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DYNAMICS OF OSCILLATION ONSET_OFFSET IN A TWO-MASS MODEL OF THE VOCAL FOLDS FOR MEN, WOMEN, AND CHILDREN

Jorge Carlos Lucero
Departamento de Matemática, Universidade de Brasília, Brasília DF 70910-900
lucero@mat.unb.br

Edson Cataldo
Departamento de Matemática Aplicada, PGMEC- Programa de pós-graduação em Engenharia Mecânica e Programa de pós-graduação em Engenharia de Telecomunicações, Universidade Federal Fluminense, Rua Mário Santos Braga s/n, Centro, Niterói RJ 24020-140
ecataldo@zipmail.com

Rubens Sampaio
Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro, Rua Marquês de São Vicente 225, Gávea, Rio de Janeiro 22453-900
rsampaio@mec.puc-rio.br

Lucas Nicolato
Departamento de Engenharia de Telecomunicações, Universidade Federal Fluminense, Rua Passo da Pátria 156, São Domingos, Niterói RJ 24120-240
lucasnicolato@yahoo.com.br

Abstract. *This work explores the capability of a two-mass model of the vocal folds to reproduce their oscillatory behavior during voice production by men, women, and children. The model includes airflow separation effects at the glottal exit and nonlinear characteristics of tissue viscoelasticity, and is coupled to a two-tube approximation of the vocal tract in configuration for vowel /a/. Male, female, and child configurations are implemented by scaling dimensions and biomechanical parameters according to available physiological data. Simulations are obtained by numerical solution of the equations, and using the subglottal pressure, neutral glottal area, and vocal fold stiffness as control parameters. In general, the results show good agreement with measured voiced records, with a clear hysteresis effect: the threshold conditions that start the oscillation are more restricted than those that stop it, as described by the subcritical Hopf bifurcation model for onset-offset proposed in previous studies. The results also show that the oscillation threshold conditions are more restricted for smaller larynges, in agreement with reported experimental data.*

Keywords*:vocal folds, oscillation, two-mass model, phonation, voice*

1. Introduction

The purpose of this paper is to analyze how the oscillatory behavior of the vocal folds at phonation changes according to laryngeal size, in cases of phonation by men, women and children, and how it is controlled during speech by individual speakers. Since the several biomechanical parameters of the vocal folds, the interaction between the vocal folds and airflow, and other terms of glottal aerodynamics, depend on the anatomical dimensions of the glottis, variations of the oscillation dynamics as functions of those dimensions might be expected. Such variations might influence the strategies for controlling voicing onset and offset during speech by women vs. men (Lucero and Koenig, 2000), and might be important to understand the development of motor control of the larynx in children (Lucero and Koenig, 2003).

At the same time, it explores the capability of low dimensional vocal fold models to reproduce vocal fold vibration onset-offset patterns observed experimentally during speech. Past research has indicated that low-dimensional models, though simpler than the human larynx, still capture many significant aspects of vocal fold vibration for speech (e.g., Titze, 1994). In various experimental settings, it has been observed that the biomechanical configuration of the vocal folds at oscillation onset is different from their configuration at oscillation offset. For example, the subglottal pressure is higher at onset than offset (Titze, Schmidt, and Titze, 1995), the intraoral pressure is lower (Munhall, Löfqvist, and Scott Kelso, 1994), the airflow is lower (Koenig, 2000), and the glottal width is smaller (Hirose and Niimi, 1987). Using the qualitative theory of dynamical systems, this phenomenon has been described by an oscillation hysteresis model (Lucero, 1998, 1999). This model is built from the combination of a cyclic fold bifurcation for limit cycles, where a stable and an unstable limit cycle are generated, with a subcritical Hopf bifurcation, where the unstable limit cycle is absorbed. The former bifurcation corresponds to oscillation offset, and the latter to oscillation onset. Thus, onset and offset occur at different bifurcations, and consequently at different values of the control parameters.

In particular, the two-mass model of the vocal folds (Ishizaka and Flanagan, 1972) has been a useful representation for voice production studies. Besides its capability to produce realistic simulations of voice, its simplicity allows for analytical treatments of the oscillatory dynamics of the vocal folds. For example, it has been applied to studies of oscillation regions and phonation threshold conditions (Lucero, 1993; Mergell et al., 1998; Steineck and Herzel, 1995; de Vries et al, 2002), irregular and pathological vibrations (Herzel et al., 1995; Jiang and Zhang, 2002, Mergell, Herzel, and Titze, 2000; Steinecke and Herzel, 1995), voice registers (Lucero, 1996; Berry, 2001), oscillation hysteresis (Lucero, 2004), prosthesis design (Lous et al., 1998), among other several works.

