Synthesizing bird song

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In this work we present an electronic syrinx: an analogical integrator of the equations describing a model for sound production by oscine birds. The model depends on time varying parameters with clear biological interpretation: the air sac pressure and the tension of ventral syringeal muscles. We test the hypothesis that these physiological parameters can be reconstructed from the song. In order to do so, we built two transducers. The input for these transducers is an acoustic signal. The first transducer generates an electric signal that we use to reconstruct the bronchial pressure. The second transducer allows us to reconstruct the syringeal tension (in both cases, for the time intervals where phonation takes place). By driving the electronic syrinx with the output of the transducers we generate synthetic song. Important qualitative features of the acoustic input signal are reproduced by the synthetic song. These devices are especially useful to carry out altered feedback experiences, and applications as biomimetic resources are discussed.

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I. INTRODUCTION

Out of the approximately 10 000 species of birds known to exist, some 4000 share with humans (and just a few other examples in the animal kingdom) a remarkable feature: the acquisition of vocalization requires a certain degree of exposure to a tutor [1]. This is the reason for which birdsong is becoming a most active research topic, particularly in the field of neuroscience. Between the complex neural architecture required for learning and producing song, and the behavior (i.e., the song), stands a delicate apparatus that the bird must control with incredible precision: the syrinx [2].

Despite the anatomic complexity of the avian vocal organ, recently it was shown that a model of very low dimension can be written in order to describe the dynamics of the membranes responsible for modulating the air flow in the process of generating the sound [3]. Maybe even more surprising: syllables of quite diverse acoustic nature could be synthesized by just adjusting the phase difference between two cyclic gestures, easy to interpret biologically [3,4]. If the number of biological parameters necessary to synthesize realistic sounds is small, a biomimetic device capable of emulating the behavior of the avian vocal organ can be conceived. Such a device can be a test-bench for the construction of biomimetic synthesizers [5], or used in experiences of altered auditory feedback (which are important experiments that try to test competing hypothesis on how birds compare their own vocalizations with memorized or innate song patterns) [6]. So far, these experiences required the computational alteration of the sound being produced, what required not only valuable computational time, but also the conversion of the results into specific formats capable of synthesizing song through loudspeakers. This fact produces a delay on the feedback of approximately one syllable which represents an important limitation to test learning hypothesis on real time.

In this work we report the construction of an electronic syrinx, i.e., an analogical circuit that performs an analogical integration of song. We drive this device with time series data emulating the air sac pressure and the tension of syringeal muscles, and show that the device is capable of synthesizing realistic sounds (as in Ref. [7]). Moreover, we test the hypothesis that time series as the ones needed to drive the system can be reconstructed from the song. In order to do so, we built two transducers. The first one, captures sound signals by means of a microphone, and generates as output a voltage signal proportional to the frequency of the sound. This allows us to estimate the tension of syringeal muscle, since previous work shows that this is proportional to the frequency of the vocalization [7]. The second transducer also receives a signal from a microphone, and generates as output a signal proportional to the amplitude envelope of the sound signal. This allows us to estimate the pressure of the air sacs, as we show in this work. Fitting procedures applied to physiological data recorded from singing birds, allow us to adjust the proportionality constants. We tested these devices by driving the electronic syrinx with known functions, and comparing them with the outputs of our transducers, which had as inputs the sound synthesized by the electronic device. Finally, we reconstruct air sac pressure and syringeal tension from the song of a cardinal, and compare the synthetic sound generated by our device with the song.

The work is organized as follows. Section II presents the electronic syrinx, as well as a brief review of the underlying model. Section III contains the preliminary studies that allow us to conjecture that the sound envelope is proportional to the bronchial pressure. Then, the transducers generating pressure and syringeal muscle tension from sound are described in Sec. IV. Our results are described in Sec. V and Sec. VI contains our conclusions.

