A Vertical Three-Mass Model of Phonation Based on Empirical Intraglottal Pressures

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Empirical intraglottal pressures obtained from a Plexiglas model (model M5) of the glottis with multiple intraglottal pressure taps, glottal angles, and minimal glottal diameters, obtained for transglottal pressures between 3 and 15 cm H_2O, were applied to a vertical three-mass model where two of the masses and ducts were similar to the Ishizaka & Flanagan (I&F) classical model, and the third mass was just inferior to the glottal entrance (where empirical vocal fold surface pressures also were obtained). The intraglottal surface pressures applied during the run of the model employed interpolation techniques using Matlab. The empirical intraglottal pressures on the lower glottal mass were less for divergent glottal shapes than in the I&F model, and thus the operational region of the model was reduced unless the tissue stiffnesses were reduced in value. The model mimics that of Ishizaka and Flanagan (1972), and thus the tissue properties and prephonatory glottal diameter and glotta angle were controlled.

Four flow sources were included -- through the membranous and cartilaginous ducts, and vertical and horizontal vocal fold surface displacements. The latter two tend to be out of phase and partially cancel each other. The cartilaginous glottis flow (Bernoulli expression with inertance) gives rise to DC flow and a delayed flow that adds a minor enhancement just after glottal closure (somewhat sharpened local peaks).

A flow hump near the flow pulse onset appears when the 4-section vocal tract is attached, and is due to a reduced transglottal pressure when the glottis begins its opening phase, creating a delay in the practical flow pulse onset. This effect becomes negligible for prephonatory diameters less than 0.02 cm. [This interesting effect mimics a similar pre-pulse flow hump seen in results for a recent bariton singer project in our lab, but may not be related; inclusion of subglottal resonances is an important enhancement, yet to be made, to help think about this “new” finding].

This model permits the examination of the loop motion (trajectory) of points on the vocal fold surface. The addition of the vocal tract stabilizes the tissue motions, increases the amplitude of motion of the three masses, and decreases the phase delay between the two glottal-proper masses. Other kinematic, aerodynamic, and acoustic aspects of this model will be discussed. In addition, a very recent equation for the flow resistance effects of various sized false vocal fold gaps (Agarwal, 2004, dissertation) will be included to explore the effects on the translaryngeal flow.

In summary, the unique aspect about this vertical 3-mass model is that the intraglottal pressures are empirically based, rather than based on adjusted theoretical equations, and the empirical pressures acting on the undersurface of the vocal folds are included. Thus, the model can be used at this stage of development to explore 2-dimensional motions of the vocal folds, and the effects on the translaryngeal flow of various sources, namely, the glottal flow per se, the vertical motion of the vocal folds, the horizontal motion of the vocal folds, the posterior glottal flow, and the gap between the false vocal folds.

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The following figures illustrate the output from the model.