In our recent work, we have used a two-mass model to simulate speech production of adults (Lucero and Koenig, 2000) and children (Lucero and Koenig, 2003) in the vicinity of an abduction gesture. There, an inverse dynamic approach was used, in which the model was fitted to collected speech records. The fit was performed by computing the time varying configuration of laryngeal parameters that best reproduce the given speech signal at the model output. Our purpose was to determine control strategies of voicing onset and offset used by speakers, and detect possible differences between female, male, and child speakers. The results showed that devoicing at the abduction-adduction gesture for /h/ is achieved by the combined action of vocal fold abduction, decrease of subglottal pressure, and increase of vocal fold tension. Each of these actions has the effect of inhibiting the vocal fold oscillation, and even suppressing it when reaching an offset threshold. Also, differences in oscillation regions between men and women were found. Women have in general more restricted conditions for the vocal fold oscillation, probably as consequence of their smaller laryngeal size.

This paper intends to explore in more deep the relation of the vocal fold oscillation dynamics with laryngeal dimensions. The next sections will present the vocal fold model, and will explore its oscillatory behavior as a function of its size.

2. Models

2.1. Vocal folds

The larynx is modeled using a modified version of the two-mass model of the vocal folds (Ishizaka and Flanagan, 1972). Fig. 1 shows a sketch of the model. Each vocal fold is represented by two mass-damper-spring systems (m_1–b_1–k_1 and m_2–b_2–k_2), coupled through a spring (k_c). The two vocal folds are assumed identical, and they move symmetrically with respect to the glottal midline, in the horizontal direction.

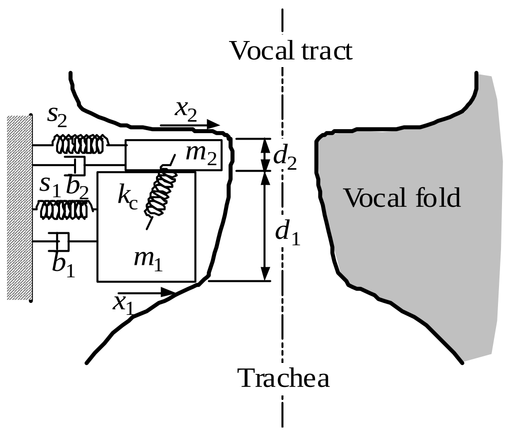

Figure 1. Two-mass model of the vocal folds (Ishizaka and Flanagan, 1972).

When the glottis is open, the equations of motion may be written as

$$\begin{cases} m_1\ddot{x}_1 + b_1(x_1, \dot{x}_1) + s_1(x_1) + k_c(x_1 - x_2) = f_1, \\ m_2\ddot{x}_2 + b_2(x_2, \dot{x}_2) + s_2(x_2) + k_c(x_2 - x_1) = f_2, \end{cases} \quad (1)$$

where b_i, s_i, f_i, with i = 1,2, denote the forces related to the tissue damping, elasticity, and the airflow, respectively, m_i are the masses, and x_i are their horizontal displacements measured from a rest (neutral) position. The tissue elastic forces have a cubic characteristics, of the form

$$s_i(x_i) = k_i x_i (1 + 100 x_i^2), \quad i = 1,2 \quad (2)$$

where k_i are stiffness coefficients.

The stiffness coefficients and masses are computed through a Q scaling factor: $k_i = Qk_{0i}$, $k_c = Qk_{0c}$, and $m_i = m_{0i}/Q$. This Q factor may be regarded as a scaling factor for the natural frequencies of the model, and provides a convenient way to control the oscillation frequency.

For the damping forces, instead of the usual linear term $r_i \dot{x}_i$, we adopted a nonlinear characteristics of the form

$$b_i(x_i, \dot{x}_i) = r_i(1 + \kappa|x_i|)\dot{x}_i, \quad i = 1,2 \tag{3}$$

where r_i and κ are coefficients. The reason was the need to limit the amplitude of the vocal fold oscillation, when the glottal width is increased. When a linear damping is used, an increase in the amplitude of the glottal pulses appears when the vocal folds are abducted (Lucero and Koenig, 2003; McGowan, Koenig, and Löfqvist, 1995). This effect does not appear in speech data, and is eliminated by the proposed nonlinear damping characteristics. The factor $r_i(1 + \kappa|x_i|)$ acts as an equivalent damping coefficient, dependent on the displacement x_i. Thus, it imposes a limit to the oscillation amplitude, by increasing the losses of the energy that fuels the oscillation, at large amplitudes. Note also that, at very low amplitudes ($x_i \rightarrow 0$) the damping factor approaches a linear characteristic. So, the threshold pressure and other conditions to start the vocal fold oscillation, which depend on the damping term, are not affected by its nonlinear part.

