Sound Modulation in Singing Katydids Using Ionic Polymer-Metal Composites (IPMCs)

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Abstract: Many insect families have evolved to produce and detect complex singing patterns for the purposes of mating, display of dominance, predator escape, and other needs. While the mechanisms of sound production by insects have been thoroughly studied, man-machine exploitation of such mechanisms has remained unreported. We therefore describe a method to modulate the frequency spectrum in the chirp call of a singing insect, *Gampsocleis gratiosa* (Orthoptera: Tettigoniidae), a large katydid indigenous to China and commonly known as Guo Guo or Chinese Bush Cricket. The chirp modulation was achieved through the contact of a ribbon of Ionic Polymer-Metal Composite (IPMC) against wing of the insect. The IPMC effectively served as an actuator when a small DC voltage was applied to the ribbon's faces. By applying a sequential on/off voltage waveform to the IPMC ribbon, the katydid's chirp was modulated in a corresponding manner. This configuration can be used as part of a broader application of using singing insects to harness their acoustic power to produce and propagate machine-induced messages into the acoustic environment.

Keywords: chirp modulation, katydid, IPMC

1 Introduction

Insects belonging to the families Gryllidae (crickets, "true crickets") and Tettigoniidae (katydids, bush crickets) employ an acoustic means of transporting information[1]. Their chirp songs, which are bandwidth confined and species specific[1–4], are used to attract females and to communicate with other males[5–7]. Their mechanism of song production is also known as wing stridulation, in which muscle contraction leads to the opening-closing of a pair of wings. One wing bears the plectrum, which is a sclerotized sharp ridge that moves across the stridulatory file ("teeth") located on the other wing[8,9]. It is suggested that such stridulation is similar to the escapement ratchet of a clock[10,11]. A one tooth impact produces a pulse that decays rapidly; a succession of pulses make up a syllable produced by the full stroke of a closing pair of wings[11–13].

The above stridulation mechanism applies to the katydid *Gampsocleis gratiosa*, the model insect of this reported effort. These insects are commonly sold in China as singing pets[14]. In this species, the right wing bears the plectrum, which is overlapped by the left wing (Fig. 1a). The underside surface of the left wing bears the stridulatory file, which is composed of a row of teeth (Figs. 1c and 1d). The stridulation excites the resonant structures within the wing in a periodic manner at a fundamental frequency near 4 kHz[12]. One resonant structure within the wing is known as the harp, consisting of a triangular area constructed from a group of wing cells that surround and are connected to another resonant structure, the circular shaped "mirror" (Fig. 1b). The resonator properties of harp and mirror in the katydid have been studied extensively[15]. It is also reported that

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the frame of the katydid’s mirror is responsible for the sound resonance but not the mirror membrane[16–18]. This contrasts to theories that the pitch and clarity of the chirp are controlled by a neural response involving subalartegminal resonance with auditory feedback[19–21].

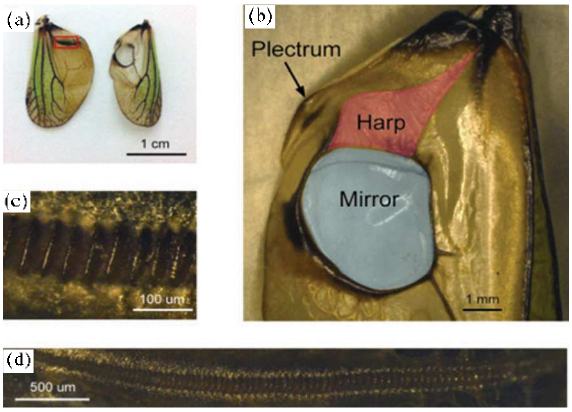

Fig. 1 The structure of both (left and right) forewings of *G. gratiosa* katydids. (a) A pair of opposing wings; (b) the structures on the right wing: plectrum, harp, and mirror; (c) and (d), the optically magnified images of the file on the underside surface of the left wing, as circled in (a); (c) high magnification; (d) low magnification.

