A Musical Instrument Based on a Bioacoustic Model of a Cicada

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Abstract

In this research, the sound production mechanism of the cicada is explored and modeled to create a new digital musical instrument. The model is implemented in an environment which offers intuitive, real-time manipulation of the model's parameters – making it suitable for live, interactive, musical performances. The model consists of a primary and secondary resonator, the former for the tymbal and the latter for the abdominal air sac. There is also an object in the model that implements the rather unique excitation mechanism of the buckling ribs.

1 Introduction

There are many musical sound sources in our environment besides those produced by traditional musical instruments. What is lacking, is an effective and intuitive means of controlling them. As a result, many composers have resorted to sampling and non-real-time processing of these sounds in order to achieve their desired effect. Yet what would it be like to manipulate a natural sound source in a more meaningful way – in a way similar to a musician playing an acoustic musical instrument?

By creating a physical model of the cicada's sound mechanism, and by creating a real-time, interactive means of controlling it, we have developed a way of understanding how the sound responds to slight changes in the model's physical parameters – an important requirement for a musical instrument if anyone is to play it successfully. The result is a new digital musical instrument suitable for live performance, and a starting point for the development of more musical instruments based on other such bioacoustic models.

2 The Sound Mechanism of the Cicada

The cicada produces it's characteristic loud tone by converting the energy of an extremely fast contracting muscle to sound energy, using both a mechanical and acoustic (Helmholtz) resonator (Young and Bennet-Clark 1994).

The former resonator, called the tymbal, is equipped with a series of convex ribs that are capable of buckling (see figure 2) under the force of a contracting muscle (Fletcher 1992). Once the first rib buckles, the tymbal plate is immediately set into vibration. Each additional buckling of a rib sustains the vibration by providing another *attack* to the resonator. The cicada has 2 such tymbals (see figure 1), located on either side of it's abdomen (Young and Bennet-Clark 1994).

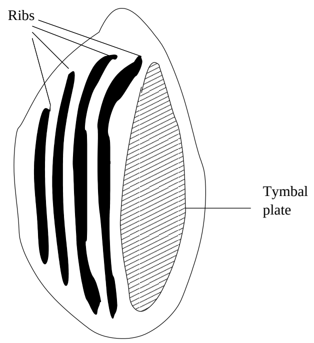

Figure 1: Simplified diagram of a tymbal

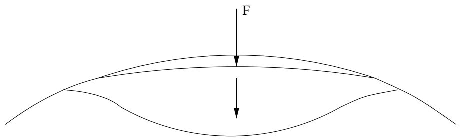

Figure 2: Inward buckling motion of a tymbal rib under a central force

The tymbal drives the abdominal air sac, an acoustic resonator tuned to approximately the same fundamental frequency. The tuning of these 2 resonators is a very important factor in the nature of the resulting sound and is certainly taken into account when controlling the instrument. In addition to providing a sort of amplification system, the abdomen smooths the waveform of the tymbal's pulse train (see figure 3).

The extremely loud sound, for which the cicada is often renowned, is also aided by the inertial element of the Helmholtz resonator – the large eardrums or *tympana* that provide a sonic aperture through which the sound may propagate. Because the tympana are much larger than the tymbals (see figure 3), they improve upon the matching of acoustic impedance to that of the surrounding air – enabling the cicada to project an extremely loud song (Bennet-Clark and Daws 1999).

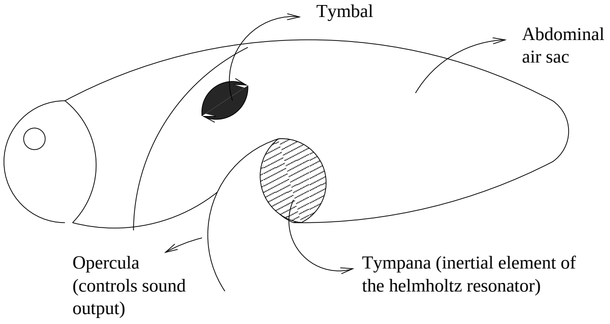

Figure 3: The Cicada

3 The Cicada Model

The model consists of a buckling tymbal and a Helmholtz resonator (representing the abdominal air sac). Each time a rib buckles, a variable width hamming impulse is sent through 2 bi-quadratic filters – one for each of the 2 resonant modes in the spectrum (see (Smith 1982) for details on resonant filters). For each *IN cycle* (referring to the sequence of buckling ribs produced by one muscle contraction), the changing mass and frequency from table 3 is considered, and the filter coefficients are updated accordingly. The output waveform of the tymbal resonator can be seen in figure 4.