II. BIRDSONG SYNTHESIZER BASED ON A MODEL: THE ELECTRONIC SYRINX

A. The model

Recently, a model for the physical processes at play dur-

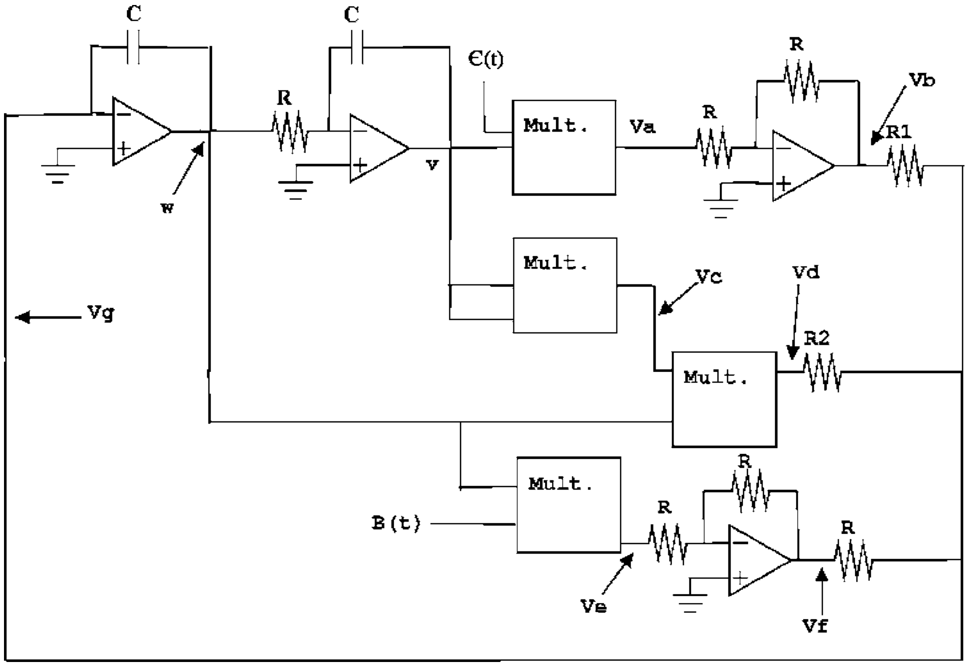

FIG. 1. The circuit of the electronic syrinx. This circuit analogically integrates a dynamical model for the behavior of a variable describing the position of a syringeal labium. Two input functions are needed to drive this device into or out of the region of the parameter space where relaxation oscillations take place.

ing the production of sound by the syrinx was presented [4]. This model contains parameters which can be qualitatively related to the activities of the muscles mentioned in the previous section. In this model, the labia move according to the coordinated dynamics of two global modes [8]. The first one is a lateral displacement, while the second mode is an upward propagating wave. If the labia are displacing away from each other (towards each other) while constituting a convergent (divergent) profile, in each cycle the labia get energy from the air flow [3]. The reason is that while presenting a convergent profile, the average pressure between the labia is closer to the bronchial pressure, whereas inter-labial pressure is closer to atmospheric pressure for a divergent profile. This results in a force in the same direction as the velocity of displacement of the labia, which might overcome the dissipation. This force acts on labia, which are also subjected to other forces: restitution (due to the elasticity of the tissues) and eventually a high dissipation if the labia displace too much from their equilibrium position (this dissipation is the loss of energy that occurs either when the labia collapse against each other or with the containing walls). A complete description of this model can be found in Ref. [3], but in Ref. [4] a simplified version was found to be able to generate realistic sounds while preserving the basic elements of the model. This model, which describes the dynamics of the departure of the midpoint of a labium from the prephonatory position x reads

$$x' = y, \tag{1}$$

$$y' = -\epsilon x - Cx^2 y + By, \tag{2}$$

where ϵ stands for the restitution constant of the labium, and B is the total dissipation constant (constituted by both the negative dissipation induced by the interlabial pressure as discussed above and the positive dissipation representing energy losses). The parameter C is the nonlinear dissipation constant. For large departures from the equilibrium position (i.e., large absolute values of x), the nonlinear dissipation term becomes very large. This models the effect of containing walls, as described in Ref. [4]. Throughout this work, we take $C = 2 \times 10^8$ dyn s/cm^3 g. More realistic models for this force lead to signals with different harmonic contents, but since the most remarkable acoustic features are determined by the time evolution of the fundamental frequency, a nonlinear saturating term is enough to model realistic sounding songs. Many birds, such as the canary (*Serinus canaria*) or the chingolo (*Zonotrichia capensis*), have songs which are assembled by syllables with a simple timbre. These sorts of songs are explained by the model.

On the other hand, other species have syllables with a more complex timbre. Several mechanisms can account for the arisal of spectral complexity: the interaction between sources and tract, the excitation of high order vibrating modes in the labia, among others [12]. For these cases, a richer model than the one used in this work should be integrated in order to synthesize the vocalized sounds.

Once the dynamics of x is unveiled [integrating Eqs. (1) and (2), in the case of our simple model], it is possible to simulate a sound pressure perturbation at the lower part of the trachea, as $P = a_1 x + a_2 x'$ [4,8], where a_i, $i = 1, 2$ will depend on both geometric factors and the frequency of the vocalization. The time series data can be processed in order to generate an audio file readable by software, or used to drive a loudspeaker in order to generate synthetic sound.

