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SOUND SOURCE LOCALIZATION WITH BIO-MIMICKING PARASITOID FLY

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Abstract

Parasitoid fly (Diptera: Tachinidae: Orminii) demonstrate a remarkable ability to detect the direction of an incident sound stimulus by means of its uniquely structured acoustic sensory organs. In this paper, based on the auditory mechanism of the fly, a nonlinear model that can determine the incident direction of the sound is established. The analytical results are testified by experiments. Directional hearing mechanism of the model as well as effects of mechanical parameters is discussed.

1. INTRODUCTION

For most animals, when they determine the incident direction of sound, it is necessary that both ears can be excited by the pressure source and is ability to detect these minute differences of distance and time. In relatively large animals where the distance between the ears is substantial relative to the wavelength, interaural time and intensity differences are large to be detectable by the central nervous system. In small animals the interaural differences in intensity and arrival time are very small. Cade et al [1-3] found that parasitoid fly in tribe *Orminii* employ an interaural mechanism that can increase the effective interaural difference and time difference. The ears of the parasitoid fly have an intertympanal bridge that can cause the mechanical coupling between the two ears [4-7]. The coupling makes the mechanical response to be sensitive to the difference in the sound field acting on the two eardrums. Neural system of the fly can calculate pressure differences between the two ears and send massage to muscle. The calculated time is 50ms. It is 1000 times faster than that of human beings.

Miles et al present a linear model based on the coupling mechanism [4]. The analytic model supports the claim that mechanical interaural coupling is very important to the fly's ability to localize sound sources. In the model, the two beams are considered as stiff ones. But Robert et al [8] find that the intertympanal bridge is flexible. To test these predictions, one side of the intertympanal bridge is set into vibration and the mechanical displacement of the bridge is measured by laser vibrometry. These experiments show that both sides of the ears can be detected to oscillate at different amplitudes and with a phase difference other than 180 degrees. The experiments approve the predictions. They also present a hypothesis that a pressure-difference receiver system is at work in the auditory system of the fly. In fact, the pressure-difference receiver system plays an important role in cicada which alsohave tympanal membrane [9-11]. In the hypothesis,the air behind the tympanal experiences compression and rarefaction as sound pressure sets the tympanal system in vibration and sound is transmitted through it. In such circumstances the air space backing the tympanal membranes is both small and stiff enough to act as a spring. He supposes that the spring contribute to the directional response. It is therefore conceivable that this air space could play a role in intertympanal coupling. To test this hypothesis, some experiments are set. The results show that there exists pressure-difference receiver system. Directional orientation, however, are not through the system.

With mimicking the fly's key structures, Nobutaka Ono [12] proposes a micro sound source localization sensor named gimbal diaphragm. When the center region is fixed, the diaphragm has three vibration modes. When a moment works, torsions of narrow inner and outer beams permit the diaphragm region to incline to any direction and the both ends of diaphragm vibrates the opposite direction. While a sound pressure works, the ring is deformed and all ends of the diaphragm vibrate the same direction. The experiments test that the gimbal diaphragm is sensitive to micro sound part and can localize the direction of the sound. But error exists from the contrast of theoretical results to the experiments.

Because the intertympanal bridge is an important structure in the acoustic system of the parasitoid fly, most studies of mechanical characteristics are focused on the structure. But membrane are important feature of the fly besides the intertympanal bridge. These structure are also characters different from other atympanate tachinids. The influence of the structures, however, have not considered into the model. Whether the structure play important roles are the subject needed to investigate. This paper proposes a nonlinear model that consider nonlinear of effects of the membrane. The model is testified by experiments which are from the work of Mlies et al [4].

2. MECHANICAL MODEL

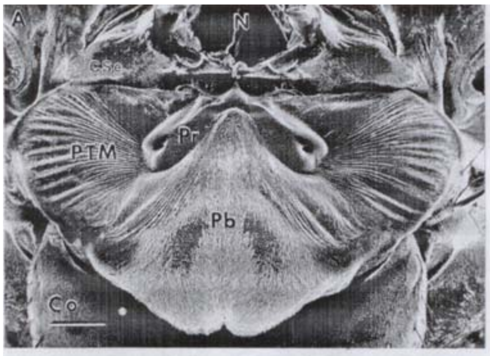


Figure 1. The anatomy of the auditory system of the fly. The picture is taken from ref. [6]. Abbreviations: prosternal tympanal membrane (PTM); probasisternum(Pb); presternum; prothoracic coxa(Co); neck(N).