Our research effort has attempted to further explore the katydid’s natural sound production mechanism, and to examine how this mechanism can be used for a “machine-induced message” in the insect chirping. To this end, we evaluated the use of an IPMC ribbon as a means of altering the above-mentioned katydid’s frequency of chirp vibration. The IPMC ribbon has a sandwich-like structure containing an ionic membrane, with metallic coatings on its two faces. A DC potential applied to the ribbon’s two faces causes the IPMC to bend due to the asymmetrical movements of ions within the membrane[22]. Given the nature of the IPMC ribbon’s flexibility and resemblance to biological muscle contraction, IPMC has been applied as “artificial muscle” material in robotic jellyfish[23], robotic fish[24], wireless tadpoles[25], artificial fingers[26], and even a robotic Venus flytrap[27]. The potential of IPMC as sensing material has also been explored[28,29]. To date, there is no report on using IPMC, or similar actuator materials, for the purposes of inducing or influencing communication among organisms.

2 Materials and methods

Experimental males of *G. gratiosa* katydids were obtained from Beijing, China. These insects were selected because of their large size (70 mm in length) and hardiness, with life spans up to 6 months in a controlled (25 ˚C; 65% RH; light:dark cycle = 12:12 hours) quarantine facility. To modulate the insect’s chirp sound, an IPMC ribbon (Environmental Robots Inc., Bangor, ME) of 10 mm by 2 mm was affixed to the pronotum of the katydid by the use of correction fluid (Wite-Out, Bic Corp., CT) as an adhesive, as shown in Fig. 2. The pronotum is a highly sclerotized plate-like cover of the first thoracic segment and it protects the membranous “neck” area of the insect in this species. Note that the ribbon’s activation circuit and battery (described below) were also mounted on this region of the insect by the application of the correction fluid. By keeping all of the components together on the insect, the insect was free to move within its cage without entanglement with external wires. Any loose wires or entanglement would “distract” the insect and prevent it from singing. Due to the curvature of the pronotum, it was necessary to “flatten” the pronotum surface by applying a thick layer of the correction fluid. The IPMC ribbon’s fixture angle was optimized so that the bent IPMC ribbon, resulting from application of a voltage to the ribbon, was able to touch the wing when the katydid was chirping. The motion of the IPMC ribbon against the insect wing produced the machine-induced modulation in the insect’s natural chirp.

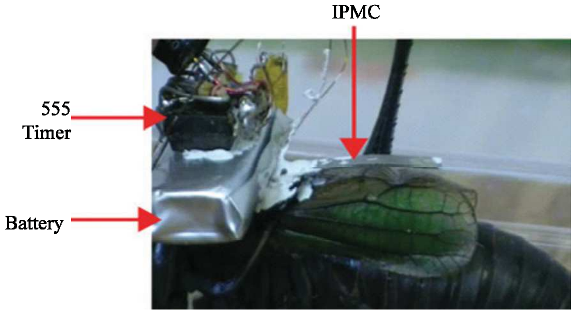

Fig. 2 The battery, the 555 timer, and the IPMC ribbon assembled on the pronotum of the katydid.

3 Results and discussions

Because the IPMC ribbon’s bending would become unpredictable when a DC voltage was applied to the ribbon’s faces over a long duration (e.g., on the order of over 20 s), short term applications of DC voltage under 10 seconds were deemed more practical. This was achieved by the use of a 555 timer oscillator circuit, which was designed to provide a sequential on/off DC voltage to the ribbon (Fig. 3a). In such design, R1, R2, and C were 1000 Ω, 220 kΩ, and 47 µF, respectively. The power supply was a 3.7 V lithium battery of 120 mAh. Leads from the 555 timer circuit were connected to the two faces of the IPMC ribbon using conductive silver paste. The output square wave is shown in Fig. 3a. When a 3.7 V was applied, the IPMC ribbon bent towards the wing from its relaxation position (Fig. 3b). The applied voltage lasted for 7.2 s, and then the voltage was set to 0 V for another 7.2 s so that the ribbon would move away from the wing. This pattern was repeated sequentially throughout the duration of the experiment. Based on this design, the system could sustain 30 minute duration of on/off cycles. An audio recorder (Sanyo ICR-RS176NX) was placed near the katydid to record the insect's chirping. The chirp modification process was also videotaped by a digital video camera (JVC Everio). The background noise in the recorded sound was removed using the software Audacity 1.3. The resulting noise-filtered audio file was later Fourier analyzed through routines in Matlab R2011a. The battery was disconnected from the 555 timer to suspend the on-and-off voltage sequence. Under this condition, the IPMC ribbon was straight and did not touch the wing (Figs. 4a and 4c). The recorded chirp song with zero voltage configurations provided a comparison against the periodic application of the voltage to the ribbon, as shown in Fig. 5.

