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5aSCa4. Modeling incomplete glottal closure due to a posterior glottal opening and its effects on the dynamics of the vocal folds

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Even though incomplete glottal closure is present in normal and pathological voices, it has received little attention in self-sustained models of phonation. The effects of acoustic interaction due to a posterior glottal gap on the tissue dynamics, energy transfer, and glottal aerodynamics were numerically investigated. The domain was prescribed as flow through two separate orifices (posterior gap and membranous vocal folds) that merge in the supraglottal tract, with the governing flow equations determined from a control volume analysis based on conservation of mass and linear momentum. The equations of motion remained unaffected, although the driving forces were indirectly altered through the acoustic interaction. The method was implemented using the body-cover model, wave-reflection-analog sound propagation, and a boundary-layer asymmetric flow solver. The inclusion of a gap area of 0.05 cm2 reduced the RMS energy transfer from the fluid to the vocal folds by more than 35% and radiated SPL by 9 dB. When compensating for this reduction with an increased subglottal pressure to match the SPL, a significant increase in MFDR and AC flow was noted, thus mimicking vocal hyperfunction. In addition, posterior gap areas yielded a glottal airflow more proportional to the incident transglottal pressure drop than the glottal area.

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INTRODUCTION

Incomplete glottal closure has been shown to be ubiquitous in normal and disordered voices (Hillman *et al.* 1989; Perkell *et al.*, 1993), with some female voices displaying no glottal contact at all (Hanson, 1997). Significant research has been done to model the acoustic effects of incomplete glottal closure, and it is currently accepted that it produces changes in the harmonic decay of the source spectra, modifies the vocal tract formant frequencies and bandwidths, adds turbulent noise, and introduces fluctuations during the closed phase of the cycle (e.g., Cranen and Boves, 1985; Cranen and Schroeter, 1995; Hanson, 1997). However, there have been only a few studies on the effects of incomplete closure on the vocal folds dynamics. The influence of a posterior gap on the airflow and net energy transfer was investigated experimentally using a driven synthetic model with no vocal tract (Park and Mongeau, 2008). However, no theoretical or numerical studies have explored the effects the incomplete closure on the tissue dynamics and energy transfer from a more general perspective.

Self-sustained models of the vocal folds are designed to provide insights into the mechanisms that control phonation in normal and pathological cases. Low-dimensional models are more commonly used, as they efficiently capture the most dominant modes of vibration and are expected to reproduce many fundamental aspects of phonation with acceptable accuracy. However, limited efforts have been made to include the effects of incomplete glottal closure in these models, and minimal attention has been paid to the changes in the net energy transfer from flow and sound to the vibrating tissue introduced by the incomplete closure.

Previous approaches that have incorporated some type of incomplete glottal closure in low-dimensional, self-sustained models have included pre-contact changes in the stiffness (Pelorson *et al.,* 1994), an anterior-posterior feature that restricted the vibration of the vocal folds (McGowan *et al.* 1995), the use of a nonlinear damping coefficient (Lucero and Koenig, 2005), and a gradual anterior-posterior closure due to a triangular glottis (Birkholz, 2011). These ideas have been used to mimic polyps and nodules (Pelorson *et al.,* 1994; Kuo, 1998), to minimize the unrealistic large amplitudes produced when increasing the degree of abduction to reproduce consonant-vowel-consonant gestures (McGowan *et al.,* 1995; Lucero and Koenig, 2005), and to synthesize different voice qualities (Birkholz, 2011). General agreement was found between human recordings and these simulations. However, none of these studies provided insights into the energy transfer due to the changes in glottal closure.

Possible pathological mechanisms that can produce incomplete glottal closure include the presence of organic vocal fold pathologies, vocal fold paralysis, and vocal hyperfunction. An opening of the posterior glottis between the arytenoid cartilages (also referred to as glottal chink) is also often observed in normal voices. Thus, in this study, the effects a posterior glottal gap on the tissue dynamics, energy transfer, acoustic interactions, and glottal aerodynamics were numerically investigated.

METHODS

The three-mass model known as "body-cover" model (Story and Titze, 1995) was employed. Model parameters were based on muscle activation principles (Titze and Story, 2002), using a 10% of CT muscle activation and 20 % of TA muscle activation. A wave-reflection-analog was used to account for sound propagation and interaction, based on a sustained vowel /e/ (Takemoto, 2006). Although, it is well-established that the presence of incomplete glottal closure is associated with an increase in turbulent noise (Hanson, 1997), this component was not included in these initial investigations.

