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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Overview

Simultaneous temporally and spatially resolved pressure and velocity measurements permitted examination of all of the terms in the streamwise integral momentum equation. Experiments were conducted using a 10x scaled-up model in a free surface water tunnel. 2-D vocal fold models with semi-circular ends were computer driven inside a square duct with constant opening and closing speeds. The time from the start of opening to fully closed was T_o, and the full oscillation period was $2T_o$. Time resolved DPIV and pressure measurements along the duct centerline were made for Reynolds numbers from 3650 to 8100 and equivalent life frequencies from 52.5 Hz to 105 Hz. It is demonstrated that transglottal pressure serves as a surrogate for vocal fold drag. As is common with flows of this type, cycle-to-cycle variations, including jet switching and modulation, *even when vocal fold wall motion does not*. The observed variations in jet motions were found to correlate with cycle-to-cycle variations of terms in the integral momentum equation related to sound production. The origins of these variations are discussed.

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[3] Howe, M. & McGowan, R., Fluid Dynamics Res., 42:15001, 2010
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[6] Krane, M.H., *et al.*, JASA, 128:372-383, 2010.
[7] McPhail, M., *et al.*, JASA, 146:1230-1238, 2019
[8] Sherman E., *et al.*, Fluid Dynamics Res., 52:015505, 2020

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Motivation

Fundamental questions:

- Does the driving transglottal pressure force from the lungs serve as a surrogate for vocal fold drag?,
- Are cycle-to-cycle variations of the glottal jet acoustically significant?, if so, how?
- What causes these cycle-to-cycle variations?

Integral Momentum Equation:

$$\rho\, \partial/\partial t \left(\iiint_{CV} u_i\, dV\right) + \iint_{CS} \rho u_i u_j\, dS_j =$$

unsteady/inertia *(forces due to changing volume and jet acceleration)* — *momentum flux* *(forces due to the jet)*

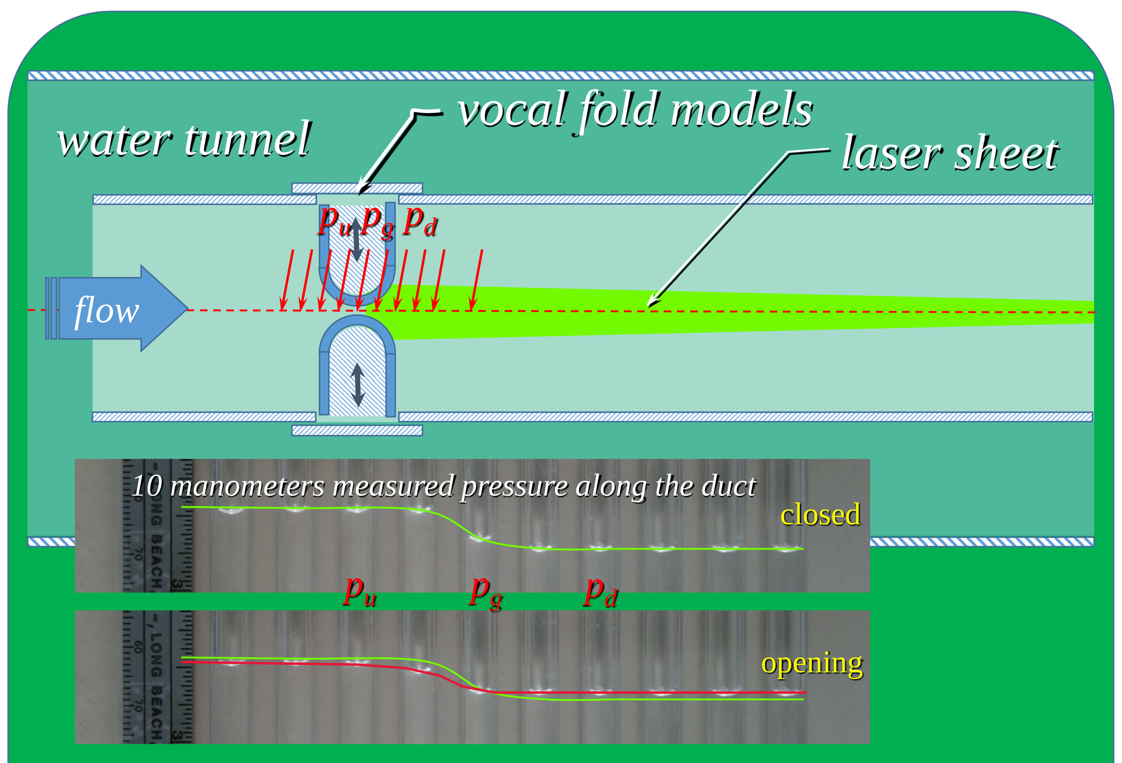
*Note that. these two terms are the '**ma**' in **F** = **ma**)*

