PROSODY AND THE MUSIC OF THE HUMAN SPEECH *

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We propose the use of a self-oscillating dynamical system –the pre-Galileian clock equation– for modeling the laryngeal tone. The parameters are shown to be the minimal control needed for generating the prosody of the human speech. Based on this model, we outline a peak delay detection algorithm for extracting the prosody of the real speech.

Keywords: Prosody; self-oscillating system; speech.

1. Introduction

One of the distinctive features of the human brain is its aptitude for communicating thoughts by speaking. In spite of its relevance for exchanging information and emotions, it is very hard to deal with the system made by the auditory-phonatory apparatus by means of physical models. The emotional component of verbal communication relies on the fundamental sound of speech –the laryngeal sound– which is generated by the vocal cords without any movement of mouth or tongue.

The glottal sound has been studied for centuries in the framework of different disciplines, and numerous explanations for its unique capability of transmitting emotions had been proposed. Among these ideas, one of the most captivating is Jean-Jacques Rousseau theory about the relation between prosody and music. In his Essai sur l’origine del languages, Chapter XII, he writes:

"La colère arrache des cris menaçants, que la langue et le palais articulent: mais la voix de la tendresse est plus douce, c’est la glotte qui la modifie, et cette voix devient un son; seulement les accens en sont plus fréquents ou plus rares, les inflexions plus ou moins aigües, selon le sentiment qui s’y joint".

Later, in the same book, he writes:

"Qu’on fasse la même question sur la mélodie, la réponse vient d’elle-même: elle est d’avance dans l’esprit des lecteurs. La mélodie, en imitant les inflexions de la voix, exprime les plaintes, les cris de douleur ou de joie, les menaces, les gémissements; tous les signes vocaux des passion sont de son ressort. Elle imite les accens des

*This paper is dedicated to Francesco Guerra.
langsues, et les tours affectés dans chaque idiôme à certains mouvements de l'ame: elle n'imite pas seulement, elle parle; et son langage inarticulé, mais vif, ardent, passionné a cent fois plus d'énergie que la parole même”.

We want to study the relation suggested by Rousseau between musical melodies and corresponding prosodic patterns, using a simple model for glottal motion. The laryngeal sound is generated by the cyclic motion of opening and the closing of vocal cords. At the beginning of the cycle air is pushed by the diaphragm, the vocal cords are drawn together and air pressure increase, but when the pressure reaches a critical value it blows the vocal cords apart and flows between them. Then the vocal cords are then drawn together as a result of the Bernoulli effect.

To understand this oscillating behavior “without spring”, we study a simple self-oscillating model for the pre-Galileian clock which produces a realistic laryngeal tone. The model can also be used as a powerful tool for the analysis of glottal sounds. The results of the analysis can be compared with some adiastematic notation to suggest a formal correspondence between prosody and music. In this direction it is possible to suggest that the prosody is the drift of the musical gusto evolution, to answer to the main question about the nature of stochastic processes which produce “beautiful” or at least meaningful sequences of sounds.

The paper is organized as follows. In the next section we introduce a non-linear dynamical system which exhibit all the main features of the glottal cycle. In section 3 the parameters of the system are used as time dependent controls for the glottis, and in the following we present an algorithm for analyzing the control of the recorded sounds. The form of this control suggest also a delay-line-like behavior for the cochlear apparatus.

2. The cycle of the glottis.

The laryngeal tone is the oscillatory variation in air pressure generated by the cyclic movement of the vocal cords. At the beginning of each cycle the vocal cords are held together by the action of the arytenoid cartilages. Air is forced into the trachea and when the pressure exceeds a threshold (the value of which depends on the strength of the vocal cords), it opens the vocal cords and flows through the glottis. Inside the constricted laryngeal passage air pressure falls (its velocity increase) giving rise, for the Bernoulli principle, to the pressure drop closing the vocal cords and completing the cycle. The cycle repeats at rates of 130-220 times per second. The ear perceives the variation in the cycle period as changes in the pitch.

The valve-like behavior producing the laryngeal tone is characteristic of self-oscillating systems. A self-oscillating system is an apparatus which produces a periodic process at the expense of a non-periodic source of energy. Self-oscillations do not depend on the initial condition but are determined by the properties of the system itself. Examples of self-oscillating systems include the electric bell, saw-tooth signal generators as well as wind and string musical instruments.
Several realistic models for the glottal behavior have been proposed over the years starting with the celebrated “two-mass model”. We will now present a minimal mechanism that exhibits all the main features of glottal behavior. In particular we want to make explicit both the dependence of the oscillation period on the forces acting on the system, and the features of the trigger mechanism producing the self-oscillations.