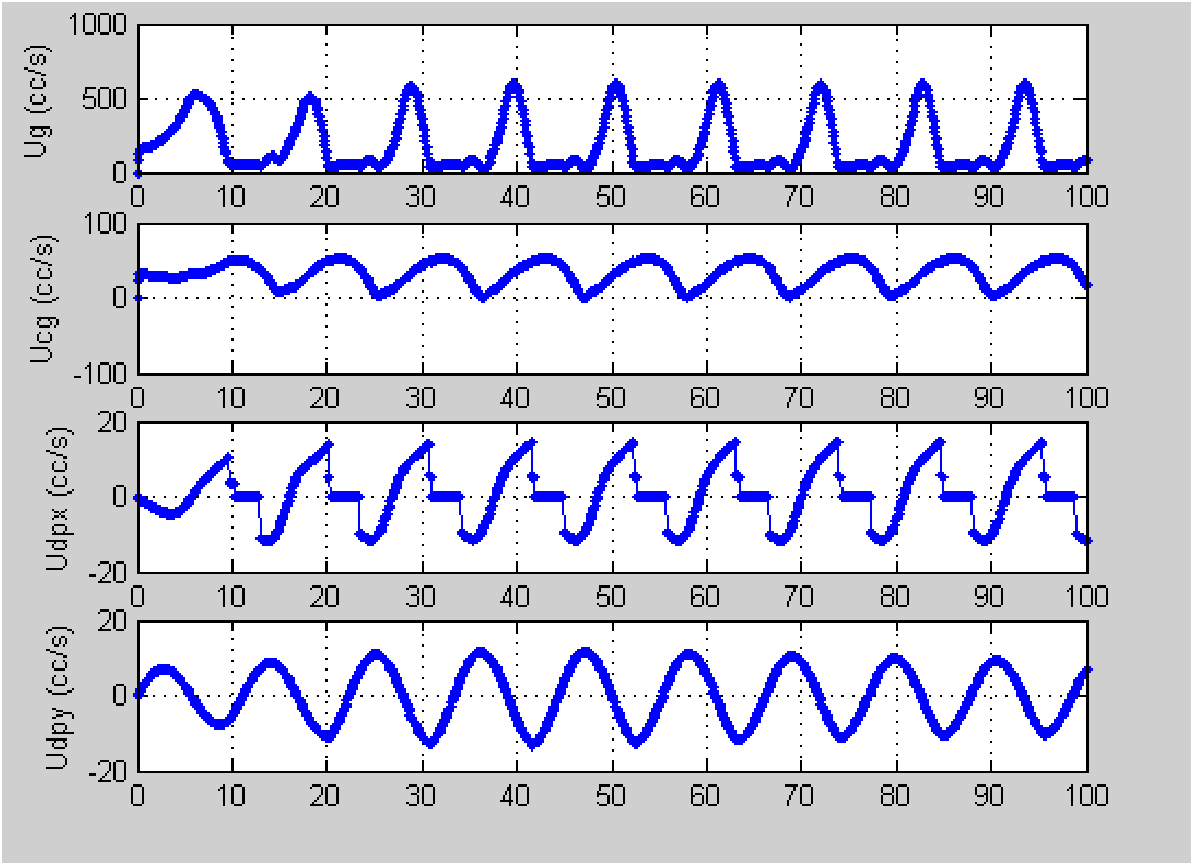

Figure 1. This figure shows the transglottal flow Ug that is an interaction among the laryngeal flow sources and the vocal tract. Ucg is the flow through the cartilaginous glottis. Udpx and Udpy are the horizontal and vertical displacement flows. For this figure and the next, nominal tissue characteristics are used, subglottal pressure was 8 cm H2O, prephonatory angle was zero degrees, prephonatory diameter was 0.04 cm, and the abduction for the cartilaginous glottis was 0.1 cm.

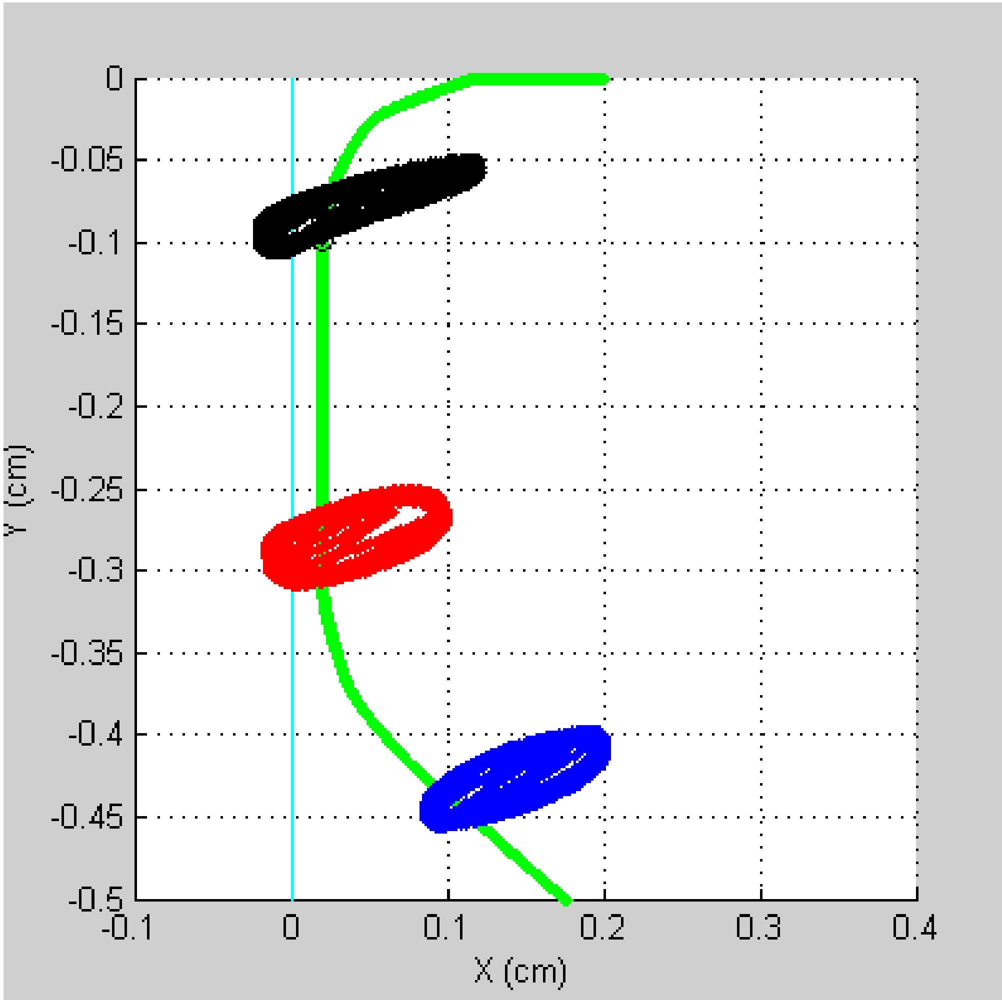

Figure 2. For the conditions of Figure 1, these are the trajectories of the three masses of the vocal fold. The outline of the vocal fold is given, as well as the prephonatory distance away from midline.