B. The analogic device

With this in mind, we will start building an analog device in order to integrate the Eqs. (1) and (2). Figure 1 displays a schematic picture of our device. Following the circuit clockwise from the top, we see that $v=-(1/RC)\int w\, dt$. The voltage v_a is obtained by multiplying v and an external signal $\epsilon(t)$ (which will represent the varying tension of the ventral muscle). In our circuit, we used a AD633JN multiplier in order to perform this operation, which multiplies the signals and divides the result by a factor 10. The voltage V_b is just $V_b=-V_a$. By means of a multiplier, we construct $V_c=v^2/(10\text{ volts})$, which is in turn multiplied by w in order to generate the function $V_d=v^2w/(100\text{ volts}^2)$. In the third layer of our circuit, the external function emulating the cyclic changes in bronchial pressure are multiplied by the voltage w, generating the voltage $V_e=B(t)w/(10\text{ volts})$, which after the inverting amplifier gives rise to $V_f=-B(t)w/(10\text{ volts})$. The resistances R_1, R_2, R_3 convert the voltages V_b, V_d, and V_f, respectively, into currents which are added a the operational amplifier noninverting input. Therefore

$$w=-\frac{1}{C}\int\left(-\frac{-\epsilon(t)v}{(10\text{ volts})R_1}+\frac{v^2w}{(100\text{ volts}^2R_2)}+\frac{-B(t)w}{(10\text{ volts}R_3)}\right)dt. \quad (3)$$

In this way, calling $V_x=v$ and $V_y=-(-w/RC)$, we get

$$V_x' = V_y, \quad (4)$$

$$V_y'=-\frac{\epsilon(t)}{(10\text{ volts}C^2RR_1)}V_x-\frac{1}{(100\text{ volts}^2CR_2)}V_x^2V_y+\frac{B(t)}{(10\text{ volts}CR_3)}V_y, \quad (5)$$

which have the same form as Eqs. (1) and (2). We chose $C=0.1\mu F$, $R_1=10\Omega$, $R_2=33\Omega$, $R_3=10k\Omega$, and $R=10k\Omega$. We drive our device with forcing functions $B(t)$ and $\epsilon(t)$ of amplitudes in the order of the volts and frequencies in the range 1–10 Hz. For small values of the function $B(t)$, the voltage v basically follows the forcing, but beyond a critical value of $B(t)$, the voltage v displays large amplitude oscillations, at a frequency much larger than the forcing frequency. This "bursts" of activity represent the oscillation of labia in our problem. For the values of capacitors and resistances chosen, these rapid oscillations have frequencies in the order of the kiloHz.

III. DRIVING THE ELECTRONIC SYRINX

As discussed in the Introduction, important efforts are being dedicated to the study of birdsong produced by oscine birds, as a model of how a brain is reconfigured in the process of learning a complex behavior (as a vocalization). There is evidence that auditory feedback is necessary not only in the learning period, but it is also actively used to maintain the stability of the song [6]. Recent experiments showed that deafening adult birds causes changes in their songs [9]. However, to learn how the song system operates it is necessary to manipulate auditory feedback without disabling neither the motor or the auditory pathways.

The device we are reporting in this work is suitable for carrying out on line alterations of auditory feedback. Yet, altered feedback experiences take long periods of time (several months), and keeping cannulae inserted in air sacs, or wired connected to muscles during them is unfeasible. For this reason, we explored the possibility of extracting the forcing functions in Eqs. (1) and (2) from a vocalization. According to previous work, the air pressure necessary to set up the oscillations and the tension of the oscillating labia are a minimal number of forcing functions required to produce a sound resembling the original song.

Mindlin *et al.* have already demonstrated the possibility to reconstruct the tension of the *ventralis syringealis* muscle (vS) using the frequency of the sound [7]. In order to reconstruct the air sac pressure from the sound signal, we first test the hypothesis that the air sac pressure is proportional to the sound envelope. We recorded 13 songs of a cardinal, simultaneously measuring the air sac pressure. The pressure was taken using a procedure which was discussed in detail in Ref. [10]. Briefly, we proceeded as follows. Air sac pressure was recorded with a flexible cannulae (Silastic tubing, 1.6 mm o.d., 6 cm length) was inserted into the thoracic air sac through a hole in the abdominal wall into the left posterior thoracic air sac, and connected to a piezoresistive pressure transducer. Surgery for performing the hole in the abdominal wall was performed under isoflourane anesthetic. The cannulae insertion site was sealed with adhesive tissue, and the free side of the tube was connected to a piezoelectric pressure transducer (FMP-02PG, Fujikura, Japan). The songs were recorded with a microphone (AT8356; Audiotechnica, Stow, USA) in front of the cage, and its output amplified (100×, Brownlee 410, San Jose, USA). Numerical integration of the rectified signal through a low pass filter (with a characteristic time $\tau=2\times10^{-4}$ s) was used to compute the envelope of the sound signal f_{SE}. Figure 2 shows the plot of the recorded bronchial pressure P_{br} *versus* the sound signal envelope f_{SE}, for values of the variable larger than 10% of the maximum sound signal envelope value. Below this threshold, the signal is simply noise. Figures 2(a) and 2(b) correspond to signals recorded from bird number 1, while Figs. 2(c) and 2(d) correspond to records of bird number 2. A linear fitting was carried out between these variables, for six songs of bird number 1, and seven of bird number 2,

$$P_{br}=af_{\text{SE}}+b. \quad (6)$$

The average values of the fitting parameters over the songs of each bird were $(a,b)=(1.5,-1260)$ for bird number 1, and $(a,b)=(2.37,-478)$ for bird number 2.

