Control volume analysis of glottal jet dynamics using time resolved pressure and velocity field measurements in a scaled up vocal fold model

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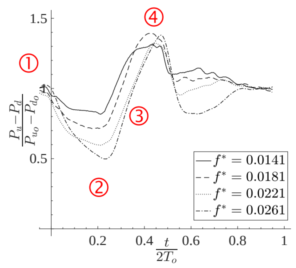

Figure 1: Transglottal pressure (TGP) vs time at Re = 7200 for the four frequencies. ① Start of cycle, ② TGP is a minimum, ③ Dynamic pressure is a maximum, ④ TGP is a maximum.

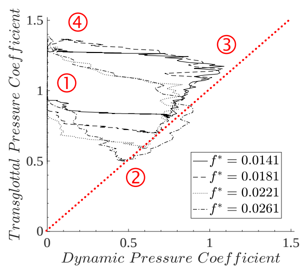

Figure 2: Phase plot of transglottal pressure and dynamic pressure for the four different frequencies at Re = 7200. Red circled numbers correspond to those shown in

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Introduction

This research sheds new light on understanding glottal jet dynamics and the role of the jet on voice production. Specific questions being addressed center around whether and when the jet is quasi-steady. This is significant in the context of reduced order modeling of phonation; the governing equations can be simplified without loss of fidelity if the flow is quasi-steady [1-3]. This work builds on a framework [4-8] involving direct measurement of terms in the integral momentum (Newton's 2nd Law) and energy equations. Now, for the first time, simultaneous temporally and spatially resolved pressure and velocity measurements in a scaled up vocal fold model have allowed detailed examination glottal jets from the perspective of those equations. This enables exploration of issues such as how significant jet momentum and transverse forces on the glottal walls are to phonation.

Methods

Experiments were conducted using a 10x scaled-up model [4] in a free surface water tunnel. The combination of 10x physical scale, and low kinematic viscosity of water allows for a 1500x reduction in frequency to match Reynolds numbers and reduced frequencies of human phonation.

Two 2-D vocal fold models with semi-circular ends, 15 cm wide, 12.7 cm long, 27.3 cm high were placed 45.7 cm downstream of a 300 cm long, 27.3 cm square duct. Each model was computer driven at constant opening and closing speeds. The time from the start of opening to fully closed was defined as T_o. Once closed, the model was kept closed for an additional T_o for every cycle, so the full oscillation period was $2T_o$.

Digital Particle Image Velocimetry (DPIV), a 2-D flow measurement technique, coupled with time resolved pressure measurements along the vocal fold model, were made at four different Reynolds numbers from 3650 to 8100 and four oscillation frequencies from 0.035 Hz to 0.065 Hz. These correspond to human and reduced frequency ranges of ~50 Hz to ~110 Hz and 0.014 to 0.023, respectively.

Results and Discussion

The contribution of this work is demonstration of the significance of whether and when the glottal jet is quasi-steady. Earlier studies [5,6] of velocity-based quantities, *e.g.* maximum jet velocity and glottal volume flow rate, showed the jet is quasi-steady only for specific times in its evolution. Specifically, during jet formation and pinch-off, inertial effects are present. This is also seen in the time histories of transglottal pressure (TGP) shown in Figure 1; these are for the four different frequencies at Re = 7200. Note that while the model starts to open, is fully open, and closes at $t = 0$, $T_o/4$ and $T_o/2$, TGP minima and maxima do not occur at those times.

Figure 2 shows TGP *vs.* dynamic pressure including key time points as indicated in Figure 1. If the flow were quasi-steady, TGP should be equal to dynamic pressure; *i.e.* it

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should follow the red line in Figure 2. Referring back to Figure 1, the time the jet is quasi-steady, between ② and ③, is only between $t/2T_o$ ≈ 0.2 and ~0.4 or ~40% of the vocal fold opening time. The time at which the jet pinches off, where sound production is most significant, is not quasi-steady.

This paper explores these issues in greater detail from the simultaneous velocity and pressure measurements and using related computational modeling work.

Acknowledgements

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