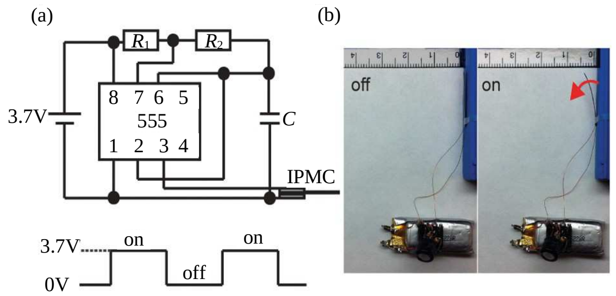

Fig. 3 (a) The 8-pin 555 timer-based oscillator circuit and the output square wave; (b) at the circuit's output (pin 3) of 0 V, the IPMC ribbon was straight. When the circuit output was at the "on" state of 3.7 V, the IPMC ribbon bent.

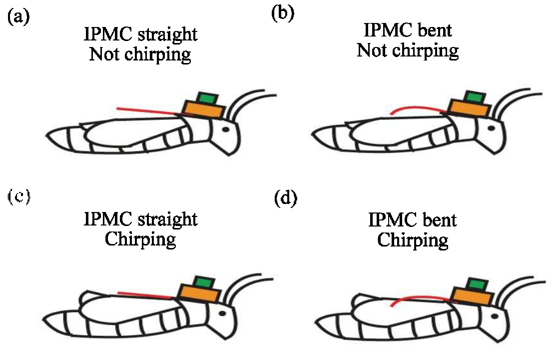

Fig. 4 Configurations between different states of IPMC and the chirping. The straight IPMC ribbon did not touch the wing of the katydid when not chirping (a) or chirping (c). When the IPMC ribbon was bent due to the applied voltage, it touched the left wing during chirping (d).

In Fig. 5a, there is one syllable in each figure, which contains 38 pulses and 27 pulses for the unmodified and electromechanically modified chirps, respectively. Fig. 5b shows the enlarged plots of the blue circled areas in Fig. 5a. The selected pulse interval under straight IPMC was half of the interval under bent IPMC, since the force of the ribbon hindered the wings from fully opening during stridulation. Fig. 5c shows Fourier spectrum plots of the chirp under two IPMC ribbon conditions: straight and bent for non-contact and contact of the ribbon against a wing, respectively. The sampling frequency f_r of the recording was 44.1 kHz, which is higher than 2× any of the frequency components of interest, thereby satisfying Nyquist sampling. In Fig. 5c, the straight IPMC did not interfere with the chirping of the katydid, resulting in a principal carrier frequency at $f_0 = 3.6$ kHz. The bent IPMC caused a similar frequency at 3.6 kHz; however, peaks of frequencies with larger amplitude were observed ranging from 5 kHz to 7 kHz. The three major peaks occurred at 5.6 kHz, 5.9 kHz, and 6.5 kHz. The inset red and green plots represent spectra as the result of sampling over the red and green shaded areas shown in Fig. 5a. It is suggested that the last pulse in Fig. 5a contributed to the peak at 3.6 kHz in the overall plot.

The bent IPMC changed the chirp waveform in the following ways: first, the bent IPMC pushed down the upper wing hence changed its mechanical properties for resonance, and resulted in the change of the principal carrier frequency f_0 (Fig. 5c bent, red inset). Second, the force from the bent IPMC caused the increase in the static friction between the plectrum and the teeth. Therefore, the opening movement of the wings was hindered and syllable length was elongated. There were more tightly locked states between the plectrum and the teeth, resulting in the scattered syllable waveform shown in Fig. 5a (bent). The last pulse required sizable force and was the loudest. Finally, we cannot rule out the