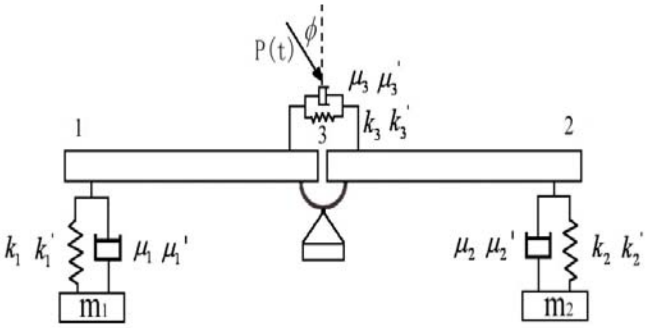


Figure 2. Mechanism of source sound localization. Intertympanal bridges increase the effective interaural difference through the mechanical coupling. The differences of vibrations are transferred to auditory nerve through bulbae acusticae.

A nonlinear dynamic model is established as in equation (1). In this model, the intertympanal bridge is assumed to consist of two rigid beams connected at the pivot. The mass of the

tympanal membranes, intertympanal bridge, bulbae acusticae and sensory organs are considered as two concentrative masses m_1 and m_2. The stiffness of location 1 and 2 are assumed as nonlinear by considering effects of tympanal membrane.
The equations of the model are

$$\begin{aligned} m_1\ddot{x}_1 + (k_1+k_3)x_1 + k_3x_2 + (\mu_1+\mu_3)\dot{x}_1 + \mu_3\dot{x}_2 + k'_1 x_1^2 &= f_1(t) \\ m_2\ddot{x}_2 + k_3x_1 + (k_2+k_3)x_2 + \mu_3\dot{x}_1 + (\mu_2+\mu_3)\dot{x}_2 + k_2' x_2^2 &= f_2(t) \end{aligned} \tag{1}$$

where the subscript 1 and 2 represent the left and right part of the ear. Subscript 3 denotes location of pivot. *k* and *k*' are linear and stiffness. μ and μ' are linear and nonlinear damping.

$$f_1(t) = F\sin(\omega t + \frac{\omega\tau}{2}), \qquad f_2(t) = F\sin(\omega t - \frac{\omega\tau}{2}) \tag{2}$$

where τ is the time delay in the arrival times of the sound wave. When the sound wave is inclined at a 45^0 angle to the fly's longitudinal axis, the time delay is approximately equal to $2.5\mu s$ [4].

In order to calculating transfer function of the equations (1), the equations must be converted to the following forms.

$$\begin{cases} \dot{x}_1 = x_3 \\ \dot{x}_2 = x_4 \\ \dot{x}_3 = -a_1x_1 - a_2x_2 - b_1x_3 - b_2x_4 - a_{11}x_1^3 - a_{12}x_2^3 - b_{11}x_3^2 - b_{12}x_4^2 + f_1/m_1 \\ \dot{x}_4 = -c_1x_1 - c_2x_2 - d_1x_3 - d_2x_4 - a_{21}x_1^3 - a_{22}x_2^3 - d_{11}x_3^2 - d_{12}x_4^2 + f_2/m_2 \end{cases} \tag{3}$$

where

$$a_1 = \frac{k_1+k_3}{m_1} \quad a_2 = \frac{k_3}{m_1} \quad b_1 = \frac{\mu_1+\mu_3}{m_1} \quad b_2 = \frac{\mu_3}{m_1} \quad c_1 = \frac{k_3}{m_2} \quad c_2 = \frac{k_2+k_3}{m_2} \quad b_1 = \frac{\mu_3}{m_2}$$

$$b_2 = \frac{\mu_2+\mu_3}{m_2} \quad a_{11} = \frac{k_1'+k_3'}{m_1} \quad a_{12} = \frac{k_3'}{m_1} \quad a_{21} = \frac{k_3'}{m_2} \quad a_{11} = \frac{k_1'+k_3'}{m_1} \quad a_{11} = \frac{k_1'+k_3'}{m_1} \quad a_{12} = \frac{k_3'}{m_1}$$

$$a_{21} = \frac{k_3'}{m_2} \quad a_{22} = \frac{k_2'+k_3'}{m_2} \quad b_{11} = \frac{\mu_1'+\mu_3'}{m_1} \quad b_{12} = \frac{\mu_3'}{m_1} \quad d_{11} = \frac{\mu_3'}{m_2} \quad d_{12} = \frac{\mu_2'+\mu_3'}{m_2}$$