$$-\iint_{CS} p\, dS_i + \iint_{CS} \tau_{ij}\, dS_j \overset{0}{} - F_{drag}$$

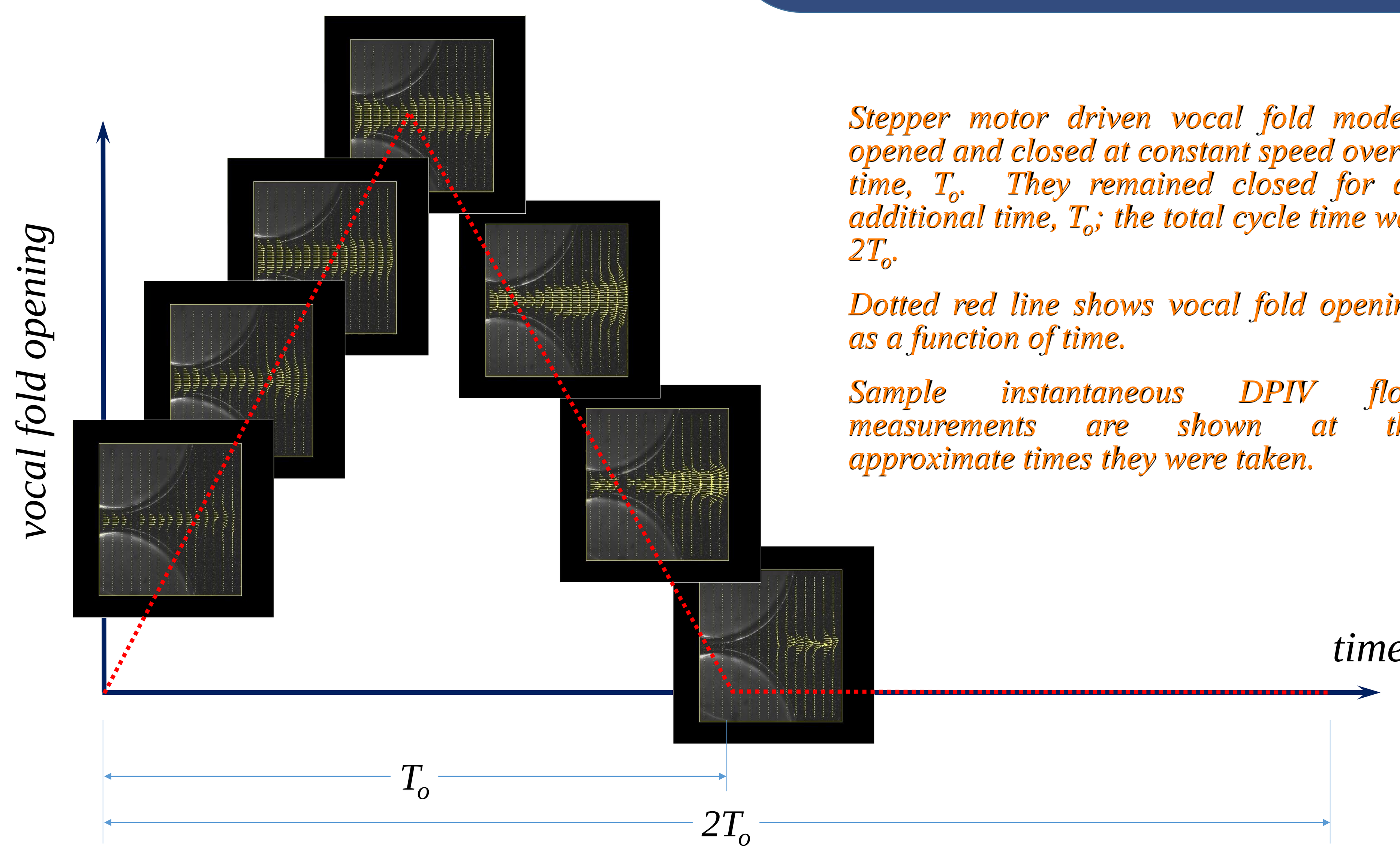
pressure forces *(driving pressure force from the lungs)* — *viscous forces* *(forces due to friction; shown to be negligible)* — *drag* *(drag on the vocal vocal folds; sound source)*

