

APPLICATIONS OF BIOACOUSTICS IN PHYSICAL MODELING AND THE CREATION OF NEW MUSICAL INSTRUMENTS

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Abstract

The similarities between biological and musical acoustic systems has lead to the idea that bioacoustics, and understanding of animal sound production, could provide models for new musical instruments. Physical modeling synthesis of these systems offers the musician the ability to manipulate natural sound, much in the same way s/he would a traditional musical instrument. In this research, the sound mechanism of the cicada is modeled and the musical potential of it's vocalization is explored. The cicada instrument is programmed in C++ and runs in real-time. A glove, equipped with force sensing resistors (FSRs) on each of the fingertips, allows for control of parameters such as the volume of the cicada's abdomen, and the stiffness of its tymbal plate.

INTRODUCTION

The way certain animal species produce sound is remarkably similar to the sound mechanism of many musical instruments. Sound sources such as vibrating membranes, plates and shells, acoustic tubes or cavities, are important components of both musical and biological acoustic systems. In both cases, it is often the coupling of these elements that enables the propagation of the resulting characteristic sound that reaches the human ear.

It has been known for quite some time that insects, as well as other animals, use vibration as a means of communication. Vibrational languages can be used for attracting mates, for predator detection, for marking territory. Whatever their purpose, many of these sounds have timbral qualities that are undeniably captivating to human listeners. The musical potential of these sounds is, perhaps, mostly heard in those with distinctive traits resembling existing instruments. Certain bird vocalizations, for example, bring to mind the sound of wind instruments: Vivaldi's flute concerto "Il gardellino" or "The Goldfinch", Debussy's "Syrinx", and the call of the cuckoo in Beethoven's Pastoral Symphony, are all clear examples of how these composers heard music in natural sound.

Physical modeling synthesis, a technique that has mostly been used to reproduce existing instruments, provides a new means for exploring the musical potential of natural sound. There are many intriguing sound sources in our environment that fall short of existing musical instruments only in our inability to control them. This paper focuses on one of these; the sound production mechanism of the cicada, and how it has been modeled to create a new musical instrument.

THE SOUND MECHANISM OF THE CICADA

The transduction from muscle energy to sound energy, in the cicada, is a 2 stage process, involving both a primary and secondary resonator [1]: the tymbal, and the abdominal air sac, respectively.

The Buckling Tymbal

Muscle power drives a small mechanical resonator, *the tymbal*, which acts as a frequency-multiplier by converting relatively slow movements of contracting muscles (117 Hz) to the fundamental frequency of the cicada’s song (4.3k Hz) [1].

The cicada has 2 domed shape tymbals located on either side of its abdomen. On the surface of the tymbal, is a series of 4 narrow verticle ribs, followed by a larger oval tymbal plate, all of which is surrounded by an elastic resilin (see figure 1) [1].

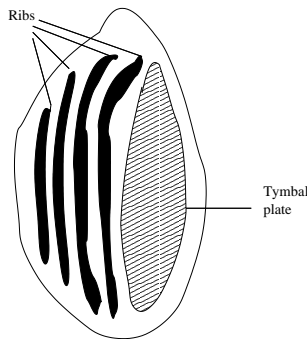


Figure 1: Simplified diagram of the tymbal

As the tymbal plate is pulled in by the contraction of the tymbal muscle, up to 4 ribs (not always all four), beginning with the one adjacent to the plate, buckle inward sequentially (buckling is a nonlinear phenomenon that results when the inward force applied to a rib causes it to spring from a convex to a concave form) (see figure 2). When the muscle is relaxed, the opposite motion occurs (though more quickly): each rib, starting from the last, returns to its convex form.

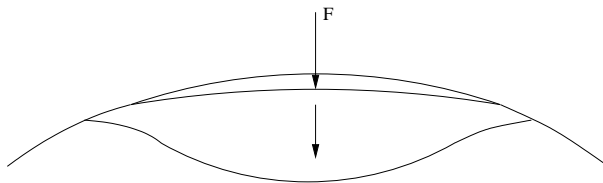


Figure 2: Inward buckling motion of a tymbal rib under a central force [2]

The buckling of the first rib immediately sets the tymbal plate into vibration (causing an *IN pulse*) — much in the same way a hammer sets a string into vibration in a piano. Each subsequent buckling of a rib adds mass (the mass of that rib) to the overall mass of the vibrating plate. A look at Equation (1) will show that an increase in mass effectively reduces the frequency at which the plate vibrates.

The fundamental frequency of a resonator can be determined using the following equation:

$$f_o = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad (1)$$

This subtle change in frequency (or “chirping”) during one *IN cycle* was accounted for in the implementation of the model. Figure 3 shows the time domain waveform produced by one *IN cycle*, when all 4 ribs buckled (anywhere from 2 to 4 ribs will buckle during an *IN cycle*, but not always all four).

