Acoust. Sci. & Tech. **25**, 6 (2004)

ACOUSTICAL LETTER

Dynamics of a scaled two-mass model of the vocal folds for men and women

Jorge C. Lucero*

Department Mathematics, University of Brasilia, Brasilia DF 70910–900, Brazil

(*Received 19 April 2004, Accepted for publication 7 June 2004*)

Keywords: Two-mass model, vocal folds, phonation, voice, oscillation hysteresis
PACS number: 43.70.Aj, 43.70.Bk [DOI: 10.1250/ast.25.478]

1. Introduction

The purpose of this work is to analyze how the oscillatory behavior of the vocal folds changes according to laryngeal size, in cases of phonation by men and women. Since air viscosity terms of glottal aerodynamics depend on the cross-sectional areas of airways, then larger losses of the airflow energy would occur in smaller larynges, which in turn would leave less energy to fuel the oscillation. Thus, 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 [1], and might be important to understand the development of motor control of the larynx in children [2].

A modified two-mass model of the larynx and two-tube model of vocal tract, in male and female configurations, are used to simulate voice production. 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. [3],). The next sections will present the models and simulation results of male and female voices.

2. Model

The larynx is modeled using a modified version of the two-mass model [4]. For the damping forces, instead of the usual linear term $r\dot{x}$, where r is a damping coefficient and x is the tissue displacement, a nonlinear characteristics of the form $r(1 + \eta|x|)\dot{x}$ is adopted, where η is a suitable coefficient. This nonlinear characteristics is required to limit the amplitude of the vocal fold oscillation [1,2]. Also, it reproduces experimental data which shows that the time constant of relaxation curves of vocal fold tissue increases with the level of strain [5]. In the present work, a value of $\kappa = 150$ was used.

The glottal aerodynamics is modeled using an updated version of Ishizaka and Flanagan's equations [4]. Following Pelorson *et al.* [6], we assume no flow contraction at the glottal entry, and the formation of a free jet inside the glottis when the glottal channel has a divergent shape. Downstream the point of flow separation from the glottal walls, the flow losses all its energy due to turbulence.

The vocal tract was represented by a standard two-tube configuration for vowel /a/ [3,4]. Its equations were derived using a transmission line analogy, terminated in a radiation load of a circular piston in an infinite baffle.

A male configuration of the models was defined by using their standard parameters. For their female configuration, the dimensions of the larynx and vocal tract were reduced by a scaling factor. According to [7], the size relation between male and female larynges is in the range 1.2–1.6, depending on the dimension. For simplicity, a single scaling factor for all dimensions was adopted, with a value $\beta = 1.4$. Masses were accordingly computed dividing by β^3, to compensate the volume reduction. The tissue stiffness coefficients were reduced by a factor β, to keep a constant tissue elasticity modulus between men and women.

3. Results

Simulations of voice records were obtained by numerical solution of the equations of the model.

Figure 1 shows simulations of oral airflow, when the glottal width is changed following an abduction-adduction gesture, as in the production of utterance /aha/. Subglottal pressure and Q factor are kept constant at $P_s = 600$ Pa and $Q = 1$, and x_0 is smoothly increased from 0.01 cm to 0.09 cm, and then decreased to the initial value.

Comparing the male and female results, we see that the male flow has a larger amplitude, and lower fundamental frequency (approximately 110 Hz vs. 200 Hz in the female flow), 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, in which the vocal fold oscillation stops and then starts at different values of the glottal width. It is a common nonlinear phenomenon in cases of flow-induced oscillations, and has been observed in several experimental studies of phonation (see a detailed discussion in [8]). In the male case, there is no interruption of the glottal pulses.

Figure 2 shows the RMS amplitude of the AC component of the oral airflow [2], when varying one of the control parameters while keeping the other two fixed at the previous reference values. In case of the male configuration, the AC amplitude increase almost linearly with the subglottal pressure. There is threshold pressure value around 200 Pa, which must be overcome for the start of the vocal fold oscillation. When the glottal half width is increased abducting the vocal folds, the vocal fold oscillation becomes more difficult, and so the AC amplitude decreases. There is a threshold value of 0.34 cm, above which the oscillation is no longer possible. Considering finally increases of the Q factor, we see that it causes the decrease of the AC amplitude. As the Q factor is larger, the vocal fold stiffness is larger, and so the oscillation

*e-mail: lucero@mat.unb.br

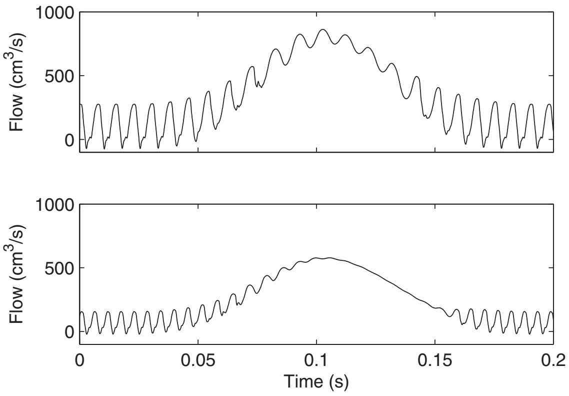

Fig. 1 Simulated oral airflow in a glottal abduction-adduction gesture. Top: male model. Bottom: female model.