The aerodynamic domain was prescribed as flow through two separate orifices (posterior gap and membranous vocal folds) that merge in the supraglottal tract, with the governing flow equations determined from a control volume analysis based on conservation of mass and linear momentum. Under the assumption that the pressure in both sections is the same at some point downstream, the approach is equivalent to solving for the total glottal airflow with the total glottal area, i.e., both posterior gap and membranous glottal areas together. In this study, a boundary-layer asymmetric flow solver (Erath *et al.*, 2011, Erath. *et al.,* submitted) was selected to compute the glottal airflow. Given that the posterior glottal opening is in a different flow channel than the membranous portion of the glottis, the equations of motion of the body-cover model remained unaffected even with the inclusion of the posterior gap. However, the driving forces were indirectly altered through the acoustic interaction. Thus, source-filter interaction is responsible for the changes in net energy transfer in this approach. Note that the proposed method does not alter the structure of the self-sustained model and only requires a minor addition when solving for the glottal flow, thus making it readily applicable to any self-sustained vocal fold model. The two-mass model representation of the membranous and posterior gap is shown in Figure 1.

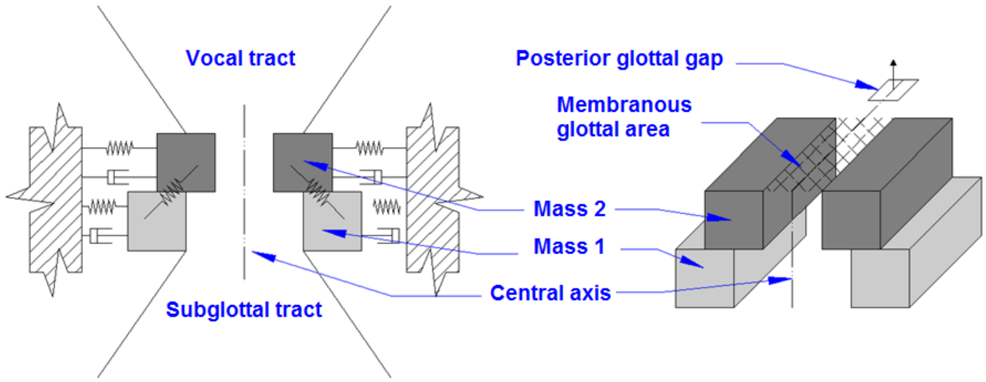

FIGURE 1. Representation of the posterior glottal gap, illustrated in a two-mass model

To evaluate the effects of the posterior gap, selected parameters were computed, including pitch (F0), maximum flow declination rate (MFDR), radiated sound pressure level (SPL), steady (DC) and unsteady (AC) glottal airflow components, spectral tilt (H1-H2), and net energy transfer (denoted as Π). SPL was obtained by subtracting 30 dB (based on empirical observations) from lip output to describe a 10 cm position. The energy transfer was computed according to Park and Mongeau (2008).

RESULTS

The predicted effects of the posterior glottal gap on the resulting glottal airflow are depicted in Figure 2, where it is also contrasted with two other flow solvers: an uncoupled Bernoulli flow solver that is proportional to the glottal area (Steinecke and Herzel, 1995), and a simplified flow solver for highly coupled scenarios that is proportional to the incident transglottal pressure (Titze, 1984). It is noted that the addition of the gap yields smooth contours during the closed portion of the cycle that are in agreement with experimental observations from inverse filtering in human subjects (Cranen and Schroeter, 1995; Alku *et al.*, 2009). During the open portion of the cycle, the resulting glottal airflow better matches the highly coupled solver (Figure 2-b), suggesting that the posterior glottal gap significantly increases the coupling parameter, and thus source-filter interaction. This relationship becomes more evident for large gap areas.