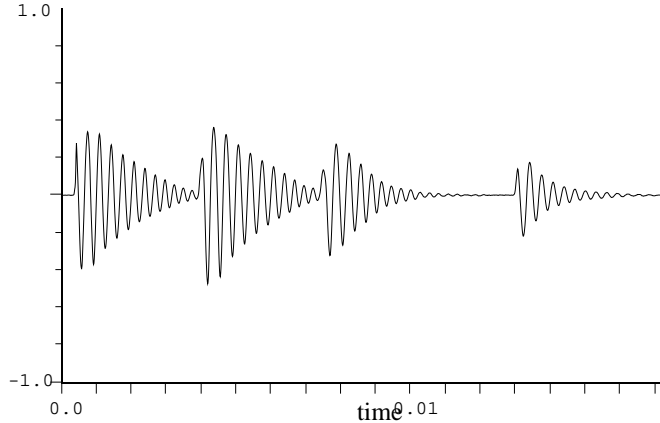


Figure 3: One buckle cycle

In the cicada model, the vibrating tymbal is implemented using 2 bi-quadratic digital filters (or biquads) – one for each of its 2 main resonant modes. The quantities of the filter can be calculated with the known (or desired) resonant frequency (which changes each time an additional rib buckles), and the quality factor (or Q), of the resonator [3]. An impulse is sent to the filter each time a rib buckles, resulting in a waveform that looks much like figure 3. The control (and variability) over the number of ribs that buckle during one *IN cycle*, reduces the periodicity of the resulting sound.

Following the contraction of the muscle, and the buckling of the ribs, the muscle relaxes. The resulting decrease in force on the buckled ribs cause them to rebound to their original convex shape. The motion, though still sequential, is much faster than the *IN cycle* and the pulses in the waveform are less obviously discrete. The result is an *OUT cycle* that seemingly contains only one pulse, rather than the number of ribs that actually buckled.

The Abdominal Air Sac

The tymbal drives the abdominal air sac, a larger acoustic resonator acting much like a *Helmholtz* resonator. The sonic aperture through which the sound propagates, the *tympanum* (or the *mouth* of the Helmholtz resonator), has an impedance closely matching that of the surrounding air [4]. This causes the sound to radiate well (creating the cicada’s characteristic loud pure tone) but at the expense of decaying more rapidly. The improved *impedance-matching* of the *tympanum*, or eardrums, and a tuning that matches that of the primary resonator, results in a filter that both smooths the discrete sound pulses and amplifies the sound.

This secondary acoustic resonator is closely tuned to the resonant frequency of the tymbal. The fundamental frequency of the abdominal air sac can be calculated using Equation (2).

$$f_o = \frac{c}{2\pi} \sqrt{\frac{A}{LV}} \quad (2)$$

In the cicada model, A is controlled by adjusting the opening of the tympanum, and V is changed by extending the abdomen. The real cicada performs these very adjustments when tuning its vocalization. It seems only appropriate that this should be the tuning mechanism of the instrument as well.

The implementation of the air sac uses a resonator similar to that of the tymbal. Since finer tuning is more important here, a greater number of poles (six) was added. The output of the

tymbal, a series of *IN* and *OUT* cycles, one cycle of which is shown in Figure 3, is filtered by the 6-pole helmholtz resonator, with variable (user controlled) tuning, ideally close to that of the tymbal plate. The resulting time-domain waveform is greatly amplified, as well as being smoother and less pulse-like. The moment at which the ribs buckle is less discernable – as seen in figure 4.

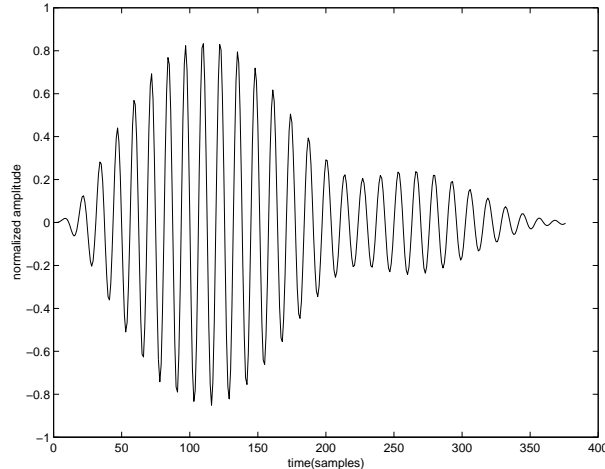


Figure 4: The waveform from figure 3 after being passed through the Helmholtz resonator, representing the cicada’s abdominal air sac

SUMMARY

Equipped with a pair of MIDI gloves, the performer is able to manipulate the physical parameters of the cicada model (the stiffness of the tymbal plate, the volume of the abdomen, the number of ribs that buckle during an *IN* cycle...), much in the same way a cicada would control some of these very parameters while vocalizing. Slightly changing the volume of the abdominal air sac, for example, will alter the tuning between the 2 resonators and produce a timbre that is controllable by the performer. As with any musical instrument, it is through experimentation and practice that musical potential is discovered.

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