Such nonlinear damping term is also in agreement with experimental data. It is known that the vocal fold tissue, and soft tissues in general, have strong nonlinearities in their viscoelastic properties (Alipour-Haghighi and Titze, 1985; Chan and Titze, 2000). More specifically, the data show that the time constant of tissue relaxation curves increase with the level of strain imposed (Alipour-Haghighi and Titze, 1985). This result may be modeled by a damping factor which increases with strain, as in Eq. (3). Note that a linear damping term combined with the nonlinear stiffness in Eq. 2, which is the standard version of the two-mass model, would produce the opposite effect: relaxation curves with time constants that decreases with the level of strain. Here, as in our previous work, a value of $\kappa = 150$ is adopted, which was selected by inspection of the simulation results.

The contact between the opposite vocal folds is modeled as in Ishizaka and Flanagan's work (1972). We assume that at their rest position, both masses are at a distance x_0 from the glottal midline, and so each mass i collides with its opposite counterpart at a displacement $x_i = -x_0$. During contact, the stiffness is increased

$$s_i(x_i) = k_i x_i(1 + 100x_i^2) + 3k_i(x_i + x_0)\left[1 + 500(x_i + x_0)^2\right] \quad i = 1,2 \tag{4}$$

and the damping coefficient r_i is increased by adding 1 to the damping ratio $\xi_i = r_i / \left(2\sqrt{k_i m_i}\right)$.

2.2. Glottal and vocal tract aerodynamics

The glottal aerodynamics, for the open glottis, is modeled using a version of Ishizaka and Flanagan's equations (1972), updated with experimental results and a simplified version of the boundary layer model (Pelorson et al., 1994, 1995)

Letting the subglottal pressure be P_s, then the drop to pressure P_{11} at the glottal entry is, according to Bernoulli's equation,

$$P_s - P_{11} = \frac{\rho u_g^2}{2a_1^2} \tag{5}$$

where ρ is the air density, u_g is the volume velocity of glottal airflow, $a_1 = 2l_g(x_1 + x_0)$ is the cross-sectional lower glottal area, and l_g is the vocal fold length. Note that, contrary to Ishizaka and Flanagan (1972), flow contraction (*vena contracta*) is not considered, following Pelorson et al. (1995).

Along mass m_1, pressure drops to a value P_{12} due to air viscosity, given by:

$$P_{11} - P_{12} = \frac{12\mu d_1 l_g^2 u_g}{a_1^3} \tag{6}$$

where μ is the air viscosity, and d_1 is the width of mass m_1.

Two cases must be considered next, according to the glottal shape. Let us consider first the case in which the glottis is convergent or slightly divergent, i.e., $a_1 > k_s a_2$, where $k_s > 1$ is a suitable constant, and $a_2 = 2l_g(x_2 + x_0)$ is the cross-sectional upper glottal area. At the boundary between both masses there is a pressure variation, given by

$$P_{21} - P_{12} = \frac{\rho u_g^2}{2}\left(\frac{1}{a_1^2} - \frac{1}{a_2^2}\right) \tag{7}$$

where P_{21} is the air pressure at the lower edge of mass m_2. Next, there is a pressure drop along mass m_2 due to air viscosity, similar to Eq. (6)

$$P_{21} - P_{22} = \frac{12\mu d_2 l_g^2 u_g}{a_2^3} \tag{8}$$

where P_{22} is the pressure at the glottal exit. At this point, and due to the abrupt area expansion, the flow detaches from the glottal wall and forms a jet stream. We assume that all energy is lost in the stream due to turbulence (Pelorson et al., 1994), and so $P_{22} = P_o$,where P_o is the pressure input to the vocal tract.

When the glottis is more divergent, with $a_1 \geq k_s a_2$, we assume that the point of flow separation from the glottal wall moves inside the glottis and occurs at the boundary between both masses. This is a gross simplification of the boundary layer model (Pelorson et al, 1994, 1995), which shows that the point of flow separation moves upstream the glottis as a continuous function of the glottal angle of divergence, and becomes asymptotically constant at high Reynolds numbers. As in our previous works (Lucero, 1999; Lucero and Koenig, 2000, 2003), we adopt a value $k_s = 1.2$ for the asymptotic constant. In this case, we assume again that all airflow energy is lost due to turbulence from the point of detachment, and so we let $P_{21} = P_{22} = P_o$.

Finally, the forces f_i acting on the masses are computed as $f_i = (P_{i1} + P_{i2})/2$.

The forces for the case of glottal closure are computed as follows (Ishizaka and Flanagan, 1972)

$$f_1 = d_1 l_g P_s, \quad x_1 \leq -x_0 \text{ or } x_2 \leq -x_0 \tag{9}$$

$$f_2 = \begin{cases} d_2 l_g P_s, & \text{if } x_1 > -x_0, x_2 \leq -x_0, \\ 0, & \text{if } x_1 \leq -x_0. \end{cases} \tag{10}$$

The vocal tract was represented by a standard two-tube configuration for vowel /a/ (Flanagan, 1972; Titze, 1994), shown in Fig. 2. Its equations were derived using a transmission line analogy, terminated in a radiation load of a circular piston in an infinite baffle. The elements of the transmission line were computed from the cross-sectional areas S_1, S_2 and lengths L_1, L_2 of the vocal tract tubes, using the standard equations of the analogy (Flanagan, 1972; Ishizaka and Flanagan , 1972).

