A Cohesive Lumped Parameter Analysis of the Mechanics of the Goldfish Peripheral Auditory System

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Abstract: A mathematical analysis has been formulated to model the dynamic behavior of the goldfish peripheral auditory system, including the swimbladders, Weberian apparatus, and saccule. Results of the analysis compare favorably to experimental data for the motions of the swimbladders and indicate that the Weberian apparatus has a significant impact on the hearing ability over a broad frequency range.

INTRODUCTION

The objective of this study was to develop a cohesive model for the goldfish peripheral auditory system, including the swimbladder, Weberian apparatus, and the saccule. Previous models of the auditory system have focused individually on the swimbladder, otoliths, or hair cells.

Figure 1 illustrates the major components of the model and their relationships. The two-chambered goldfish swimbladder is treated as a two degree-of-freedom mechanical system consisting of two coupled mass-spring-damper arrangements. The anterior swimbladder is coupled to the Weberian ossicles using a phenomenological analysis of the anterior swimbladder tunic externa which permits both stretching and sliding. Analysis of the saccule features only a single degree-of-freedom, corresponding to the direction of orientation of the ciliary bundles. Inputs to the saccule consist of the transverse canal fluid motion and the motion of the animal’s head, which is assumed to match the local acoustic particle motion. The acoustic field at the location of the saccule is the superposition of the direct field radiated from the source and the indirect field scattered from the two swimbladder chambers. Mechanical properties required for the system equations were estimated from published literature and direct measurements.

FIGURE 1. Block diagram of the major components of the model.

RESULTS AND DISCUSSION

Figure 2(a) compares the results of the model analysis to experimental data for the anterior swimbladder radial velocity. The experimental data were obtained using a noninvasive, noncontact ultrasonic measurement system (1). The amplitude data were normalized with respect to \( \rho_w c_w \sqrt{E(\omega)/\rho_w} \), where \( \rho_w \) and \( c_w \) are the density and sound...
speed in water and \( E(\omega) \) is the acoustic energy density. The phase data were normalized with respect to the acoustic pressure. The model response compares favorably with the experimental data, especially near the bladder resonance frequency (approximately 1000 Hz).

**FIGURE 2.** Model results for a 53.7-g goldfish. (a) Anterior swimbladder radial velocity (line) compared to experimental measurements (symbols). (b) Relative displacement between the saccular otolith and sensory epithelium in terms of direct, indirect, and Weberian components.

Figure 2(b) shows the model relative displacement between the saccular otolith and sensory epithelium for a monopole source located 1 m in front of the fish. The motion is separated into the individual components due to the direct, indirect, and Weberian paths. The results indicate that the Weberian apparatus has a significant impact on the hearing ability over a broad frequency range and that the saccule functions as a displacement sensor above approximately 300 Hz.

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**REFERENCES**