Let $s \in [-1,1]$ the variable related to the aperture of the glottis: in the extreme positions $s = -1$ indicates that the glottis is completely closed and $s = 1$ that the vocal cords are open. We represent $s$ in the $[-1,1]$ interval in agreement with the usual representation of the acoustic signals. Assuming that the laryngeal tone is proportional to the opening, $s$ can be assimilated to the signal itself

$$[T_0, T_1] \ni t \rightarrow s(t) \in [-1,1]$$

where $[T_0, T_1]$ is a time interval. For simplicity we assume that the forces act on the glottis instantaneously: for $s(t) \geq +s_0$ the Bernoulli effect produces a force which closes the glottis, for $s(t) \leq -s_0$ the pressure opens the glottis, and for $-s_0 < s(t) < +s_0$ no force is acting on the glottis. This approximation is useful for solving the model, but can be easily relaxed in computer simulations. When the glottis is opening, the force $P(s)$ acting on it is negative and when it is closing $P(s) > 0$. Therefore over the interval $-s < s < +s$ the force $P = P(s)$ is a two-valued function of the variable $s$ representing the opening of the glottis. Following the Andronov argument $P(s)$ imposes limitations on the shape of the phase plane trajectories, since assigning $(s, \dot{s})$ does not uniquely determines the state of the system where $-s_0 < s < s_0$. Instead we have to use a phase surface with two half-planes superimposed: (a) $s < s_0$ and (b) $s > -s_0$. The points on this two-sheet phase surface have a one-to-one correspondence with the states of the system, the passage of the representative point from sheet (a) to the sheet (b) occurs for $s = +s_0$, the reverse passage for $s = -s_0$, and the abscissa remains unvaried in both the cases.

To further simplify the model we assume that the force $P(s)$ applied to the glottis by the air pressure is constant in absolute value: $P(s) = +P_0$ for the closing and $P(s) = -P_0$ for the opening. To model the vocal cords tension we introduce the constant resistance $f_0$, which does not depend on the position of the glottis. On the basis of these simple assumptions it is possible to describe two different laryngeal sounds. The first one, that we call prosody, does not have a natural period because there is no elastic force contributing to the movement of the vocal cords. This system does not exhibit high stability and is therefore a good model for cases in which the period of oscillation has to be sensitive to variations in control parameters. The second type has a natural period due to the elastic term, and in absence of feeding can perform damped oscillations. This model can be used to describe singing, but is out of the scope of this paper.

The dynamic equation for the model without the elastic force is

$$m \ddot{s} = f(s, \dot{s}) + P(s)$$

(2)
where \( m \) is the glottis mass, \( P = P(s) \) the force produced by air pressure on it and \( f(s, \dot{s}) \) is the resistance of the vocal cords. If we assume \( f(s, \dot{s}) = -f_0 \text{sign}(\dot{s}) \) during the motion \( \dot{s} \neq 0 \), equation (2) becomes

\[
m\ddot{s} = -f_0 \text{sign}(\dot{s}) \pm P_0
\]

Introducing the variables \( x = s/s_0 \) and \( z = +\sqrt{P_0/m s_0 t} \), equation (3) can be rewritten as

\[
\begin{align*}
\dot{x} &= y \\
\dot{y} &= -F \text{sign}(y) - (-1)^n
\end{align*}
\]

where the dot operator is now the derivative with respect to the scaled time \( z \), \( y \neq 0 \), \( F = f_0/P_0 \) and \( n \) is even when the glottis is closing and odd when the glottis is opening. If the air pressure outside the glottis is a linear function of the glottis aperture, the \( x \) variable can be studied as the waveform of the laryngeal tone.

If \( F \geq 1 \) and the glottis is at rest (\( y = 0 \)) the force produced by the air pressure can not open the vocal cords, \( \dot{y} = 0 \) and the point \((x, 0)\) is the equilibrium state. Therefore, for the case when \( f_0 < P_0 \) the system has no states of equilibrium. From equation (4) we have for the \((a)\) half plane \((x < +1 \text{ and } P = -P_0)\)

\[
\frac{dy}{dx} = 1 - F \text{sign}(y) - (-1)^n
\]

and integrating we have \( y^2/2 - (1 + F)x = k \) for \( y < 0 \) and \( y^2/2 - (1 - F)x = k \) for \( y > 0 \), \( k = \text{const} \), so that the phase path on the sheet \((a)\) is made by two parabolae and the representative point moves to the left on the lower half of the sheet \((y < 0)\) and to the right on the upper one. All the phase paths on sheet \((a)\) reach their boundaries on the semiaxis \( x = +1, y > 0 \), and the phase paths on sheet \((b)\) are symmetrical with respect to the origin of the coordinates.