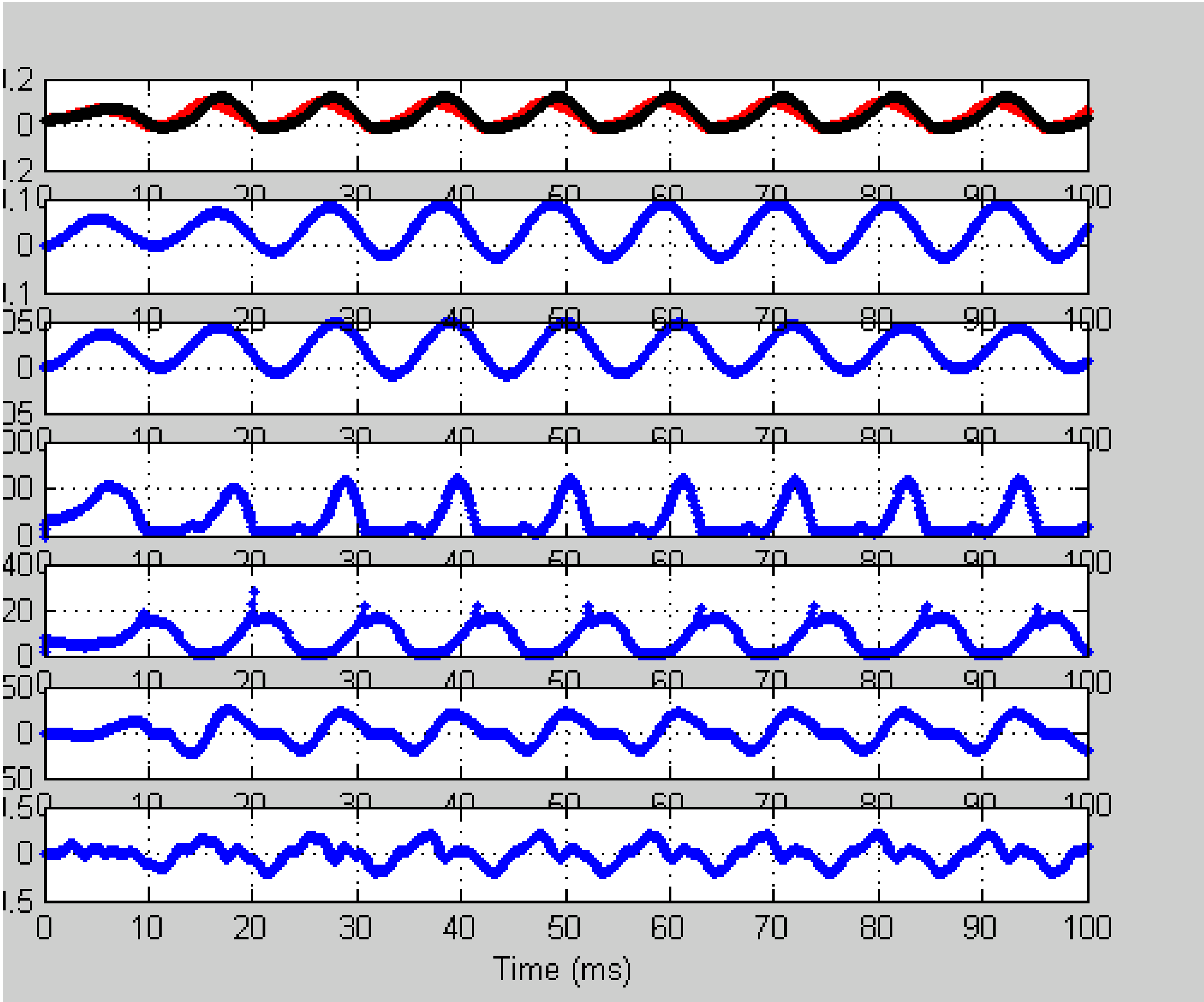

Figure 3. This figure, from top to bottom, is (1) the horizontal displacement of the two glottis-proper masses (like in the 2-mass models), (2) the horizontal displacement of the lowest (subglottal) mass, (3) the vertical displacement of the vocal folds, (4) the resultant laryngeal flow, (5) the transglottal pressure, (6) the glottal angle (positive is divergent, negative is convergent), and (7) the acoustic pressure at the lips (ala Ishizaka and Flanagan).