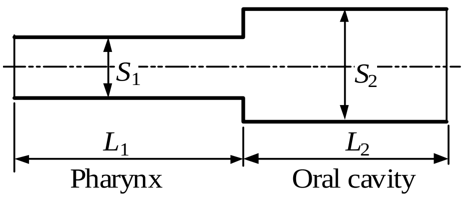

Figure 2. Vocal tract model for vowel /a/ (Titze, 1994).

2.3. Dimension scaling and control parameters

The following values were adopted for a standard male configuration of the vocal fold and vocal tract models (Flanagan, 1972; Ishizaka and Flanagan, 1972): $m_{01} = 0.125$ g, $m_{02} = 0.025$ g, $k_{0c} = 25$ N/m, $k_{01} = 80$ N/m, $k_{02} = 8$ N/m, $\xi_1 = 0.1$, $\xi_2 = 0.6$, $l_g = 1.4$ cm, $d_1 = 0.25$ cm, $d_2 = 0.05$ cm, $x_0 = 0.02$ cm, $P_s = 800$ Pa, $Q = 1$, $S_1 = 1$ cm^2, $S_2 = 7$ cm^2, $L_1 = 8.9$ cm, $L_2 = 8.1$ cm.

To control the model dimensions, a single scaling factor β for all dimensions is used. This is a simplification of the actual size variations of the larynx and vocal tract. According to Titze (1989), two main scaling factors for the size relation between male and female larynges may be identified, depending on the specific dimension. The relative lengths between the pharynx and oral cavity also differs for men, women, and children. Here, the single factor β was adopted as a convenient and simple way to control the overall size of the model. This strategy is in agreement with the objective of this study, which is to achieve a general understanding of how the vocal fold oscillatory behavior depends on their size, and not to obtain detailed simulations of vocal output. Thus, an adult female configuration would correspond to an approximate factor of $\beta = 0.72$ (according to data by Titze, 1989), and a 5-year-old configuration to $\beta = 0.64$ (according to data by Goldstein, 1980).

All linear dimensions are then scaled by multiplying by β. Masses were accordingly computed by multiplying by β^3, to compensate the volume increase. For the tissue stiffness, we assumed a constant elasticity modulus for all sizes. This assumption is again a simplification, since Titze (1989) reported slightly stiffer tissue for females than for males, probably as a result of differences in tissue composition. Similar differences between child and adult tissues have also been reported (Kurita, Hirano, and Nakashima, 1983). For a constant elasticity modulus, the stiffness coefficient is directly proportional to the cross-sectional area of the tissues, and inversely proportional to their length. Hence, the scaling of all dimensions by a factor β implies that stiffness is also scaled by this same factor. For the tissue damping, we assumed a constant damping ratio for all sizes.

3. Preliminary theory

The dynamics of the two-mass model in the vicinity of its rest position has been analyzed in previous studies (e.g., Lucero, 1993; Steinecke and Herzel, 1995). Let us briefly recall that the stability of that position may be determined by taking the linear part of the equations of motion in its vicinity. Simplifying the equations by neglecting losses by air viscosity, and assuming that the load presented by the vocal tract to the vocal folds is negligible (i.e., setting $P_o = 0$), we find and equilibrium position (rest position) at $x_1 = x_2 = 0$. The linearized differential equations of the two-mass model around that position, are:

$$\begin{cases}\left(\beta^3 m_{01}/Q\right)\ddot{x}_1 + \beta^2 r_1 \dot{x}_1 + \beta Q k_{01} x_1 + \beta Q k_{0c}(x_1 - x_2) = 2\beta^2 d_1 l_g Ps / x_0, \\ \left(\beta^3 m_{02}/Q\right)\ddot{x}_2 + \beta^2 r_2 \dot{x}_2 + \beta Q k_{02} x_2 + \beta Q k_{0c}(x_2 - x_1) = 0,\end{cases} \tag{11}$$

where we have already introduced the Q factor and the scaling coefficient β. Its characteristic equation is

$$s^4 + \frac{Q}{\beta}\left(\frac{r_1}{m_{01}} + \frac{r_2}{m_{02}}\right)s^3 + \frac{Q^2}{\beta^2}\left(\frac{k_{01}+k_{02}-\Gamma}{m_{01}} + \frac{k_{02}+k_{0c}}{m_{02}} + \frac{r_1 r_2}{m_{01}m_{02}}\right)s^2 + \frac{Q^3}{\beta^3 m_{01}m_{02}}\left[r_1(k_{02}+k_{0c}) + r_2(k_{01}+k_{0c}-\Gamma)\right] + \frac{Q^4}{\beta^4 m_{01}m_{02}}\left[(k_{01}+k_{0c}-\Gamma)(k_{02}+k_{0c}) - k_{0c}(k_{0c}-\Gamma)\right] = 0 \tag{12}$$