(a) (b)

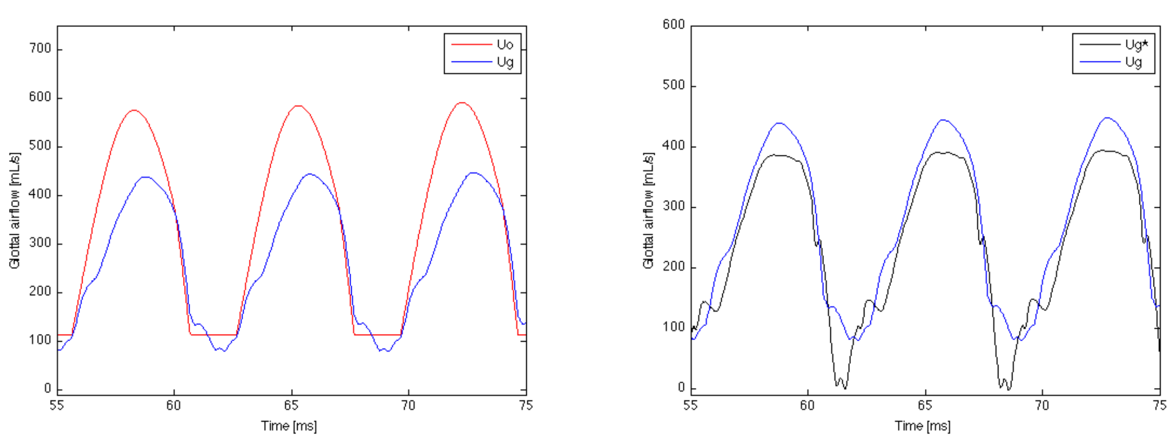

FIGURE 2. Glottal airflow (in blue) contrasted with: (a) Uncoupled Bernoulli flow solution (in red), and (b) Highly coupled airflow solution (in back)

The acoustic and aerodynamic effects of a parametric variation of the posterior gap are presented in Figure 3. As expected, the increment in gap area increases the DC component of the glottal airflow linearly. In contrast, a decay in AC flow and MFDR is observed with larger gap areas. The gap area has similar acoustic effects in the source spectra and radiated SPL.

(a) (b)

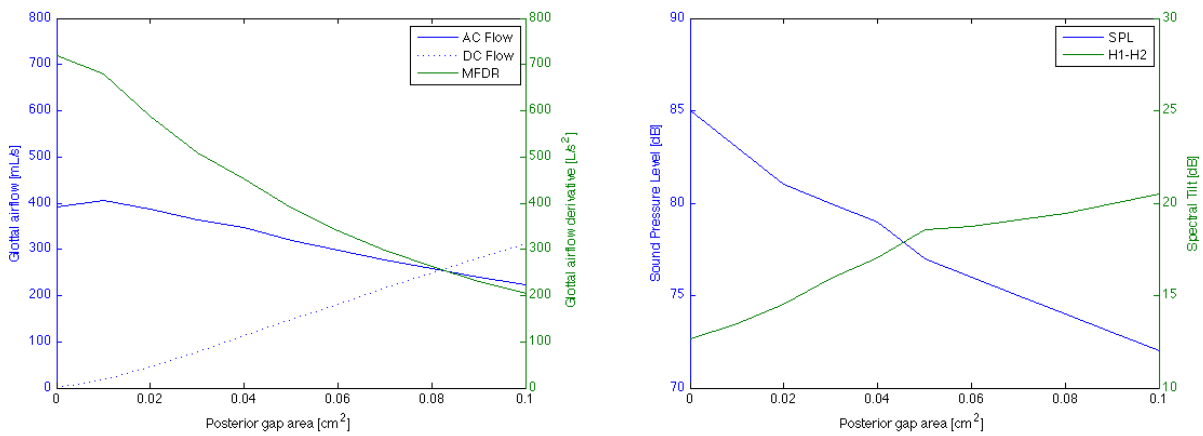

FIGURE 3. Effect of the posterior glottal gap on selected glottal measures. (a) Aerodynamic measures (b) Acoustic measures

The energy transfer from the flow to the vocal fold tissue is also affected by increments in gap area, as observed in Figure 4. Larger gap areas reduce the net energy that drives the vocal fold vibration, where the superior cover mass (mass 2) suffers a more rapid decay, due to the more predominant influence of the downstream pressure in its driving force.