IV. DESIGN OF THE TRANSDUCERS

In Fig. 3, we display an electronic device that implements the process of getting the air sac pressure from the sound signal in real time, by means of the numerical test shown in

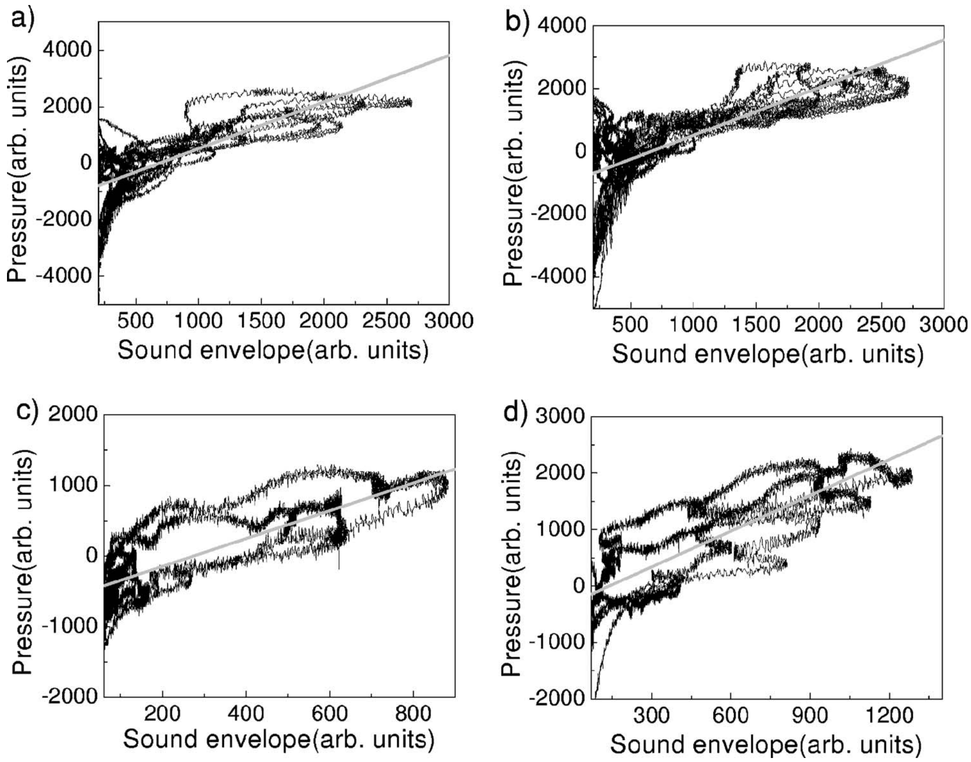

FIG. 2. The relationship between sound envelope and bronchial pressure. In this work we assume this relationship is linear for sound values above a threshold.

Sec. III. In Fig. 3(a) the different operations implemented by the device are shown, whereas in Fig. 3(b) the detailed circuits used to implement the operations are presented. The input of the device is a sound signal, recorded by a microphone. The first step is to rectify the signal with a full wave rectifier. The particular implementation of this rectifier produces an output that is all negative (the output signal of the rectifier is the inverted modulus of the input).

A half wave rectifier is a circuit that when is driven by a signal with a domain in the positive and negative voltages only allows one of the signs to pass and gets the other part to zero. In contrast, a full wave rectifier converts the whole signal to positive or negative voltages [11]. In the chosen implementation, the core of the circuit is the operational amplifier with the diodes connecting the inverting input with the output which guarantee the existence of feedback for positive and negative inputs and finally the full wave rectification.

The following stage is a low pass filter with a characteristic time $\tau=2\times10^{-4}$ s. In order to ensure a more abrupt transition between the frequencies that the filter let pass and the ones that eliminates we built a second order filter [11].

The third step is to determine what parts of the signal do exceed a threshold, to finally amplify that part. This was implemented by a voltage clamp. The operational amplifier with the diode connecting the inverting input with the output causes that if the input is less than the threshold (voltage at the non-inverting input) there is no feedback and the output is equal to the input ("follower" regime). Otherwise, the output displays a constant value ("constant output" regime). The "follower" regime corresponds to phonation and the "constant output" regime corresponds to silence. The multiplier incorporated in the same stage allows us to separate the two regimes. Finally, the signal is linearly amplified.

Our second transducer aims at the reconstruction of a time series signal capable of driving the electronic syrinx, emulating the tension of the *ventralis syringealis* (vS) muscle. As we have already described in the previous section, Goller and Suthers found that the activity in the vS muscle correlates through a monotonic increasing function with the frequency of the vocalizations. In this work we use a linear approximation for this relationship, reasonable within the range of frequencies spanned by the syllables under analysis. The core of the device is a frequency/voltage converter: an integrated circuit which converts the frequency of the input signal into an output voltage (LM2907, National Semiconductors). In Fig. 4 we show the steps and the circuits implementing them [Fig. 4(b)]. The first step is a voltage clamp. As in the previous transducer, this guarantees that the input signal to the frequency/voltage converter corresponds to a phonation signal (i.e., that it has a well-defined frequency). This avoids the generation of outputs corresponding to noise. The threshold voltage is adjusted to make it equivalent to the one used in the other transducer.