Substituting Volterra series $x_1 = \sum_{i=1}^{\infty} x_{1i}$, $x_2 = \sum_{i=1}^{\infty} x_{2i}$, $x_3 = \sum_{i=1}^{\infty} x_{3i}$, $x_4 = \sum_{i=1}^{\infty} x_{4i}$ into（3）. Equalling the first order of both sides of the equation (3) can obtain

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -a_1 & -a_2 & -b_1 & -b_2 \\ -c_1 & -c_2 & -d_1 & -d_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{f_1}{m_1} \\ \frac{f_2}{m_2} \end{bmatrix} \tag{4}$$

Based on the definition of transfer matrix with zero initial value, the equation (4) can be written as

$$X_1(s_1) = (s_1 I - A)^{-1} \begin{bmatrix} 0 \\ 0 \\ \dfrac{se^{i\omega\tau/2}}{m_1} \\ \dfrac{se^{-i\omega\tau/2}}{m_2} \end{bmatrix} P(s_1) \tag{5}$$

The first transfer function is

$$H_1(s_1) = \frac{X(s_1)}{P(s_1)} = (s_1 I - A)^{-1} \begin{bmatrix} 0 \\ 0 \\ \dfrac{se^{i\omega\tau/2}}{m_1} \\ \dfrac{se^{-i\omega\tau/2}}{m_2} \end{bmatrix} \tag{6}$$

In the same way, we can obtain the second and third transfer functions as below.

The second transfer function $$H_2(s_1, s_2) = \frac{X_3(s_1, s_2)}{P(s_1)P(s_2)} \tag{7}$$

where $$X_2(s_1, s_2) = [(s_1 + s_2)I - A]^{-1} \bullet \begin{bmatrix} 0 \\ 0 \\ -a_{11}X_{11}(s_1)X_{11}(s_2) - a_{12}X_{21}(s_1)X_{21}(s_2) \\ \quad -b_{11}X_{31}(s_1)X_{31}(s_2) - b_{12}X_{41}(s_1)X_{41}(s_2) \\ -a_{21}X_{11}(s_1)X_{11}(s_2) - a_{22}X_{21}(s_1)X_{21}(s_2) \\ \quad -d_{11}X_{31}(s_1)X_{31}(s_2) - d_{12}X_{41}(s_1)X_{41}(s_2) \end{bmatrix} \tag{8}$$

3. EXPERIMENTAL COMPARISION

Miles [4] measured the mechanics of the ears of adult female. The expressions for the transfer functions given in Eqs.(6) and (7) can be evaluated to compare with the experimental data. Figure 3 to 5 are the comparison of the theoretic results and experimental data.

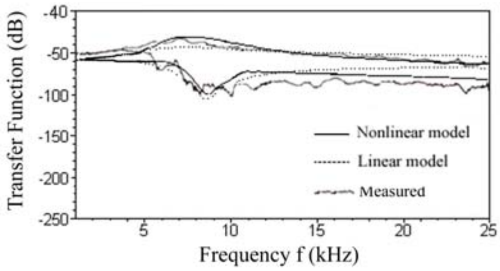


Figure 3. The measured and predicted interaural level differences between the two pits.

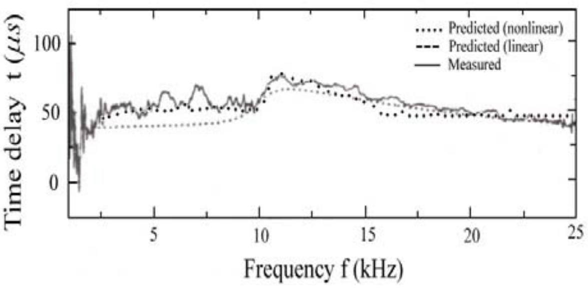


Figure 4. The interaural time delay with frequency varying. The rhombic lines are nonlinear theoretic curves. The solid lines are experimental curves.

Figure 3 indicates that difference in intensity between ears varies with change of stimulus frequency. The intensity difference is especially large in range of 7kHz to 12kHz. The predicted curves agree well with the experimental results. It is more precise than that of the linear model. The time delay of ipsilateral and contralateral ears is shown in the Figure 4. The figure shows that the time delay is about 50 μs. The maximum amplitude is 75 μs in the range of 10kHz to 15kHz. It is obviously that the theoretic curves obtained by the nonlinear model agree fairly well with the experimental data.