Following the Andronov treatment \(3\) we draw the two axes \( v \) where \( x = -1 \), \( y = -v < 0 \) and \( v' \) where \( x = 1 \), \( y = v' > 0 \) and consider the sequence of the points of intersections with them of an arbitrary phase path: \( v, v_1, v_2, v_3, \ldots \).

The representative point pass at the point \((-1, -v)\) from sheet \((b)\) to sheet \((a)\) and reach the axis of the abscissa at the point \((-\xi, 0)\), where \( \xi \) is given by the equation \( v_1^2 = 2(1 + F)(\xi - 1) \). Then the representative point moves on the upper half of the sheet \((a)\) and reaches its boundary at \((+1, v_1)\) where \( v_1 \) is given by \( v_1^2 = 2(1 - F)(\xi + 1) \). The phase path on \((a)\) establishes a one-to-one correspondence between the points of the axes \( v \) and \( v' \), a point transformation where the sequence function is parametrized by the peak \( \xi \) of the laryngeal tone. Then the representative point passes on the sheet \((b)\) and reaches the semi-axis \( v \) on \((-1, -v_2)\), where \( v_2 \) is determined by the same sequence (due to the symmetry of the sheets \((a)\) and \((b)\)) and the point transformation of \( v' \) in \( v \) is the same of \( v \) in \( v' \). The fixed point \( v = v_1 = \bar{v}, \) corresponding to a symmetric limit cycle, is given by the equation \((1 + F)(\xi - 1) = (1 - F)(\xi + 1)\) and is determined by the glottal peak

\[
\bar{\xi} = \frac{1}{F}
\]
and $v^2 = 2^{1-F^2}$. The Lamerey’s ladder given by the two curves $v^2 = v^2(\xi)$ and $v_1^2 = v_1^2(\xi)$, tends to the fixed point if $v^2 = 2(1 + F)(\xi - 1)$ has a steeper slope than $v_1^2 = 2(1 - F)(\xi + 1)$ and the unique periodic motion is reached from any initial conditions. The period of the oscillation can be easily computed by the evaluation of the transit time on the parabolae arcs

$$T = 4\sqrt{\frac{2s_{om}}{P_0}} \frac{1}{F(1 - F^2)}$$

(7)

and depends on both the air pressure and the vocal cord resistance.

Fig. 1. The plot of the signal as a function of time (on the left) and the corresponding phase path (on the right), where the two sheets are glued together and the vocal cords resistance is different for the opening and the closing. The value of $s$ has been scaled to fit in the $[-1, 1]$ interval.

If we assume that the vocal cords resistance is not the same for the opening and closing glottis, the equation (4) gives the signal of figure 1. The corresponding sound is very similar to the sound obtained by placing a microphone on the throat and directly recording the glottal sound.

3. The prosodic patterns of the controlled glottis

The stability of equations (3) can be evaluated by the ratio of the percentage variation of the period to the percentage variation of the two parameters, and shows to be very small. Because of this low stability, the system is not suitable for building clocks. However its sensitivity to variation in the parameters and the fast convergence to the limit cycle, make it a suitable model for a controlled glottis.

Let us suppose that the air pressure and the strength of the vocal cords are controlled by the speaker. Controlling $P(t)$ and $f(t)$ it is possible to change the amplitude and the period of the laryngeal tone to produce the prosodic patterns conveying the non semantic aspect of the speech.

In order to decode the prosodic pattern we need to know the time evolution of the control function

$$C(t) = \left( f(\bar{\xi}(t), T(t)), P(\bar{\xi}(t), T(t)) \right)$$

(8)
In other words we suggest that when the cochlea decode the prosody of the speech it needs only to detect the value of $\bar{\xi}$ and the time delay of $\bar{\xi}$ with respect to the previous one. This stands in agreement with recent studies about the delay lines inside the cochlea. Therefore the system can be controlled by a piecewise constant function which changes the period and the amplitude. If we choose a control function (see figure 2) we determine the time evolution of $s(t)$ given by equation (3). The resulting phase path and waveform are plotted in figure 3. Note that in this case the phase paths intersect because now the system is controlled and non-autonomous.