We are looking at these questions through the lens of the streamwise (x) momentum equation.

Methods



We simultaneously measured velocity and pressure in a 10x scaled up vocal fold model



Stepper motor driven vocal fold models opened and closed at constant speed over a time, T_o. They remained closed for an additional time, T_o; the total cycle time was $2T_o$.

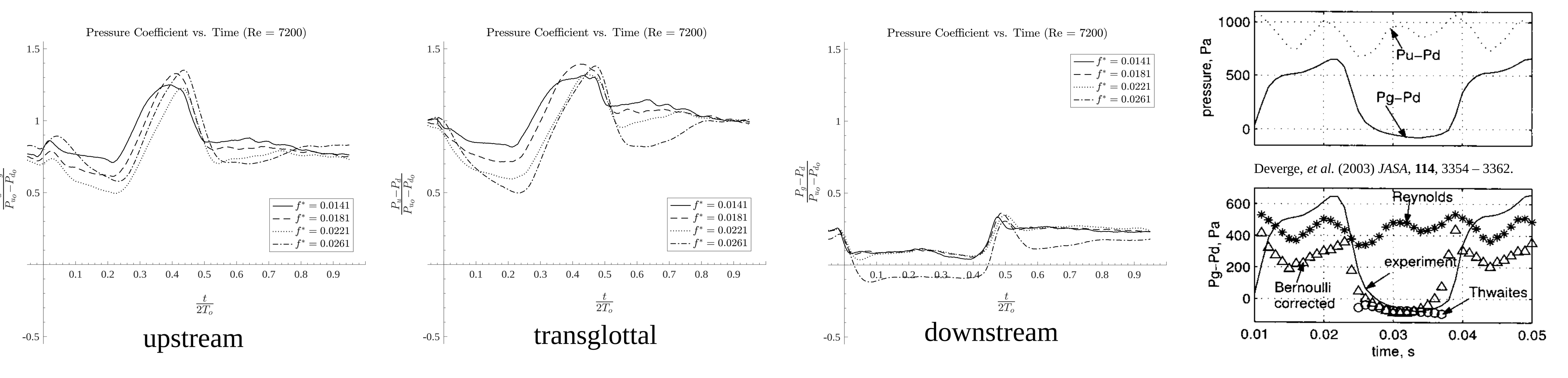
Dotted red line shows vocal fold opening as a function of time.

Sample instantaneous DPIV flow measurements are shown at the approximate times they were taken.