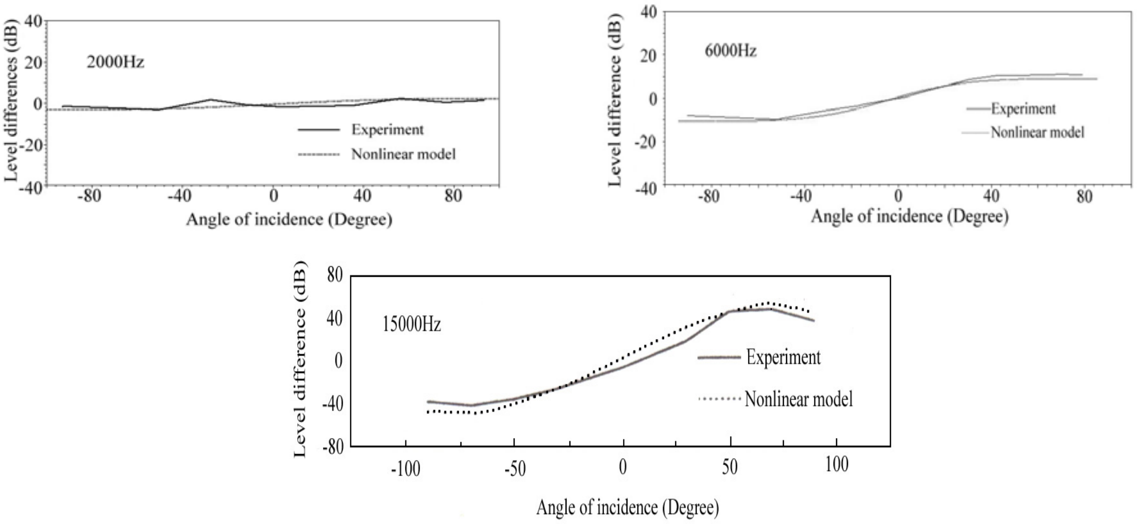


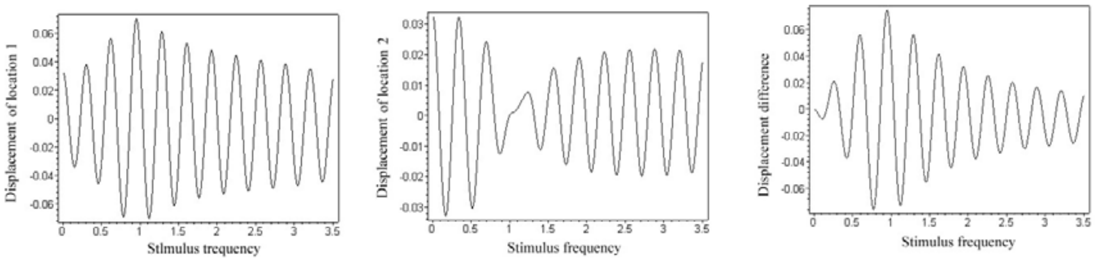
Figure 5. The interaural level difference with angle varying.

Fig.5 shows the interaural difference at the frequency 2 kHz, 6 kHz and 15 kHz for incident angles varying from -90^0 to 90^0. As the angle of incidence varies, the interaural level difference at the frequency of 2 kHz varies little. At the higher frequencies, however, greater level differences appear. The level difference is zero at the angle of zero and reach maximum at ± 90 degrees. From the figure 5, we can see that the level differences of the nonlinear model provide good agreement with measurements.

Both the differences with incident angle of linear model and nonlinear model agree with experiments well in the frequency of 2 kHz. In the frequency of 6 kHz and 15 kHz, the interaural difference of the nonlinear model has more precision than that of linear model. With the frequency increasing, errors in the linear model will add. The consistence of the agreement in the nonlinear model can keep with the frequency increasing.

4. NUMERICAL ANALYSIS

The figure 6 shows the vibrating amplitude of the location 1, 2 and difference between the two locations. The figures show that the amplitude varying with the stimulus frequency changing. For the location 1, the amplitude increases at first, then reach maximum and decrease with the frequency adding. For the location 2, the amplitude decreases firstly and then increases. So the amplitude difference has a peak value near the frequency of 7 kHz (dimensionless quantity is 0.9). This means that the interaural difference has been magnified.