The output of the tymbal is then put through another similar resonant filter representing the abdominal air sac. Since finer tuning is more important here, a greater number of poles is added to the filter. The resulting waveform is greatly amplified as well as being smoother and more coherent. The moments at which the individual ribs buckle are not as clearly discernible, as seen in figure 3.

4 The Instrument

The current model has been developed as an external object for an interactive software environment called Pd (pure data). This environment has been chosen for the performing ability it affords the musician in real-time, live musical situations.

	m	**total mass**	f_o
plate	$550\mu g$	—	—
load	$380\mu g$	—	—
1st rib	$100\mu g$	$1030\mu g$	$3.5kHz$
2nd rib	$85\mu g$	$1115\mu g$	$3.37kHz$
3rd rib	$80\mu g$	$1195\mu g$	$3.26kHz$
4th rib	$55\mu g$	$1250\mu g$	$3.18kHz$
OUT	$550\mu g$	$550\mu g$	$6.54kHz$

Table 1: This table shows the mass of the individual tymbal elements, and the increasing total mass of the vibrating tymbal plate after the buckling of each additional rib. The result is a slight decrease in the fundamental frequency of the resonator during one buckling cycle, creating a sort of chirping effect. OUT refers the point of muscle relaxation, when the ribs spring back to their convex shape. Only the mass of the plate is used in calculating the frequency at this point.

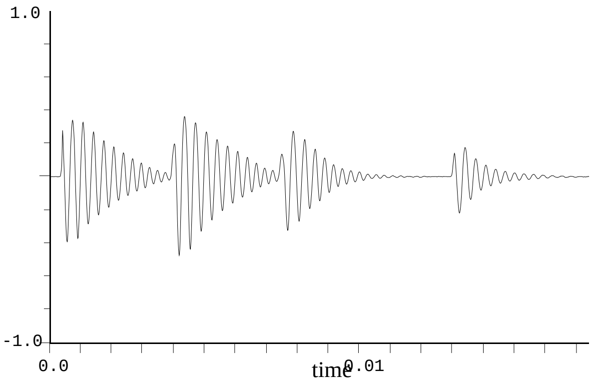

Figure 4: The waveform of one IN cycle produced by one contraction of the tymbal muscle

4.1 The Controller: Midi Gloves

A Glove controller was developed for use with this model, and via the MIDI protocol, allows for simple communication with the Pd environment. In the glove, the tip of each finger, as well as the heels of each hand, is equipped with a force sensing resistor (FSR). The variable voltage (between 0-5V) from each sensor, proportional to the amount of pressure applied to the finger or heel, is sampled using an analog to digital converter (MAX1270) before being sent on its own channel to the Basic Stamp (a programmable micro-controller). The final output of the stamp is a continuous controller MIDI message, with a MIDI channel for each FSR. This is then read by Pd's midi object and the data is mapped to the various parameters of the model.

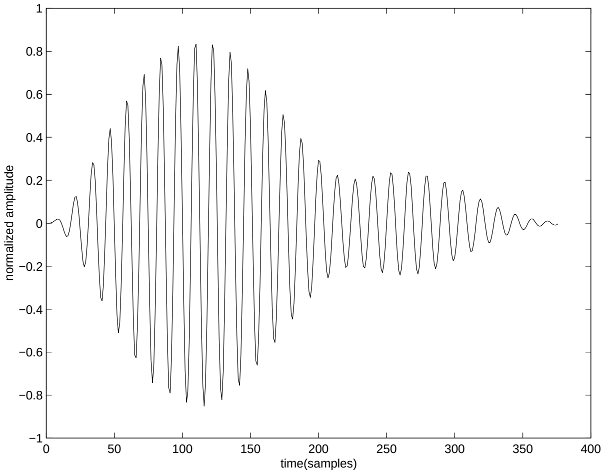

Figure 5: The waveform from figure 4 after being passed through a Helmholtz resonator representing the cicada's abdominal air sac.

4.2 Control Parameters

The 3 major parameters which contribute to the nature of the cicada's sound are: the rate of contraction of the tymbal muscles, the structure of the tymbals (the number of (buckling) ribs, the stiffness of the dorsal plate, the etc.) and the resonant frequency of both the tymbal and the abdominal air sac (Ewing 1989).