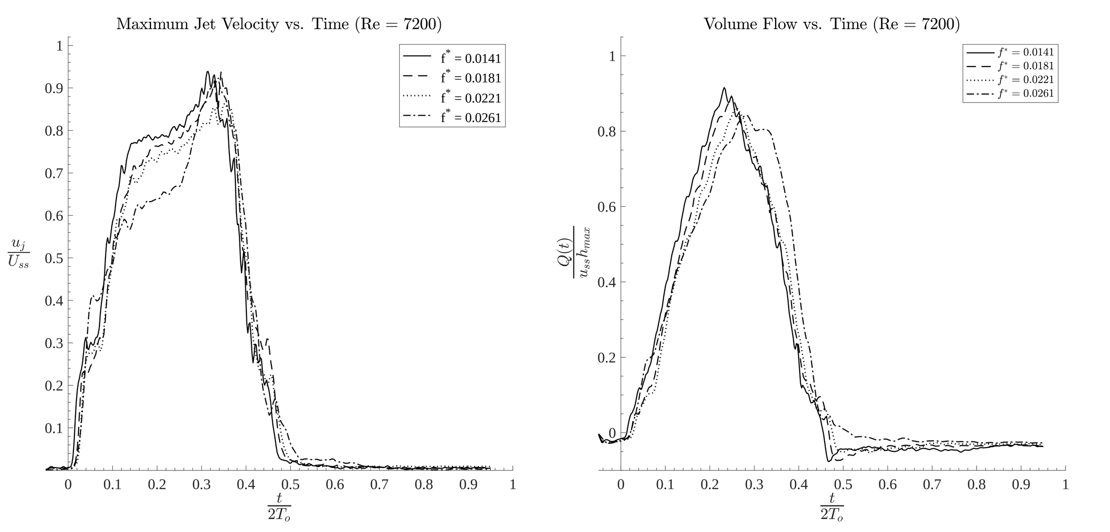
Key Point: *We can directly measure all of the terms in the x-momentum equation and study precisely how the flow is coupled to the pressure forces that lead to sound production.*

Results

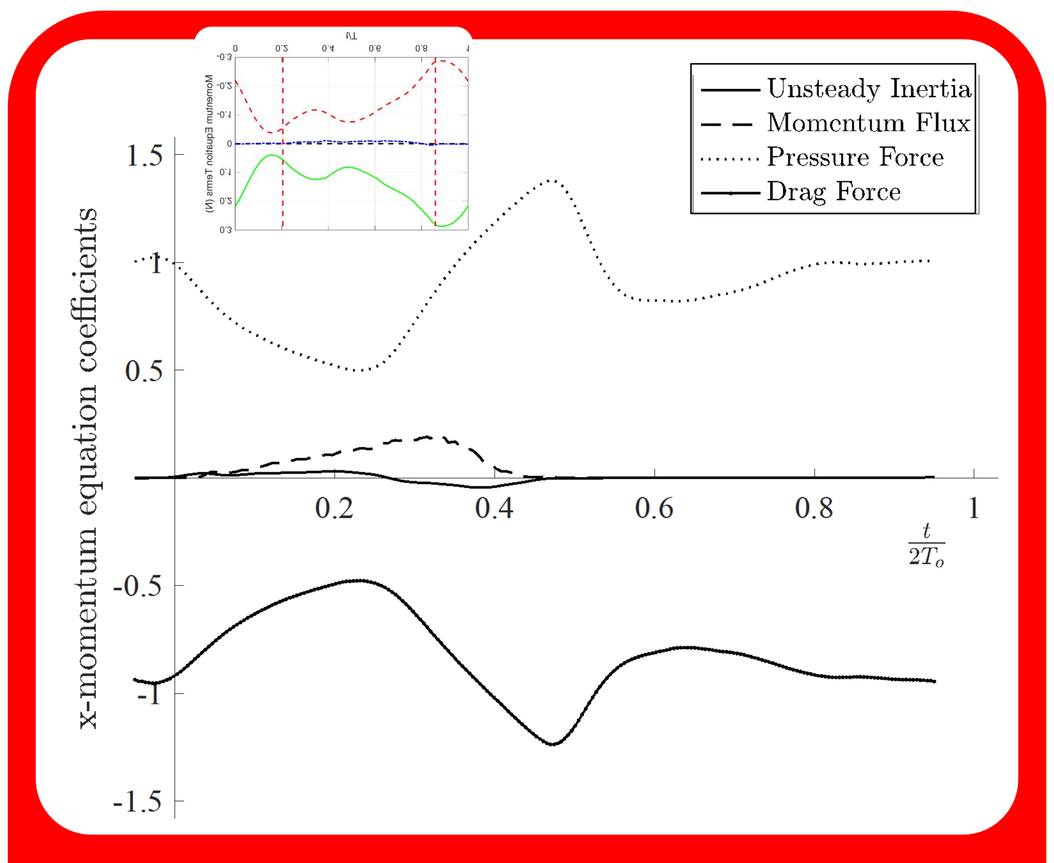
We examined: i) four speeds (Re = 3650, 5350, 7200 & 8100) at one frequency, corresponding to 105 Hz and ii) four frequencies (corresponding to 52.5 Hz, 67.5 Hz, 82.5 Hz & 105 Hz) at one speed, Re = 7200.



