"From song of birds to extended virtual reed instruments"
Physical modeling of birds' vocal tracks and application to a new kind of sound sustain virtual instruments

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Abstract
The vocal tracks of animals show a wide variety of sound generation processes. They present similarity with human vocal track but they are sometimes rather different. In order to find new physical models for synthesis and control of musical sounds, we have studied and built models of the vocal track of birds. A bird has to produce sound (as a means to indicate its localization and territory to the others) with a great acoustical efficiency, in comparison to its size. Moreover, the vocal track of birds, the syrinx, has an interesting characteristic: it is composed of two pipes receiving the air flow from the lung, linked to the trachea. The air flow produces an excitation of the "membrane tympaniforme" (the analog of the human vocal string) and the difference of the two air pressures in these pipes gives a very characteristic way to control the sound. Using the CORDIS-ANIMA physical modeling language developed at ACROE, we achieved a physical model of the syrinx. We used for the "vocal string" a model of clarinet reed previously achieved in our laboratory. Then, we introduced the two pipes as two air flows. We introduced also two types of muscular action: the control of the air flow through bronchi, and the control of the membrane action. From this basic model, it is possible to developed extended models in several ways, allowing timbre mutation "from the bird to the clarinet". But mainly, it is possible to set a new range of gesture performance exploration within virtual instruments: using a force-feedback interface, we can sing with our fingers, like (or unlike) the birds.

1. Introduction
The general structure of a musical instrument is a single or multiple chain of four physical components linking the hands (or more generally the gesture) to the hearing: the excitation structure (ES), the vibrating structure (VS), the local environment (LE) and the global environment (GE) (cf. figure 1). The vibrating structure is the seat of the acoustical vibrating phenomenon. This deformable object can be put out of its equilibrium state by an excitation from the ES. Coming back to this state through oscillatory movements, it produces the acoustical vibrating phenomenon. The LE (local environment) adapts the vibrating phenomenon to the propagation (aerial) medium and the GE (global environment), in which the sound sources and the hearing subjects are both placed, gives some new characteristics to the sound and some informations about relationships between sources, space and hearing subjects.

We find the same components and functions in the humans or animals vocal tracks.

In the case of human vocal track, the sound is controled in several ways: at the level of the "gesture" (the breath) or at the level of the vibrating structure (the vocal string), by changing its anatomic configuration. The local environment (the vocal cavities) can also be modified in order to produce the vocal articulation through resonators shape modifications.

The physical modeling of the human vocal track resonance cavities is quite complex [1]. Here, we focus on a physical model of the syrinx, the vocal track of the birds. Syrinx is a curious and interesting acoustical production device by the fact that it is composed of two sound sources. Indeed, the bird has two vibrating structures that it can control [2]. The richness of the bird singing does not come from its ability to control the shape of resonators, which are much simpler than in the human vocal track, but from its capacity of using two separate excitation sources and to control the vibrating structure configuration.

![Diagram](image)

**Figure 1:** from gesture to hearing: the instrumental chain

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2. The syrinx

It is generally assumed that for simple singings, the syrinx works almost as a clarinet [3,4]. Indeed, the reed makes the air flow issued from the lungs vibrates, while the pipe interacts with this vibration and "characterizes" it. For the birds, the role of the reed is played by the membranes tympaniformes (MT). The phonatory apparatus of the birds takes place at the junction of the primary bronchial tubes at the beginning of the trachea (cf. figure 2). The syrinx is constituted of membranes tympaniformes which are put into vibration during the sound emission. An important system of muscles is associated to this apparatus: the extrinsic muscles (tracheolateralis, sternotrachealis). They play an important role for the strain of the membranes tympaniformes.

![Figure 2: Anatomic position of the bird phonatory apparatus](image)

The syrinx works as follow: during the tensing of the respiratory muscles, the aerian bags internal pressure increase. The interclaviculaire bag, situated between the two membranes tympaniformes makes them enter the area of the bronchea. The equilibrium position of the membranes results of the balance between the aerian bag pressure and the membranes strain. The membranes deformation depends on the air flow and begins only after a certain threshold. The suction force draws the membrane into the bronchea hole. The membrane strain becoming too high, it allows the membrane to go back to its equilibrium position. The sound results of the air flow variations due to the bronchea hole opening and closing.