Rate of Muscle Contractions. Depending on the species of Cicada, the rate of muscle contractions can vary a great deal. However, in the species on which this model is based, the muscles contractions occur about 117 times per second (Bennet-Clark 1997). This is, of course, extremely fast, and beyond the capability of any human. The idea, however, is not that the player of the instrument produce 4 impulses per muscle contraction and 117 muscle contractions per second. This is all taken care of in the instrument. The player's role is to control other physical parameters while the instrument controls the more *impossible* tasks of the excitation mechanism.

Structure of the Tymbal. The cicada can change the loudness of its sound by changing the curvature of its tymbal (using a tensor muscle) (Ewing 1989). The greater the convexity of the tymbal, the greater the amount of energy required to buckle the ribs (which are also made more convex), and the more acoustic energy released as a result (Ewing 1989). This parameter is an important one in the model. It is accounted for by allowing the user the ability to change the height and width of the hamming impulse that is sent to the primary resonator at the time of buckling. This is the primary way in which the player controls the excitation mechanism, since, as previously mentioned, it would be impossible for a human to duplicate the speed of the neurogenic contractions of the cicada's tymbal muscle.

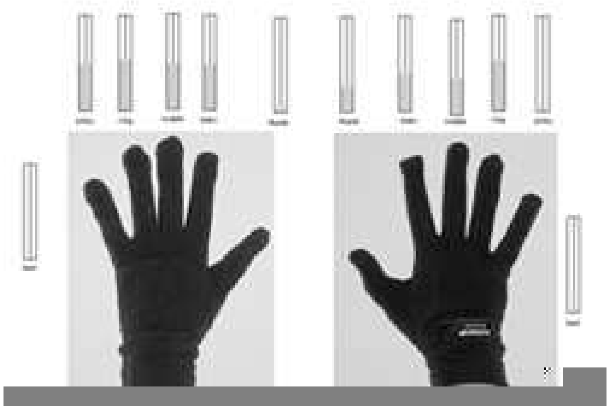

Figure 6: A Max (MSP) patch is used to demonstrate the sensitivity and resolution of the sensors. Each finger and heel of the glove is mapped to a level meter, and gives visual feedback to the amount of pressure being applied.

Another tymbal parameter that is controllable in the model is the stiffness and mass of the tymbal plate. The tymbal behaves like a mass and spring system, with the reactive elements being the mass of the tymbal plate, and the stiffness of the tymbal's dorsal support (Bennet-Clark 1997). As previously stated, the buckling of each individual rib contributes to an increase in the overall mass of the tymbal plate according to table 3.

The decrease in fundamental frequency of the vibrating tymbal plate during a buckle cycle is a direct result of an increase in the plate's mass after an inward buckling of a rib. The can be seen in equation 1.

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

where k is the stiffness factor, and m is the changing mass. The user is able to adjust the frequency by changing the stiffness (something which is not at all automated in the model). As this is one of the reactive elements in the resonator, changing it causes a change in the resonant frequency. This can result in less *consonant* tunings with the secondary resonator, and create a more complex tone.

Resonant Frequency The coupling of the tymbal to the abdominal air sac, tuned to the same frequency, allows the signal to project very strongly. In addition to giving volume, the secondary resonator acts as a filter to smooth the discrete pulses from the output of the primary resonator (see figure 4 and 3.

The nature of the sound can be changed by altering the tuning of the resonators. Depending on their relative frequency, the secondary resonator will have a different affect on the resulting sound. As in the case of the primary resonator, the player also has control over the tuning of the secondary resonator. Just as the cicada has the ability to fine tune the frequency of its song by making slight adjustments to the volume of the abdominal air sac, the instrument permits the same control.

Recall that the frequency of a bottle shaped resonator can be found using equation 2.

$$f_o = \frac{c}{2\pi}\sqrt{\frac{A}{LV}} \tag{2}$$

where c is the speed of sound, A is the area of the neck, L is the length of the neck, and V is the volume of the cavity (Bennet-Clark and Daws 1999). It can be seen therefore, that increasing V lowers the frequency, while increasing A (this is done by adjusting the opening of the tympana), increases the frequency of the resonator.

5 Conclusion

Physical modeling synthesis has provided a means of manipulating natural sound in a meaningful, interactive and expressive way, and is an alternative to using non-real-time processing of sampled sound. The use of bioacoustic systems as models offers new sounds to electronic musicians – sounds that have a natural quality in a digital medium.

6 Acknowledgments

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