The following step is the frequency to voltage converter. The input signal to this device requires to be prepared for the correct reconstruction of the frequency. The input signal must cross the zero level. Otherwise, if the input signal is all positive or negative the converter can no longer generate an output proportional to the frequency of the input. The optimization of the converter's response in order to ensure a correct reconstruction up to phonation frequencies of 10 Hz has been done by changing the electronic components connected to it. As a result of this optimization the output is rippled. The characteristic frequency of this ripple is of about 400 Hz. To avoid it, a low pass filter was built. A fifth order active filter is used to ensure a complete blockage of the ripple frequency without perturbing the slow frequency of

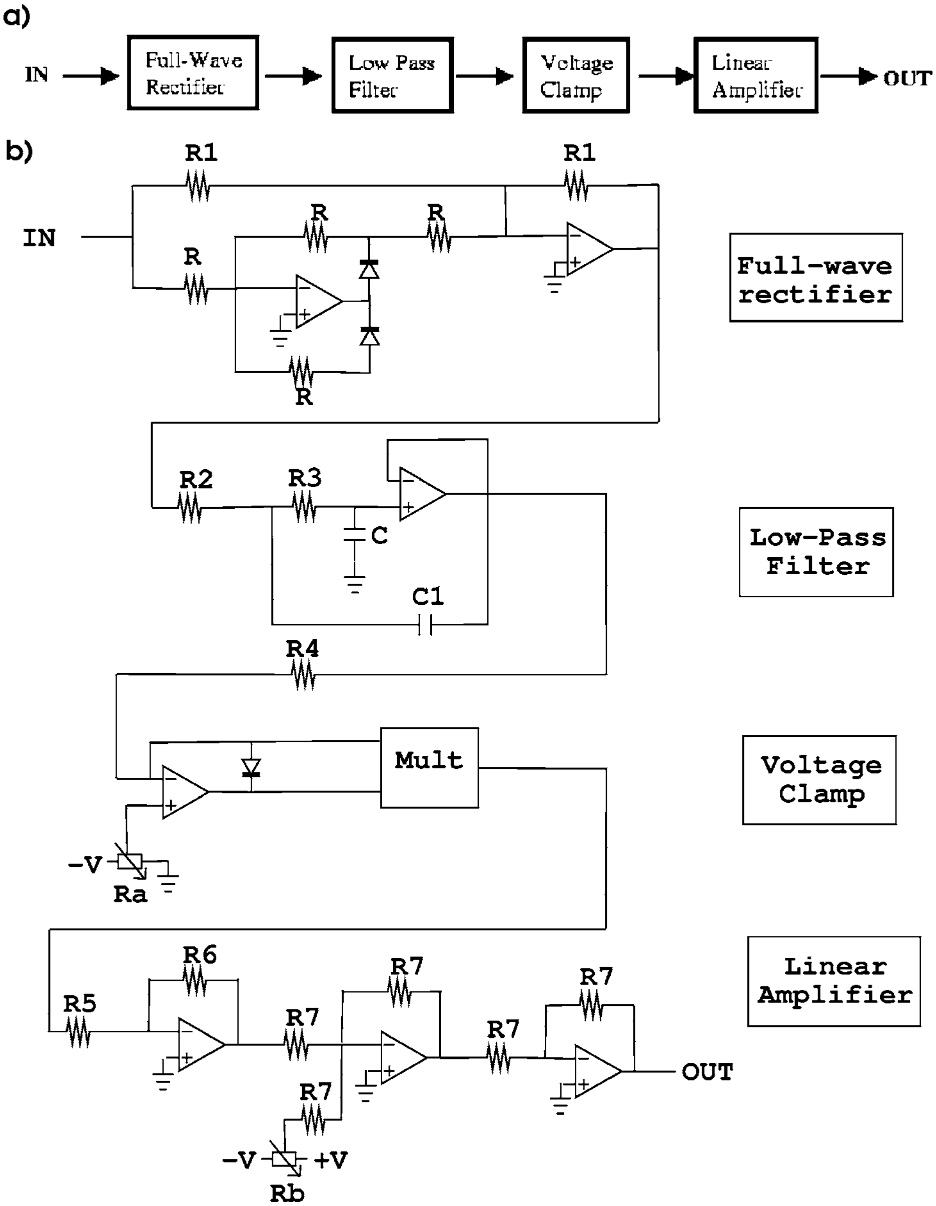

FIG. 3. The first transducer carries out a sequence of operations (rectification of the signal, low band filtering, clamping and amplification) (a), by means of integrated circuits (b). The values of the resistances used in this device are $R=100\ \mathrm{k}\Omega$, $R_1=200\ \mathrm{k}\Omega$, $R_2=680\ \Omega$, $R_3=18.2\ \mathrm{k}\Omega$, $C=330\ \mathrm{nF}$, $C_1=100\ \mathrm{nF}$, $R_4=2.2\ \mathrm{k}\Omega$, $R_5=3.2\ \mathrm{k}\Omega$, $R_7=1\ \mathrm{k}\Omega$, while R_6, R_a, and R_b were linear resistances up to $R_{6,\max}=25\ \mathrm{k}\Omega$, $R_{a,\max}=1\ \mathrm{M}\Omega$, and $R_{b,\max}=5\ \mathrm{k}\Omega$.

the phonation. The last stage is a linear amplification circuit. In the two transducers, the operational amplifiers used in our construction are LM348 (National Semiconductors), and the multiplier used is an AD633JN (Analog Devices).

