Power Flow Analysis Of Nonlinear Finite Difference Model Of Bionic Acoustic Sensing Device

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Abstract. Parasitoid fly *Ormia ochracea* has a remarkable ability to detect the direction of incident sound stimulus via its unique acoustic sensory organs. Based on the anatomy of them, a bionics acoustic sensing device is designed to mimic the localization function of the ears of the parasitoid fly *Ormia ochracea*. In this paper, the nonlinear dynamic model for the bionic acoustic sensing device is established. The dynamic characteristics of the nonlinear mechanical model and influence of the nonlinear factors under different exciting condition are estimated by means of finite difference method. These works will establish theoretical basis of the bionic acoustic sensor's design.

Introduction

Microphone arrays have been used to locate an aerial sound source for many years, these arrays usually consist of 2, 3 microphones or even more^[1-3]. The arrival times of the sound stimulus applied to these microphones are determined and sent to the arithmetic-logic sections which could find out position of the sound sources later on.

The distance between each two microphones placed in the space is about 20cm, or equivalent amount, so that the arrival times of the sound pressures at these microphones can be detected and processed by the subsequent arithmetic-logic sections. The sizes of these appliances are always big relatively, and they usually consist of many components.

These physical characters of the structures mentioned above sometimes will narrow their applications in industry. And if the microphones, in other words, the acoustic sensory devices, can be placed in very close proximities to each other, these types of sound source localizers will have broader applications definitely.

An analysis is presented of mechanical responses to a sound field of the ears of the parasitoid fly *Ormia ochracea* [4-6]. It shows that the ears of this kind of parasitoid fly have a cuticular structure which can couple the ears mechanically in order to achieve the directional sensitivity. Based on the mechanism of the directional hearing of the parasitoid fly *Ormia ochracea*, some devices were invented as mimic products of the acoustic organ of the parasitoid fly *Ormia ochracea* [7].

In this paper, the mechanisms of the parasitoid fly *Ormia ochracea* for sound source localization are discussed, based upon this, a mini instrument for sound source localization is designed to accomplish the purpose of localizing the sound source by a relatively compact structure.

Analysis of the dynamic behavior of this instrument shows that incident angles of the sound have special relationship to the responses of this instrument, and the incident angles can be estimated by detecting the vibrations of it.

Mechanisms of the Parasitoid Fly *Ormia ochracea* for Sound Source Localization

The structure of the ears of the parasitoid fly *Ormia ochracea* and its simplified mechanical modal is shown [4] in Figure.1 and Figure.2.

Let x_1 and x_2 denote the displacement of the two ends of the intertympanal bridge shown in Figure.2, p denote the incident pressure at the pivot point, f_1 and f_2 denote the ipsilateral and contralateral forces added up to the two sides of the system.

Figure 1. Hearing organ of *Ormia ochracea* Figure 2. Mechanical model of the hearing organ

The vibration equation of this mechanical modal can be expressed ^[4] as:

$$\begin{bmatrix} k_1 + k_3 & k_3 \\ k_3 & k_2 + k_3 \end{bmatrix} X + \begin{bmatrix} c_1 + c_3 & c_3 \\ c_3 & c_2 + c_3 \end{bmatrix} \dot{X} + \begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix} \ddot{X} = F \quad (1)$$

The transfer functions between the displacement x_1 and x_2 and the incident pressure at the pivot point p can be shown [4] as:

$$H_{x_1 p} = \frac{s(k_3 + i\omega c_3) \times (e^{j\omega\tau/2} - e^{-j\omega\tau/2}) + s(k + i\omega c - m\omega^2) e^{j\omega\tau/2}}{(k + i\omega c + k_3 + i\omega c_3 - m\omega^2)^2 - (k_3 + i\omega c_3)^2} \quad (2)$$

$$H_{x_2 p} = \frac{s(k_3 + i\omega c_3) \times (e^{-j\omega\tau/2} - e^{j\omega\tau/2}) + s(k + i\omega c - m\omega^2) e^{-j\omega\tau/2}}{(k + i\omega c + k_3 + i\omega c_3 - m\omega^2)^2 - (k_3 + i\omega c_3)^2} \quad (3)$$