where

$$\Gamma = \frac{2\beta d_1 l_g P_s}{x_0 Q} \tag{13}$$

Writing the above equation as $s^4 + a_1 s^3 + a_2 s^2 + a_3 s + a_4 = 0$, it may be shown that a pair of complex roots cross the imaginary axis from left to right when $a_1 a_2 a_3 - a_1 a_3 - a_1^2 a_4 = 0$ (Lucero, 1993). This fact signals the occurrence of a Hopf bifurcation, at which the rest position becomes unstable and a limit cycle is produced, and determines the onset threshold of the vocal fold oscillation.

Here, we want to analyze how the oscillation onset condition depends on the subglottal pressure P_s, the glottal half-width at the rest position of the vocal folds x_0, the Q factor, and the scaling factor β. The glottal half-width characterizes the degree of abduction-adduction of the vocal folds and is one of the major parameters for controlling their oscillation onset-offset. The Q factor represents the degree of tension of the vocal folds, and is the main control for the fundamental frequency of the vocal fold oscillation. The subglottal pressure is a main control for the amplitude of the oscillation, and thus for voice intensity.

Replacing the coefficient values from Eq. (12) into the onset threshold condition, it may be shown that it is independent of the individual values of the above four parameters, when keeping constant the relation

$$\frac{\beta P_s}{x_0 Q} = C \tag{14}$$

where C denotes a constant (the demonstration is straightforward and therefore is omitted here). For example, for the standard parameters we obtain $C = 1.1049 \times 10^6$ N/m^3. Equation (14) tells that, for smaller larynges (smaller values of β), the threshold value of the subglottal pressure to start the vocal fold oscillation must be higher (larger P_s), the vocal folds must be driven closer together (smaller x_0, or larger adduction), and the tension of the tissues must be smaller (smaller Q). Let us note that this conclusion is not related to the existence of any losses due to air viscosity; in fact, such losses were neglected at the start of this analysis. Looking at the above equations, we may note that factor β appears in Eq. (14) due to the reduction in the medial surface of mass m_1, on which the air pressure acts (if this surface was constant, then the previous conclusions would be just the opposite). This is an important result, which shows that smaller larynges might have more restricted phonation regions simply because their glottal surface is smaller, and so they absorb less energy from the airflow to fuel the vocal fold oscillation. The restriction is not necessarily caused by a larger glottal resistance to the airflow, although this might be a significant additional factor.

4. Simulation results

Figure 3 shows plots of simulated oral airflow, as an example of the model's output. The simulations were obtain by varying the glottal half-width from 0.02 cm to 0.1 cm, and then back to the original value, following a sinusoidal pattern. This variation pattern imitates the glottal abduction-adduction gesture during the production of utterance /aha/ in running speech (see Lucero and Koenig, 2000, 2003). All other parameters were kept fixed at their standard values.

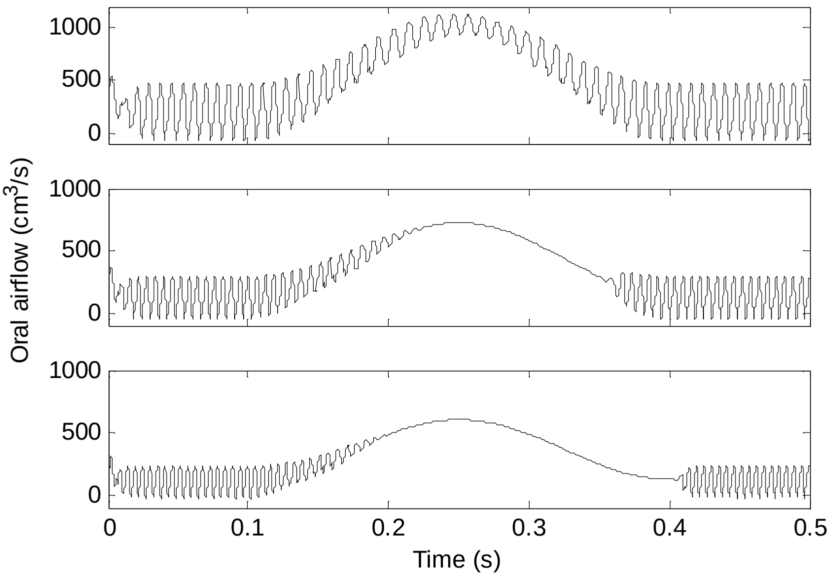

Figure 3. Oral airflow patterns during a vocal fold abduction-adduction gesture. Top: $\beta = 1$ (male adult), middle: $\beta = 0.71$ (female adult), bottom: $\beta = 0.64$ (5-year-old child).