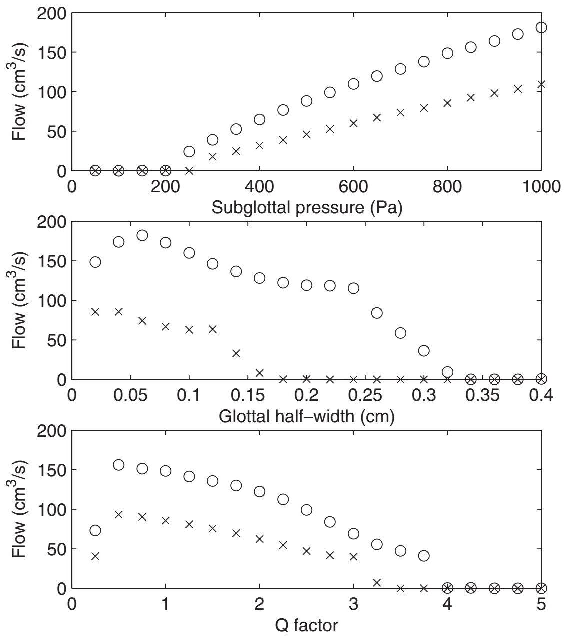

Fig. 2 RMS amplitude of the AC component of the oral airflow when varying the subglottal pressure (top), glottal half-width (middle), and Q factor (bottom). Circles: male model. Crosses: female model.

is difficulted. Here too, there is a threshold value of 4.0, which sets an upper limit for the oscillation. The results for the female configuration are qualitatively similar to the male case. The threshold value of the subglottal pressure is around 230 Pa, larger than the male value, and the thresholds for the glottal half width and Q factor are 0.18 cm and 3.3, respectively, smaller than the male values. These results, together with the larger threshold pressure, implies that the female larynx has a more restricted region of vocal fold oscillation. Thus, voice would be harder to sustain in women than in men. Particularly, the smaller threshold for the glottal width would explain the larger occurrence of devoicing in glottal abduction-adduction gestures for producing /h/ in running speech by women, compared to men [9]. As the vocal folds abduct, they easily reach the oscillation offset threshold in women, whereas men would still require more effort.

4. Conclusion

In general, the results show the capability of the two-mass model of the vocal folds to reproduce their oscillatory behavior at phonation by men and women. A hysteresis effect is present at voice onset-offset, with threshold conditions to start the vocal fold oscillation more severe than those to stop it. The oscillation threshold conditions are more restricted for the smaller female larynges, in agreement with reported experimental results. This effect seems consequence of increased losses for air viscosity, due to smaller cross-sectional areas of airways.

Acknowledgments

This work was supported by CNPq (Brazil).

References

[1] J. C. Lucero and L. L. Koenig, "Simulations of voice onset-offset hysteresis in /aha/ utterances," *J. Acoust. Soc. Am.*, **108**, 2508 (2000).

[2] J. C. Lucero and L. L. Koenig, "Simulations of VhV sequences in children," *Proc. 15th ICPhS*, pp. 2905–2908 (2003).

[3] I. R. Titze, *Principles of Voice Production* (Prentice-Hall, Englewood Cliffs, 1994).

[4] K. Ishizaka and J. L. Flanagan, "Synthesis of voiced sounds from a two-mass model of the vocal folds," *Bell Syst. Tech. J.*, **51**, 1233–1268 (1972).

[5] F. Alipour-Haghighi and I. R. Titze, "Viscoelastic modeling of canine vocalis muscle in relaxation," *J. Acoust. Soc. Am.*, **78**, 1939–1943 (1985).

[6] X. Pelorson, A. Hirschberg, R. R. van Hassel, A. P. J. Wijnands and Y. Auregan, "Theoretical and experimental study of quasisteady-flow separation within the glottis during phonation. Application to a modified two-mass model," *J. Acoust. Soc. Am.*, **96**, 3416–3431 (1994).

[7] I. R. Titze, "Physiologic and acoustic differences between male and female voices," *J. Acoust. Soc. Am.*, **85**, 1699–1707 (1989).

[8] J. C. Lucero, "A theoretical study on the oscillation hysteresis at phonation onset-offset," *J. Acoust. Soc. Am.*, **105**, 423–431 (1999).

[9] L. L. Koenig, "Laryngeal factors in voiceless consonant production in men, women, and 5-year-olds," *J. Speech Lang. Hear. Res.*, **43**, 1211–1228 (2000).