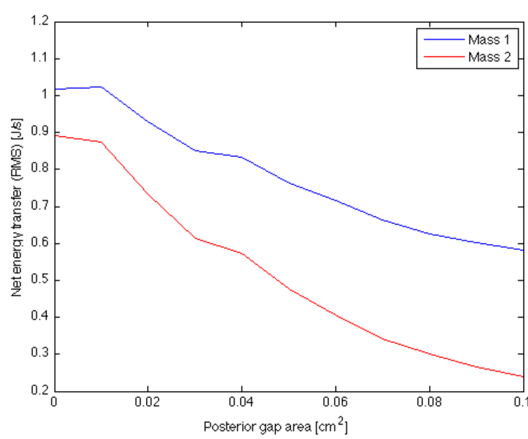

FIGURE 4. Effect of the posterior glottal gap on the energy transfer to each cover mass

Speakers may compensate for the acoustic effects introduced by an excessive posterior glottal gap (reduced SPL and change in voice quality) by increasing subglottal pressure. This pattern has been observed in patients with hyperfunctional voice disorders and is believed to contribute to a "vicious cycle" in which increased muscular and aerodynamic forces cause further deterioration in vocal function (e.g., vocal fatigue, vocal fold tissue damage, dysphonia, etc.) and the need to drive the system at ever increasing levels (Hillman *et al.*, 1989). Table 1 illustrates this principle, where a scenario without a posterior gap is compared with cases of 0.03 cm^2 and 0.05 cm^2 gap areas. When compensating for the reduction in SPL in the latter case to match the no-gap scenario with an increased subglottal pressure, an increase in MFDR and AC flow is observed, which is in agreement with measurements in hyperfunctional subjects (Hillman *et al.,* 1989). It is interesting to note that the increase in net energy transfer is obtained from both the opening and closing phases of the glottal cycle, which explains the increase in both AC flow and MFDR.

TABLE 1. Simulation of hyperfunction due to the compensation of the reduction in SPL by an increased subglottal pressure. The increase column is with respect to the no gap scenario, which was the target for SPL.

Parameters	Units	No gap	Normal	Adducted	Hyperfunct.	Increase
Amin	cm^2	0	0.03	0.05	0.05	-
Ps	Pa	800	800	800	1300	63%
SPL	dB	85	79	76	85	-
F0	Hz	144.9	140.6	137.1	146.7	1%
MFDR	L/s^2	755.2	476.7	350.8	982.4	30%
DC flow	mL/s	0.0	82.5	149.5	166.4	-
AC flow	mL/s	403.9	349.0	301.1	666.4	65%
AC area	cm^2	0.14	0.13	0.12	0.21	47%
H1-H2	dB	13.7	16.4	17.7	15.3	12%
Π m1 (RMS)	J/s	1.1	0.8	0.7	2.3	105%
Π m2 (RMS)	J/s	1.0	0.6	0.4	2.2	109%
Π m1 opening	J/s	2.3	2.0	1.8	5.3	128%
Π m1 closing	J/s	0.1	0.2	0.4	0.1	-
Π m2 opening	J/s	0.9	0.9	0.8	2.9	238%
Π m2 closing	J/s	1.4	0.7	0.4	2.6	85%

DISCUSSION

The proposed representation of a posterior glottal gap is simple and could be readily applied to any self-sustained model of the vocal folds with acoustic interaction. Current results are in agreement with observations in normal and hyperfunctional speakers (Hillman *et al.* 1989, Perkell *et al.* 1993) and rubber model experiments (Park and Mongeau, 2008). In this approach, the presence of an incomplete glottal gap produces changes in the resulting upstream and downstream acoustic pressures that, in turn, affect the glottal airflow and net energy transfer to the vibrating vocal fold tissue. It is also observed that the ratio between total glottal area and the effective vocal tract area, normally referred to as coupling parameter (Titze, 2008), becomes larger due to the offset in the total glottal area, thus reducing the amplitude of the AC component of the glottal airflow and making it proportional to the incident transglottal pressure term (incident pressures in the wave reflection analog scheme). For larger gap areas, the transglottal pressure term becomes smoother and relatively proportional to the glottal area, further reducing the harmonic content of the source spectra.

Future studies will explore other compensation mechanisms to increase radiated sound pressure such as vocal tract constrictions and vocal fold posturing, as well as the effects of turbulent noise on the interaction and asymmetric tissue properties.

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