Comparing the plots, we see that the male flow has larger amplitude and lower fundamental frequency (approximately 123 Hz, 165 Hz, 187 Hz, from top to bottom), as expected. In the female case, the glottal pulses stop at the peak abduction, and restart at the end of the following adduction. This is a clear oscillation hysteresis phenomenon, discussed in the Introduction, in which the vocal fold oscillation stops and starts at different values of the glottal width. In the child case, the glottal pulses stop even earlier than the female case, at a lower value of the glottal width. The plots clearly show that the oscillation region becomes more restricted as the laryngeal size decreases. Similar results may be obtained when varying the other two main parameters, the subglottal pressure P_s and the Q factor.

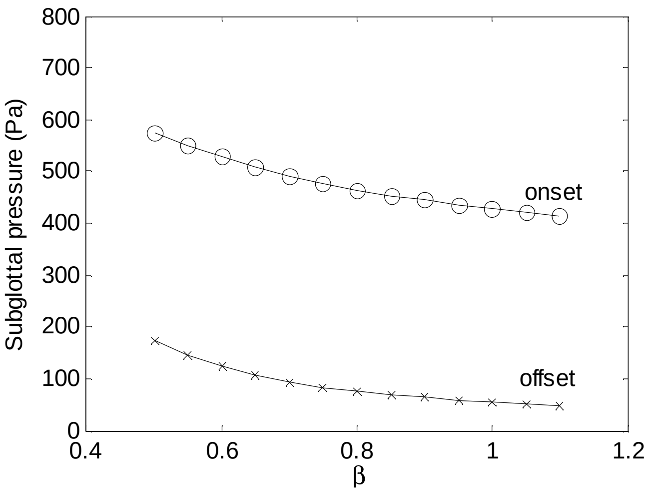

Figure 4. Oscillation threshold values of subglottal pressure

The next plots show the threshold conditions of parameters as function of the scaling factor β. Let us consider first the subglottal pressure thresholds (Fig. 4). Simulations of vocal fold oscillation were performed, while varying the subglottal pressure from 0 to 1000 Pa, and back to 0, following a sinusoidal curve (similar to Fig.3). The simulated glottal airflow was next low-pass filtered at a 50 Hz cut-off to eliminate glottal pulses, using a sixth order Butterworth filter. The AC flow component was next computed as the difference between the unfiltered airflow and the filtered result. From the AC component, we computed next the rms amplitude, using a zero-crossing algorithm with low pass filtering (Titze and Liang, 1993) to identify the individual cycles. The oscillation onset was determined as the instant of time at which the rms flow amplitude increased above a threshold value of 1 cm^3/s. Similarly, the offset was determined as the instant of time at which the rms flow decreased below 1 cm^3/s. Identification of the onset threshold is in general an easy task, because the oscillation builds up quickly at that point. The offset threshold, on the other hand, is more difficult and imprecise, because the oscillation amplitude tends to vanish slowly, and it is not clear at which point the rest position has become a stable equilibrium point (Lucero, 2004). However, our objective here is to see how the threshold vary for different laryngeal sizes, and the above criterion suffices

In Fig. 4, we can see that there are two different values of the thresholds, one for onset, and a lower value for offset. The existence of such two thresholds confirms again the occurrence of an oscillation hysteresis phenomenon (Lucero, 1999). Both thresholds increase when the larynx size is reduced, as predicted by Eq. (14).

Figures 5 show the glottal half-with threshold. Again, we note the existence of two thresholds, with the onset one smaller than the offset. This mean that to start the oscillation, the vocal folds must be adducted closer together than the position at which oscillation stops, as shown in the simulations in Fig. 3. Also, we note that both thresholds decrease with the laryngeal size.

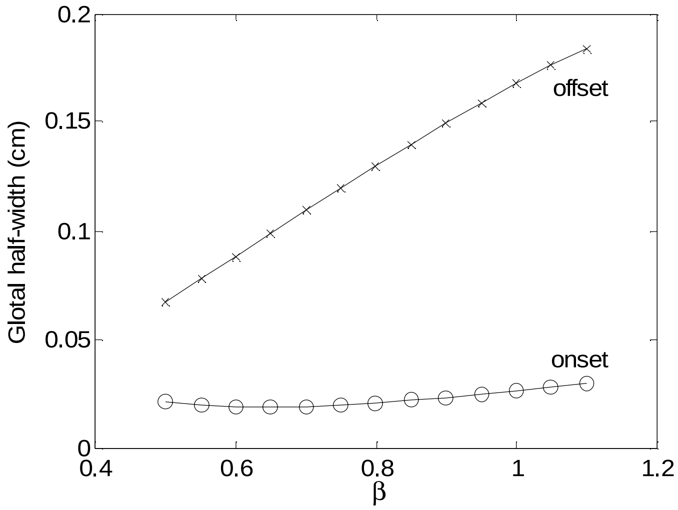

Figure 5. Oscillation threshold values of glottal half-width.

