle.

array produces the phase difference within the range of 0°–13° for coupled circuit, which causes an intensity difference response with the range of nearly 0–20 dB. It indicates that the response has remarkable linear sensitivity within a wide angle range.

5. Conclusion

In conclusion, we have designed a miniature two-microphone array based on the coupled circuit for sound source localization. This is inspired by the ears of the fly *Ormia ochracea* which has impressive ability of directional hearing. The coupled circuit in the array is considered to detect two signals with tiny phase difference output from microphones. The response of the circuit demonstrates an intensity difference, which depends sensitively on the incident angle of sound. Under the precondition of monotonic response, the circuit can be optimized to get maximum sensitivity to the incident angle. The directional characteristics have been demonstrated in the experiment. The system works well within a wide angle range around the natural frequency. The coupling miniaturizes the size of the traditional array and makes the intensity difference available as a directional cue for microphone array using only time difference. This biomimetic system could be useful for various size-limited applications such as portable devices and micro-air-vehicles. It is also promising for underwater sound-source localization in which the size of the array is larger because of the higher acoustic speed in water.

Acknowledgments

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