Time traces of pressure differences upstream, downstream and across the glottis at Re = 7200 for the four different frequencies. Note similarity to by Deverge, et al. (2003). For quasi-steady flow, the transglottal pressure waveforms should be sawtooth shaped, decreasing from $t/2T_o = 0$ to 0.25, increasing to $t/2T_o = 0.5$ and then returning to $C_p = 1$.

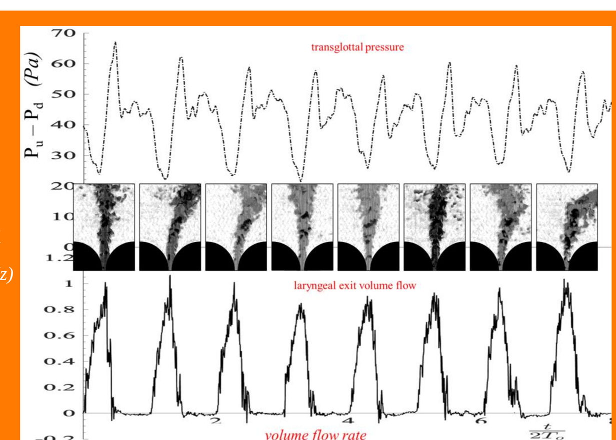


Corresponding flow measurements. For quasi-steady flow, maximum jet velocity profiles should be square and volume flow should be symmetric triangles between $t/2T_o = 0$ and 0.5.

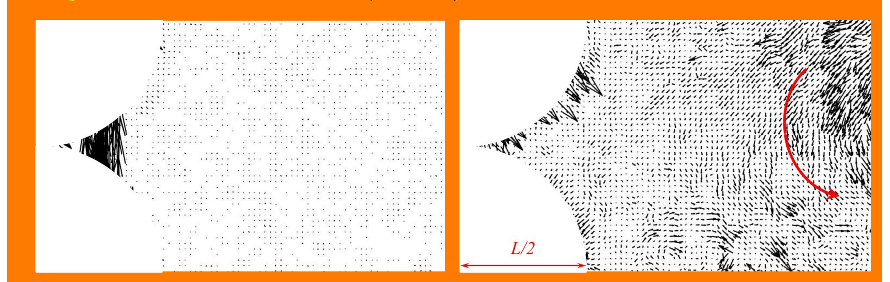


The momentum balance shows that pressure force and VF drag match to ~20%. But momentum flux from the jet and inertia from VF motions are not negligible. (Inset from coupled fluid-structure computations from Zhang's group).

Re = 7200
$f^* = 0.0261$
(f_{life} = 97.5 Hz)



Even for a highly repeatable, symmetric experiment, variations occur from cycle-to-cycle. Also observed in a separate experiment by Sherman, et al. (2020).



$t/2T_o = 0.004$ $t/2T_o = 0.95$

$Re = 7200$; $f^* = 0.0261$ (f_{life} = 97.5 Hz)

Note that the vector lengths in both fields are five times longer than in previous slides.

Conclusions:

- Transglottal pressure is a viable surrogate for vocal fold drag (which, in turn is a measure of acoustic source strength),
- Cycle-to-cycle variations in volume flow rate and TGP are correlated with jet switching,
- Residual jet motions during vocal folds closure influence cycle-to-cycle jet variations.