Finally, Fig. 6 shows the threshold values of *Q* factor, with similar results than the other parameters. Such results suggest the possibility of using the *Q* factor (vocal fold tension) to control the onset and offset of the oscillation. In fact, past studies have argued that the cricothyroid muscle may be activated around abduction movements to help suppress the vocal fold oscillation (Löfqvist et al., 1989)

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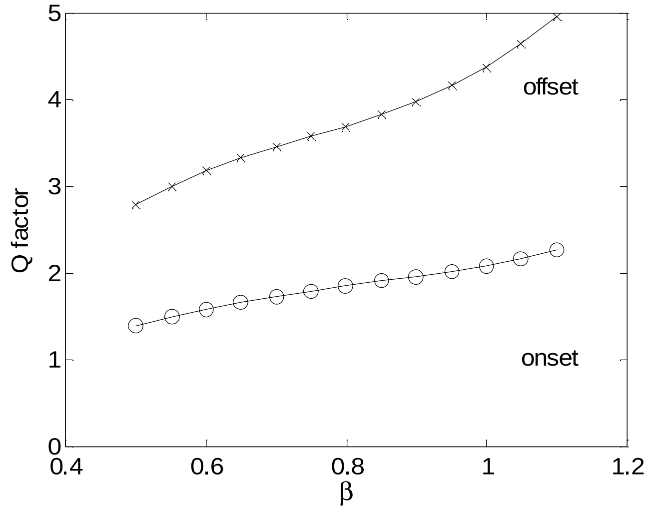

Figure 6. Oscillation threshold values of *Q* factor.

In the three plots above, the thresholds vary with laryngeal size always in the sense of restricting the vocal fold oscillation region for smaller sizes.

5. Conclusions

In general, the results show that the dynamics of the vocal fold oscillation depends on laryngeal size, and thus varies for men, women, and children. For all parameters studied here, the oscillation conditions become more restricted as the size is reduced. This restriction seems consequence of a reduction of the glottal area in contact with the airflow, on which energy is transferred from the flow to fuel the vocal fold oscillation. This result would explain the larger occurrence of devoicing in glottal abduction-adduction gestures, compared to men (Koenig, 2000). In the child cases, the restricted conditions would result in the higher values of subglottal pressures, compared to adults, as observed experimentally (Lucero and Koenig, 2003). A hysteresis effect is always present at voice onset-offset, with threshold conditions to start the vocal fold oscillation more severe than those to stop it, as described by the subcritical Hopf bifurcation model.

6. Acknowledgments

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7. References

Alipour-Haghighi, F., and Titze, I.R., 1985, “Viscoelastic modeling of canine vocalis muscle in relaxation”, Journal of the Acoustical Society of America, Vol. 78, pp. 1939-1943.

Berry, D., 2001, “Mechanisms of modal and nonmodal phonation”, Journal of Phonetins, Vol. 29, 431-450.

Chan, R.W., and Titze, I.R., 2000, “Viscoelastic shear properties of human vocal fold mucosa: Theoretical characterization based on constitutive modeling”, Journal of the Acoustical Society of America, Vol. 107, pp. 565-580.

de Vries, M.P, Schutte, H.K, Veldman, A.E.P., and Verkerke, G.J., 2002, “Glottal flow through a two-mass model: Comparison of Navier–Stokes solutions with simplified models”, Journal of the Acoustical Society of America, Vol. 111, pp. 1847-1853.

Flanagan, J.L., 1972, “Speech Analysis, Synthesis, and Perception”, Springer Verlag, New York, USA.

Goldstein, U. , 1980, “An articulatory model for the vocal tracts of growing children", Doctoral Dissertation, Massachusetts Institute of Technology, Cambridge, MA.

Herzel, H., Berry, D., Titze, I. R., and Steinecke, I., 1995, “Nonlinear dynamics of the voice: Signal analysis and biomechanical modeling”, Chaos, Vol. 5, pp. 30-34.

Hirose, H., and Niimi, S., 1987, “The relationship between glottal opening and the transglottal pressure differences during consonant production”, in: “Laryngeal Function in Phonation and Respiration”, edited by T. Baer, C. Sasaki, and K. Harris, College-Hill, Boston, EUA, pp. 381-390.

Ishizaka, K., and Flanagan, J.L., 1972, “Synthesis of voiced sounds from a two-mass model of the vocal folds”, Bell System Technical Journal, Vol. 51, pp. 1233-1268.

Jiang, J.J., and Zhang, Y., 2002, “Chaotic vibration induced by turbulent noise in a two-mass model of the vocal folds”, Journal of the Acoustical Society of America, Vol. 112, pp. 2127-2133.