V. RESULTS

In this section, we test the devices described in the previous section. In our first experiment, the electronic syrinx is driven by two harmonic signals in phase $[B=3\ \text{volts} \times \sin(\omega t)+2\ \text{volts};\ \epsilon=0.25\ \text{volts}\times\sin(\omega t)+0.25\ \text{volts};\ \omega=5\ \text{Hz}$; see Fig. 5]. These functions drive the electronic syrinx in and out the phonation regime (see Ref. [3]), generating a series of syllables. In Fig. 5 we display the result of this experiment. Figure 5(a) shows the driving function emulating the tension (in black), and the signal reconstructed by our vS tension transducer (in grey). Notice that within the time intervals in which phonation takes place, the signal reconstructed from the sound follows closely the instruction that drove the syrinx. In Fig. 5(b) we show the second harmonic instruction used to emulate the air sac pressure and drive the syrinx, and the reconstructed signal. Figures 5(c) and 5(d) display sonograms, i.e., the time evolution of the spectral content of a window of the audio signal. Figure 5(c) shows the sonogram of the synthetic sound produced by the syrinx, when driven by the original harmonic functions. In Fig. 5(d) we show the sonograms of the sound synthesized by the electronic syrinx, when driven by the reconstructed gestures. The qualitative features of the original sound are reproduced. We repeated the experiment for driving gestures presenting a phase delay ϕ between them such that $\phi=\pi/2$ $[B=3\ \text{volts}\times\sin(\omega t+\pi/2)+1\ \text{volts};\ \epsilon=0.75\ \text{volts}\times\sin(\omega t)+1.25\ \text{volts};\ \omega=5\ \text{Hz}$; see Fig. 6]. The sonogram of the synthetic sound generated in this circumstance is built upon u shaped syllables, and the sounds generated by the reconstructed instructions share that qualitative feature (see Fig. 6).