In the case of more complex singing, the comparison with the wind instruments doesn't work, on account of the muscle system complexity. Moreover, the number and the arrangement of these muscles are different according to the species. In general, we find extrinsic muscles, playing on the control of the membranes strain, and intrinsic muscles, playing on the bronchea space (cf. figure 3).

![Figure 3: Sketch of the syrinx](image)

3. Modeling the syrinx with CORDIS-ANIMA

CORDIS-ANIMA [5,6] is a formalism to describe and simulate physical objects. It has been developped by ACROE since 1980's. Using four concepts: punctual material element <MAT>, links <LIA>, non-linear links <LIC> and full modularity/interaction, it allows simulations in a very efficient way of a wide variety of physical objects: vibrating, moving, deformable objects, components of musical instruments, marionettes, vehicles, sand, pastel, flows of fluids, etc... We use it for the sound synthesis, the animated image synthesis, the simulation of complex multisensorial objects with gestural manipulation and force feedback interaction [7,8].

We used CORDIS-ANIMA to create the model of the syrinx.

The membranes (membranes tympaniformes) are considered as oscillators which movements are sustained. The equations of the clarinet model [9], adapted to the syrinx allow to state:

\[ y''(t) + Z \cdot y'(t) + \omega_0 \cdot y(t) = \frac{p(t) - p_0}{\mu} \]

where \( p_0 \) is the pressure at the bronchus, \( p(t) \) is the pressure in the trachea, \( Z, \omega_0, \mu \) and \( y(t) \) are respectively the damping coefficient, the pulsation, the masse per unit of surface and the position of the membrane. The non-linear relation between the flow and the pressure (specific to the wind instruments) comes from the general equation of movement quantity conservation and is layed out in:

\[ \frac{p_0}{\rho} + \frac{1}{2} V_0^2 = \frac{p(t)}{\rho} + \frac{1}{2} V^2 \]

where \( V_0 \) is the velocity of air in the bronchus, \( V \) the velocity of air under the membrane and \( \rho \) the air density. From these equations, it goes the
characteristic relation between pressure and flow (cf. figure 4).

Within the CORDIS-ANIMA language, it is possible to simulate such an oscillator with a specific <MAT> module which name is CEL (standing for second order cellule). The CEL module is composed of a punctual mass (MAS), a linear spring (RES) and a linear damper (FRO) attached at a fixed point (SOL) [6].

![Figure 4: shape of the non-linear relation between pressure and flow in a clarinet reed](image)

We verified the capacity of the model to produce the “two tracks” phenomenon. Experimental measurements [12] show that the two sides of the syrinx emit signals with shifted frequencies. So we have choose two different set of parameters for each side of the model.

Then, we took as inputs for the F1(t) and F2(t) functions, experimental measurements of the air flow in the branches. We can see on the sonograms that the temporal distribution of the signal is the same than in the experimental sonogram.

Finally, we put in the model the left and right inputs (F3(t) and F4(t)) from experimental measurements of the muscles activity during the frequency modulation. In spite of the low accuracy of the experimental signals, we can observe significant correspondences between the simulation and the experimental sonograms (cf. figures 7a and 7b).

4. Conclusion

This model shows good properties as a general model for synthesis of birds singing. But of course its main interest is in its generality: It can be considered as a general model for musical instrument with sustained sounds. Further, using several gestural interfaces and a suitable matching between the inputs F1(t), F2(t) and excitation gesture, F3(t), F4(t) and modification gesture (see the instrumental gesture typology [13,14]), it is possible to use our hands to sing like (or unlike) a bird.

We have made, at ACROE in 1998 such an experience using the CRM (Clavier Rétroactif Modulaire [8]).
References