(a) Displacement of location 1 (b) Displacement of location 2 (c) Displacement difference between two locations

Figure 6. Amplitude with stimulus frequency varying. The stimulus frequency and amplitude are dimensionless quantities.

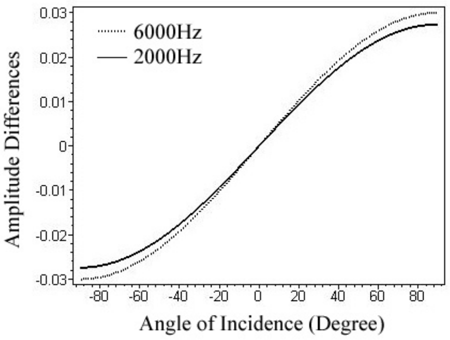


Figure 7 Amplitude difference with angle of incidence varying. The amplitude differences are dimensionless quantities.

The figure 7 illuminate that the amplitude differences between the two locations vary with angle of incidence changing. The amplitude difference is zero at the angle of zero and reach maximum at ± 90 degrees. The differences at the frequency of 6 kHz are larger than that at the frequency of 2kHz when the angle of the incident sound is apart from the zero degree. This means the model is sensitive to the angle of the incident sound.

5. EFFECTS OF MECHANICAL PARAMETERS

The figure 8 shows the amplitude difference vary with the stiffness k_1. The amplitude differences reach maximum when the stiffness $k_1 = 13.6$. When the stiffness keeps increasing, the difference no longer adds. From the Fig.9 we can see that there are two peak values appear with the stiffness k_3 varies.

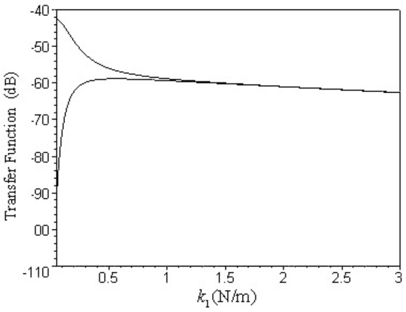


Figure 8. Differences of amplitude between the two locations when the stiffness k_1 varies.

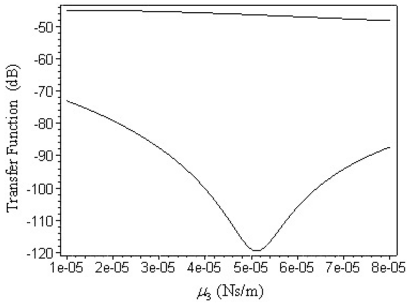


Figure 9. Differences of amplitude between the two locations when the stiffness k_3 varies.

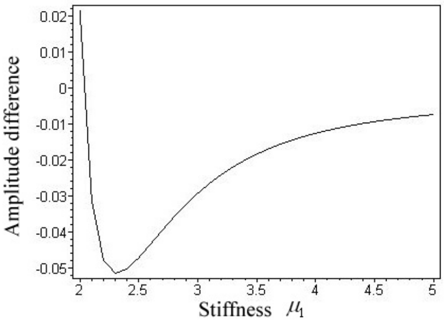


Figure 10. Differences of amplitude between the two locations when the damping μ_1 varies.

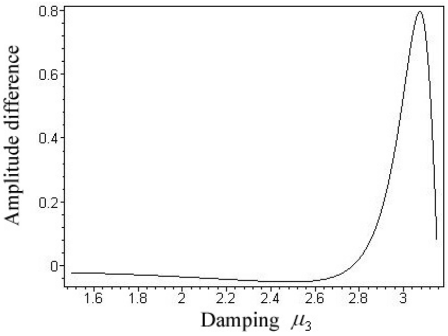


Figure 11. Difference of amplitude between the two locations when the damping μ_3 varies.

The figure 10 and 11 show the amplitude difference varies with the damping μ_1 and μ_3. The amplitude difference increases with the damping μ_1 and μ_3 until they reach maximum. This means that the differences will enlarge by selecting parameters properly

6. CONCLUSIONS

A nonlinear model of the auditory system of the parasitoid fly is presented and compared with the experiments. The analytical results provide good agreement with mechanical response measurements. Through the comparison of linear and nonlinear model, one can see that the latter agree with the experimental data perfectly, which will provide a firmly theoretical base for the research and development of systems such as novel high precision bionic micro sensory. Mechanical parameters can affect the amplitude difference of the response. Through correctly selecting the parameters, interaural difference between the two ears can be magnified.

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