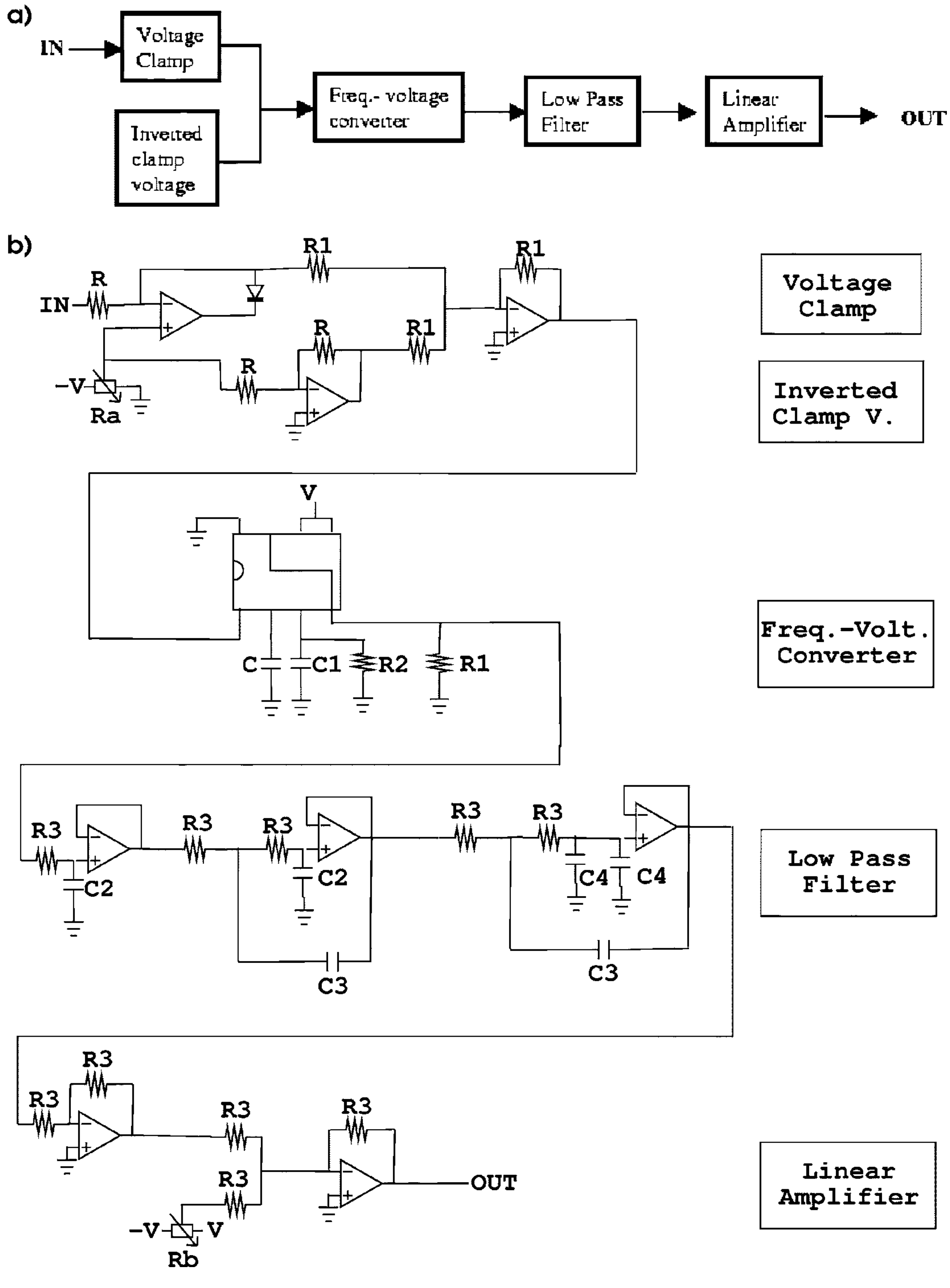

FIG. 4. The second transducer generates a signal which we assume will be proportional to the tension of the syringealis ventralis (vS) muscle. At the core of this device lies a frequency/voltage converter. The values of the resistances used in this device are $R=2.2$ kΩ, $R_1=10$ kΩ, $R_2=440$ kΩ, $R_3=1$ kΩ, $C=1$ nF, $C_1=2.2$ nF, $C_2=1.5$ μF, $C_3=2.2$ μF, $C_4=220$ nF, while R_a and R_b were linear resistances up to $R_{a,\max}=100$ kΩ, and $R_{b,\max}=10$ kΩ.

Our second set of tests consisted in the generation of song by the electronic syrinx, when the driving functions where not harmonic functions but the physiological variables measured while the bird was singing a song. The sonogram of the vocalization is displayed in Fig. 7. As the sound [spectrally described in Fig. 7(a)] was being generated, the vS tension transducer, as well as the transducer generating pressure gestures were activated, generating a couple of function driving the electronic syrinx. Therefore, in real time, a "copy" of the song was being produced. The spectral analysis of this synthetic sound is displayed in Fig. 7(b). Notice the qualitative agreement between the spectral features of the natural and synthetic signals, both being up-sweeps between 2 and 3 kHz.

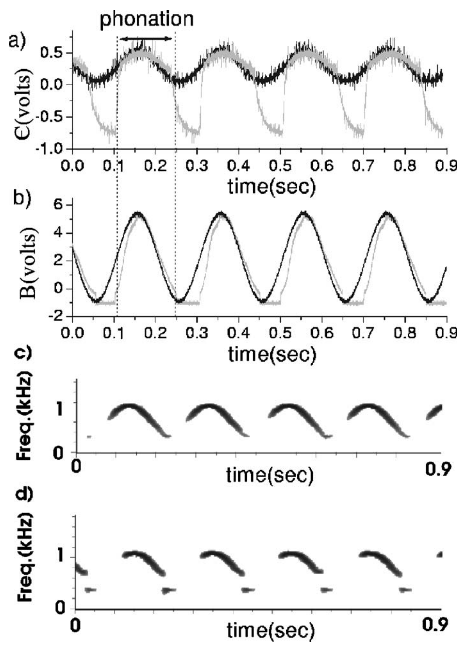

FIG. 5. Testing the devices. Harmonic functions representing tension of vS muscle and air sac pressure [in black, in (a) and (b), respectively] are used to drive the electronic syrinx. The sound is analyzed by the two transducers, generating gestures [(a) and (b), in grey] that resemble the original ones. In (c) and (d) we show the spectral properties of the original sound and the synthetic sound. The original gestures are in phase.

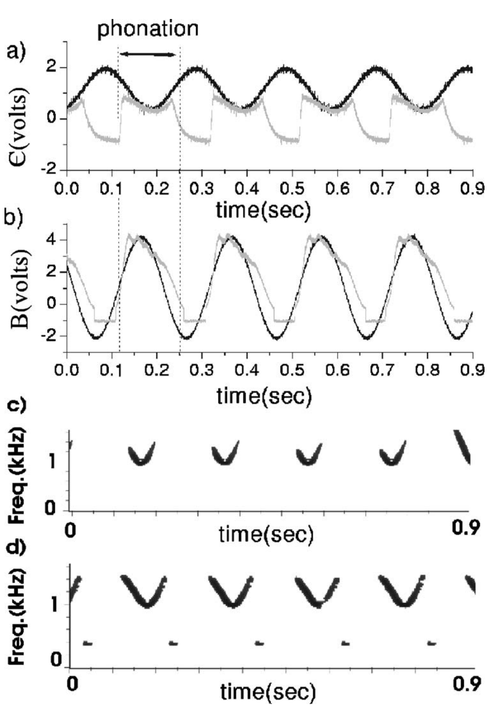

FIG. 6. Same as in Fig. 5, but with a phase difference $\phi = \pi/2$ between the driving gestures.