From Eqs. (2) and (3), let $H_{x_1 x_2}$ denotes the proportion of $H_{x_1 p}$ and $H_{x_2 p}$, we may obtain Eq. (4):

$$H_{x_1 x_2}(\omega) = \frac{H_{x_1 p}}{H_{x_2 p}} = \frac{s(k_3 + i\omega c_3) \times (e^{j\omega\tau/2} - e^{-j\omega\tau/2}) + s(k + i\omega c - m\omega^2) e^{j\omega\tau/2}}{s(k_3 + i\omega c_3) \times (e^{-j\omega\tau/2} - e^{j\omega\tau/2}) + s(k + i\omega c - m\omega^2) e^{-j\omega\tau/2}} \quad (4)$$

The calculated values of the incident angles θ can be derived from:

$$\sin(\theta) = \frac{c \cdot \ln \left(\frac{(k_3 + i\omega c_3 + k + i\omega c - m\omega^2) H_{x_1 x_2} + k_3 + i\omega c_3}{k_3 + i\omega c_3 + k + i\omega c - m\omega^2 + H_{x_1 x_2}} \right)}{\omega d} \quad (5)$$

Nonlinear Model of Bionic Structure

In order to localize the sound resource in three-dimensional space, we will introduce a mini instrument in this section. The structure of the auditory sensation devices in this instrument is shown in Figure.3.

Figure 3. mechanical model bionic structure

Figure 4. Discretization of the diaphragm

The coupling spring k_3 is a nonlinear spring, the spring force can be given by:

$$F(x_1 + x_2) = k_{31}(x_1 + x_2) + k_{32}(x_1 + x_2)^2 + k_{33}(x_1 + x_2)^3 \quad (6)$$

As in Figure.3 and Figure.4, The vibration equation of the point 3, 4 in this mechanical modal can be expressed as:

$$D\nabla^4 W = q_t + q_m + q_k \quad (7)$$

For the other points in the diaphragm, it can be given out as:

$$D\nabla^4 W = q_t + q_m \quad (8)$$

Where D is the composite bending modulus, W the normal displacement, q_t the exciting load, q_m the inertia force, and q_k the spring force, can be derived as following.

$$D\nabla^4 W = 20W_0 - 8(W_1 + W_2 + W_3 + W_4) + 2(W_5 + W_6 + W_7 + W_8) + (W_9 + W_{10} + W_{11} + W_{12}) \quad (9)$$

$$q_t = p \cdot \bar{s} \quad (10)$$

$$q_m = -\bar{m} \frac{d^2 W}{dt^2} \quad (11)$$

$$q_k = F(x_1 + x_2) \quad (12)$$

As the phase locus and Poincaré section map when incident sound pressure 100pa shown in Figure.5, when the incentive intensity is relatively low, the nonlinear characteristics of this system are not very remarkable. But when the sound pressure increase to 1Mpa, the nonlinear characteristics occur obviously, as shown in Figure.6.

Power Flow Analysis of the Nonlinear Finite Difference Model

Power always flow from ipsilateral side to contralateral side although the mechanical energy contained in ipsilateral side is higher than contralateral side as shown in Figure 7, where $I_2 - I_1$ is the power flow from ipsilateral side to contralateral side.

When the stiffness of coupling spring k_3 is very small, the power flows slightly from ipsilateral side to contralateral side. The both sides vibrate almost desperately in such a case. As k_3 increases the power flow will increase simultaneously, the peak value of this curve indicates the maximum power flow efficiency.

Figure 5. Phase locus and Poincaré section map when incident sound pressure 100pa

Figure 6. Phase locus and Poincaré section map when incident sound pressure 1Mpa

Figure 7. the power flow from ipsilateral side to contralateral side

Conclusion

In this paper, a nonlinear mechanical model for sound source localization is introduced, and its mechanism is discussed. The localization algorithm is given according to the analysis of the dynamic behaviour of this model. The dynamic characteristics of the nonlinear mechanical model and influence of the nonlinear factors under different exciting condition are estimated by means of finite difference method. Power flow analysis of the nonlinear finite difference model indicate that Power

always flow from ipsilateral side to contralateral side although the mechanical energy contained in ipsilateral side is higher than contralateral side. These works will establish theoretical basis of the bionic acoustic sensor's design.

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