We observe also that the characteristic time of the control change is larger than the period of the wave, in agreement with studies comparing of the laryngeal tone period with the muscular control time. Therefore we state that the prosodic information is all contained in $C$ and that in order to decode the prosodic pattern the listener needs to decode the $C$ function.
4. Perception of the laryngeal tone

The dynamical system given by equation (4) can be used to detect and represent the prosody of real speech. To accomplish this we only need to know the discrete function

\[ [T_0, T_1] \ni t \rightarrow \bar{\xi}(t) \in [0, 1] \]  

(9)

Even though the sound of (9) is different from the fundamental sound (1), their prosody is identical. Moreover during the speech process the time interval between two consecutive \( \bar{\xi} \) is changed continuously to produce the prosodic meaning.

The \( \bar{\xi}(t) \) function can be extracted from a recorded sound by means of the simple procedure of sliding a temporal fixed window on the signal, and selecting for each window the value of \( s(t) \) not exceeded backward and forward\(^{11}\). The resulting signal is shown in figure 4 on the left.

In order to obtain the control \( C \) function we have to know the \( T(t) \) value also. To do this we plot the delay of each peak \( \bar{\xi}(\tau_i) \) with respect to the previous one \( \bar{\xi}(\tau_{i-1}) \) as function of time (figure 4 right) where \( \tau_1, \tau_2, \ldots, \tau_N \) are the times where \( \bar{\xi}(t) \) is non zero.

![Fig. 4. The glottal peaks for the wave in figure 3 (left) and the \( \bar{\xi} \) delay (right) as function of the time.](image-url)

In this way it is possible to construct a map of the control \( C \) and therefore to decode the prosody of the speech. The amplitude and the delay of \( \bar{\xi} \) are the only information needed. The control function represented in figure 2 can be obtained by the data represented in figure 4 via the equations (6) and (7). If we take the fundamental given by the Fast Fourier Transform of \( s(t) \) we obtain a rough map of \( C \) because the FFT needs some cycles to detect the period.

When applied to the real speech, the “peak detection” yields maps which resemble the neumatic notation of the gregorian chant. This is not surprising given that during the middle age the rules of the correspondence between text and the music were very strict, and the composer had to put the known melodies together rather than inventing anything new\(^{12}\). Following the ideas of Rousseau, the algorithm proposed for the analysis and the synthesis of the laryngeal tone can be a
tool for studying the correspondence between prosody and music by means of the comparison of the control maps with the adiastematic notation system

5. Conclusion

Although it is still not clear how the proposed system is related to the fluidodynamics of the glottis, the self-oscillating system used to model the laryngeal behavior is very simple and exhibits good agreement with the main features of the glottal sounds. It produces a realistic laryngeal sound an can be used to extract the prosody from a recorded sound. Its main features, shared with many “natural” oscillators is the lacking of the elastic term. The control of this system suggests also that the cochlear behavior is related to delay line detection. The equation is very simple to simulate in real time on a computer, and can be used for generating prosodic patterns or for manipulating the prosodic meaning of recorded sentences.

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References

1. J. J. Rousseau, *Essai sur l’origine des languages*, A. Belin, Paris, 1817.
2. L. D. Stephens, A. M. Devine, *The Prosody of the Greek Speech*, Oxford University Press, 1994.
3. A. A. Andronov, A. A. Vitt, S. E. Khaikin, *Theory of Oscillators*, Pergamon Press, Oxford, 1965.
4. C. Baffioni, F. Guerra, L. Tedeschini Lalli, *The theory of stochastic processes and dynamical systems as a basis for models of musical structures* in “Musical grammars and computer analysis”, (L. S. Olschki, Firenze, 1984).
5. An good description and some animations about the glottis movement can be seen at [http://www.phon.ox.ac.uk/~jcoleman/phonation.htm](http://www.phon.ox.ac.uk/~jcoleman/phonation.htm)
6. J. L. Flanagan, *Speech Analysis Synthesis and Perception*, Springer Verlag 1972.
7. K. Ishizaka, J. L. Flanagan *Synthesis of Voiced Sounds from a Two-Mass Model of the Vocal Cords*, Bell. Syst. Tech. J., vol. 51, pp. 1233-1268, 1972.
8. I. Titze, The human vocal cords: A mathematical model, part I, Phonetica 28, 129-170, 1973.
9. I. Titze, The human vocal cords: A mathematical model, part II, Phonetica 29, 1-21, 1974.
10. R. Nobili, F. Mammuno, *Biophysics of the cochlea. II. Steady-state non linear phenomena*, J. Acoust. Soc. Am.,99: 2244-2255, 1996.
11. R. D’Autilia *Non Linear Models for Speech Melody*, in Human and Machine Perception, Kluver Academic Publishers, 1999.
12. Idelsohn A. Z., *Jewish Music*, Dover, 1992.