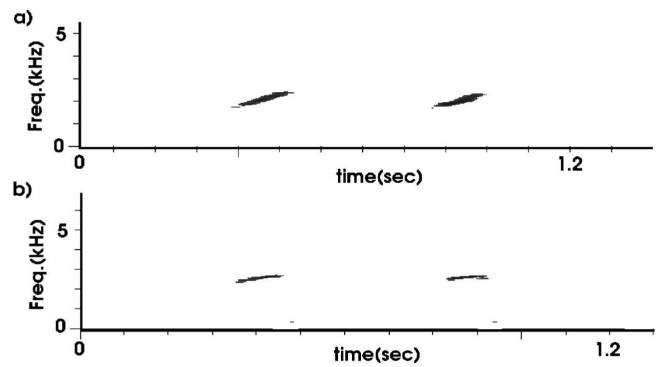

FIG. 7. Application of the transducers to copy sound. A cardinal is recorded, and two driving functions are reconstructed by the two transducers. These functions are used to drive the electronic syrinx, in order to generate sound. The sonograms of the natural song (a) and the one of the synthetic song (b) present qualitatively similar features.

VI. CONCLUSIONS

In this work we report the construction and test of three analogical devices: an "electronic syrinx," and two transducers. The electronic syrinx is an analogical integrator of the differential equations describing the dynamics of a syringeal labium which is equivalent to the acoustic pressure pattern of a tonal bird. In order to develop a device for nontonal birds with wide timbre syllables, it is necessary to enrich our model as described in Ref. [12].

From the variable describing the labial dynamics in our model, it is possible to drive a loudspeaker in order to generate sound. Yet, the power of the model consists in relating the time-dependent driving parameters with physiologically sensible variables. In Ref. [7] this model was tested, driving the differential equations with physiological data, and comparing recorded and synthetic sounds.

Beyond the construction of an analogical integrator of the equations, we design and construct transducers that allow us to reconstruct these gestures from acoustic properties of the song. We tested these devices by driving the electronic syrinx with known functions and comparing the reconstructed gestures with the known functions, as well as the recorded sounds with the ones generated after driving the syrinx with the reconstructed gestures. Finally, the same procedure was implemented, but comparing the natural song with the synthetic one generated with reconstructed gestures.

As we have discussed in the Introduction, birdsong is an important test bench where to explore the mechanisms by which a complex behavior is learned. Within that paradigm, the set of experiments known as "altered auditory feedback" are of a key importance. So far, experiments used mostly computationally assisted alteration of acoustical features of the song being played back to the bird. Our devices open a new perspective for experimental work. So specific parameters with biological interpretation can be changed, and the delays between the original song and the reconstructed songs is a small fraction of the syllable duration (approximately 10%).

The search of a minimal number of functions capable of synthesizing a song, by the integration of simple models with biologically sensible parameters might be of clinical importance. It is likely that the larger the number of parameters are included, the better will the synthetic sound be. Yet, the possibility of generating a reasonable approximation to the sound with a few physiological variables brings closer thissort of circuits to viable biomimetic devices.

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[1] M. S. Brainard and A. J. Doupe, Nat. Rev. Neurosci. **1**, 31 (2000).
[2] F. Goller and O. N. Larsen, J. Comp. Physiol., A **188**, 841 (2002).
[3] T. Gardner, G. Cecchi, M. Magnasco, R. Laje, and G. B. Mindlin, Phys. Rev. Lett. **87**, 208101 (2001).
[4] R. Laje, T. Gardner, and G. B. Mindlin, Phys. Rev. E **65**, 051921 (2002).
[5] R. Reuter, R. Orglmeister, and H. Herzel, Int. J. Bifurcation Chaos Appl. Sci. Eng. **9**, 1075 (1999).
[6] A. Leonardo and M. Konishi, Nature (London) **399**, 466 (1999).
[7] G. B. Mindlin, T. J. Gardner, F. Goller, and R. Suthers, Phys. Rev. E **68**, 041908 (2003).
[8] I. R. Titze, J. Acoust. Soc. Am. **83**, 1536 (1988).
[9] K. W. Nordeen and E. J. Nordeen, Behav. Neural Biol. **57**, 58 (1992).
[10] F. Goller and R. A. Suthers, J. Neurophysiol. **75**, 867 (1996).
[11] P. Horowitz and W. Hill, *The Art of Electronics* (Cambridge University Press, Cambridge, 1989).
[12] G. B. Mindlin and R. Laje, *The Physics of Birdsong* (Springer Verlag, Berlin, 2005).