Koenig, L.L., 2000, “Laryngeal factors in voiceless consonant production in men, women, and 5-year-olds”, Journal of Speech, Language, and Hearing Research, Vol. 43, pp. 1211-1228.

Kurita, S., Hirano, M., and Nakashima, T., 1983, “Growth, development, and aging of human vocal folds”, in “Vocal fold physiology: Contemporary research and clinical issues”, edited by D. M. Bless and J. H. Abbs, College Hill Press, San Diego, USA, pp. 22-43.

Löfqvist, A., Baer, T., McGarr, N.S., and Seider Story, R., 1989, “The cricothyroid muscle in voicing control”, Journal of the Acoustical Society of America, Vol. 85, pp. 1314-1321.

Lous, N. J. C., Hofmans, G. C. J., Veldhuis, R. N. J., and Hirschberg, A., 1998, “A symmetrical two-mass vocal-fold model coupled to vocal tract and trachea, with application to prosthesis design”, Acta Acustica, Vol. 84, pp. 1135-1150.

Lucero, J.C, 1993, “Dynamics of the two-mass model of the vocal folds: Equilibria, bifurcations, and oscillation region”, Journal of the Acoustical Society of America, Vol. 94, pp. 3104-3111.

Lucero, J.C., 1996, “Chest- and falsetto-like oscillations in a two-mass model of the vocal folds”, Journal of the Acoustical Society of America, Vol. 100, pp. 3355-3359.

Lucero, J. C., 1998, “A subcritical Hopf bifurcation at phonation onset”, Journal of Sound and Vibration, Vol. 218, pp. 344-349.

Lucero, J. C., 1999, “A theoretical study on the hysteresis phenomenon at vocal fold oscillation onset-offset”, Journal of the Acoustical Society of America, Vol. 105, pp. 423-431.

Lucero, J. C., 2004, “Oscillation hysteresis in a two-mass model of the vocal folds”, Journal of Sound and Vibration (in press).

Lucero, J.C., and Koenig, L.L., 2000, "Simulations of voice onset-offset hysteresis in /aha/ utterances", Journal of the Acoustical Society of America, Vol. 108, p. 2508.
Lucero, J.C., and Koenig, L.L., 2003, "Simulations of VhV sequences in children", Proceedings of the 15th International Conference on Phonetic Science, Barcelona, Spain, pp. 2605-2608.
McGowan, R.S., Koenig, L.L., and Löfqvist, A., 1995, "Vocal tract aerodynamics in /aCa/ utterances: Simulations", Speech Communication, Vol. 16, pp. 67-88.
Mergell, P., Herzel, H., and Titze, I.R., 2000, "Irregular vocal fold vibration – High-speed observation and modeling", Journal of the Acoustical Society of America, Vol. 108, 2996-3002.
Mergell, P., Herzel, P., Wittenberg, T., Tigges, M., and Eysholdt, U., 1998, "Phonation onset: Vocal fold modeling and high-speed glottography", Journal of the Acoustical Society of America, Vol. 104, pp. 464-470.
Munhall, K.G., Löfqvist, A., and Scott Kelso, J.A., 1994, "Lip-larynx coordination in speech: Effects of mechanical perturbations to the lower lip", Journal of the Acoustical Society of America, Vol. 95, pp. 3605-3616.
Pelorson, X., Hirschberg, A., van Hassel, R.R., Wijnands, A.P.J., and Auregan, Y., 1994, "Theoretical and experimental study of quasisteady- flow separation within the glottis during phonation. Application to a modified two-mass model", Journal of the Acoustical Society of America, Vol. 96, pp. 3416-3431.
Pelorson, X., Hirschberg, A., Wijnands, A.P.J., and Bailliet, H., 1995, "Description of the flow through in-vitro models of the glottis during phonation", Acta Acustica, Vol. 3, 191-202.
Steinecke, I., and Herzel, H., 1995, "Bifurcations in an asymmetric vocal fold model", Journal of the Acoustical Society of America, Vol. 97, pp. 1878-1884.
Titze, I.R., 1989, "Physiologic and acoustic differences between male and female voices", Journal of the Acoustical Society of Amrica, Vol. 85, pp. 1699-1707.
Titze, I. R., 1994, "Principles of Voice Production", Prentice-Hall, Englewood Cliffs, USA, 354 p.
Titze, I. R., and Liang, H., 1993, "Comparison of F0 extraction methods for high-precision voice perturbation measurements", Journal of Speech and Hearing Research, Vol 36, pp. 1120-1133.
Titze, I.R, Schmidt, S.S, and Titze, M.R., 1995, "Phonation threshold pressure in a physical model of the vocal fold mucosa", Journal of the Acoustical Society of America, Vol. 97, pp. 3080-3084.

8. Responsibility notice

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