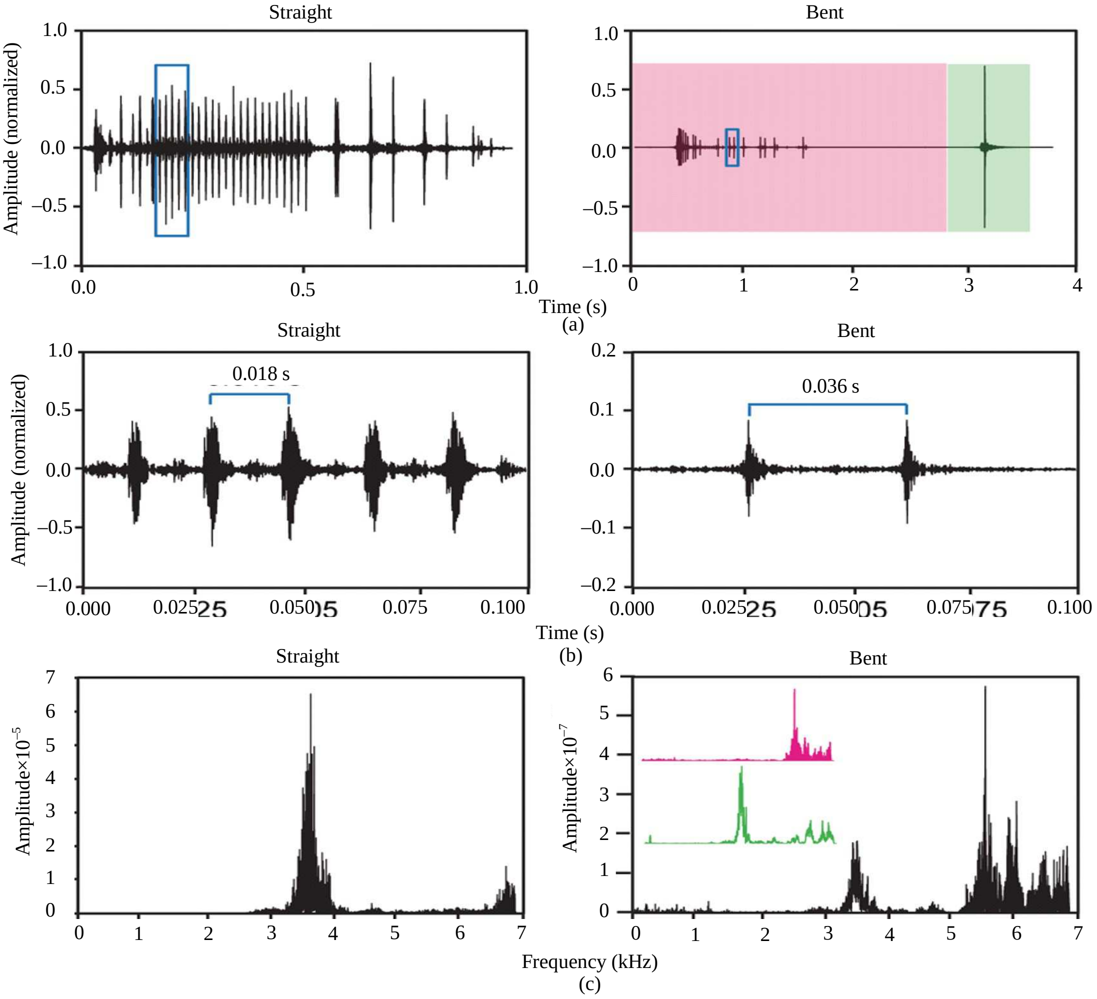

Fig. 5 Chirp waveforms. Left column: straight IPMC not touching the wing; right column: bent IPMC touching the wing. (a) Recorded chirp waveform for a single syllable; (b) magnified area as circled in blue in (a); (c) frequency spectrum of the chirp waveform in (a). The inset red/green plots represent the separated frequencies of the red/green shaded areas in (a).

possibility of neuro-muscular control of the wing movement in response to the presence of the IPMC perturbation. These results demonstrate the feasibility of using polymer actuators to modify the acoustic output of an insect's singing.

4 Conclusion

In the present research, we demonstrated a novel approach for modulating the sound of singing katydids. The method applied a ribbon of IPMC to electromechanically induce a change in the acoustic properties of a katydid's wings and chirp. By applying a low voltage (3.7 V) to a stationary IPMC ribbon mounted on the insect's pronotum (upper neck), the ribbon's flexing due to the applied voltage would cause it to come into contact with the upper wing, thereby modulating the insect call with respect to the chirp's frequency, harmonic content, and amplitude. This work constitutes fundamental research that points to a new machine interface to nature that can harness the acoustic power of insects for communications purposes, such as in the transmission of sensor or stealth messages via insect's calls. Likewise, this effort points to a highly efficient model of acoustic transducer system based on the structure and function of insect wings that have evolved for chirping.

Acknowledgment

This work is supported by the US Army Advanced Research Office and the US Army Chemical Biological Center, Edgewood, MD, contract #W911NF-09-C-0069. The content of the information does not necessarily reflect the position or the policy of the Government, and no official endorsement should be inferred.

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