Measurements of phonatory power flows and efficiencies in a human airway phantom

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OVERVIEW

We present empirical characterization of phonation power flows and efficiencies for three distinct regions of a human airway phantom: the larynx, the vocal tract, and the combination of larynx and vocal tract. A control volume power flow formulation [1], which identified inputs, outputs and losses in terms of joint statistics between volume flow and pressure, guided the measurements. The measurements presented here are used to estimate the terms in the energy equation for the larynx, the vocal tract and the system composed of their combination. From these estimates the efficiencies are also estimated.

References

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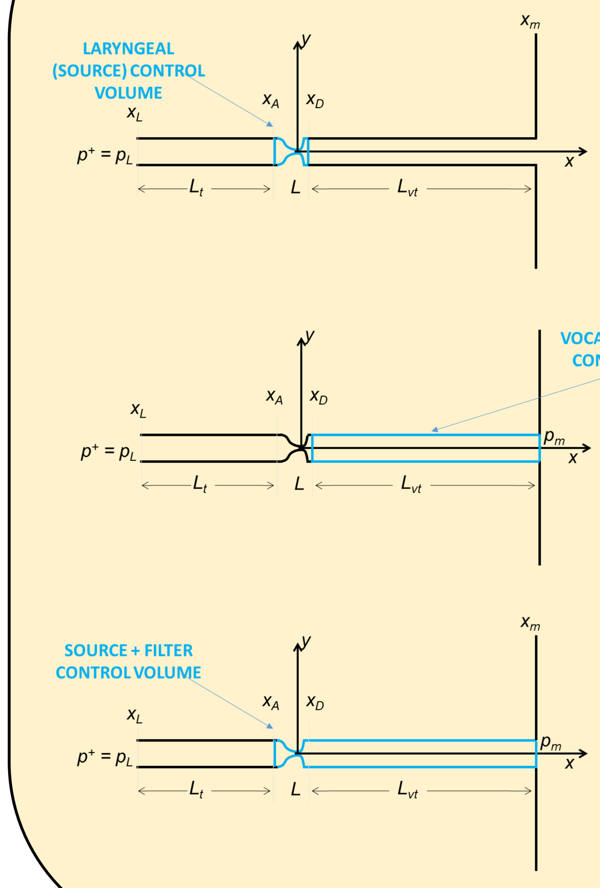
GOALS

- Develop physical basis for voice efficiency measures
- Characterize aeroelastic-aeroacoustic power flows characteristic of phonation
- Measure power flows and efficiencies in airway phantom

Control volume analysis yields definitions for efficiency

This analysis yields an equation for work done in region of interest, over a single cycle.



$$0 = \underbrace{2\left(\overline{p_A^{+}} - \overline{p_D^{-}}\right)\overline{Q} + 2\left(\overline{p_A^{+\prime} Q_A'} - \overline{p_D^{-\prime} Q_D'}\right)}_{\text{INPUT}} \underbrace{- \frac{\rho c}{S_{VT}}\overline{Q_D'^2} + \overline{\dot{W}_{VF}}}_{\text{OUTPUTS}} \underbrace{- \frac{\rho c}{S_{VT}}\overline{Q_D}^2 - \frac{\rho c}{S_T}\overline{Q_A}^2 - \frac{\rho c}{S_T}\overline{Q_A'^2} + \overline{\dot{W}_{v,Larynx}}}_{\text{LOSSES}}$$

Larynx (source) acoustic efficiency:

$$\eta_{larynx} = \frac{\frac{\rho c}{S_{VT}}\overline{Q_D'^2}}{2\left(p_L \overline{Q_A} + \overline{p_A^{+\prime} Q_A'} - \overline{p_D^{-\prime} Q_D'}\right)}$$

$$0 = \underbrace{\frac{\rho_0 c}{S_{VT}}\overline{Q_D'^2}}_{\text{INPUT}} \underbrace{- \frac{S_m}{\rho_0 c}\overline{p_m' Q_m'}}_{\text{OUTPUT}} \underbrace{+ 2\overline{p_D^{-\prime} Q_D'} + \frac{\rho_0 c}{S_{VT}}\overline{Q_D}^2 + \overline{\dot{W}_{V,VT}}}_{\text{LOSSES}}$$

Vocal tract (transmission) efficiency:

$$\eta_{VT} = \frac{\frac{S_m}{\rho_0 c}\overline{p_m' Q_m'}}{\frac{\rho_0 c}{S_{VT}}\overline{Q_D'^2}}$$

$$0 = \underbrace{2 p_L \overline{Q_A} + 2\overline{p_A^{+\prime} Q_A'}}_{\text{INPUT}} \underbrace{- \overline{p_m' Q_m'} + \overline{\dot{W}_{VF}}}_{\text{OUTPUTS}} \underbrace{- \frac{\rho c}{S_{trach}}\overline{Q_A}^2 - \frac{\rho c}{S_{trach}}\overline{Q_A'^2} + \overline{\dot{W}_{f,Larynx}} + \overline{\dot{W}_{f,VT}}}_{\text{LOSSES}}$$

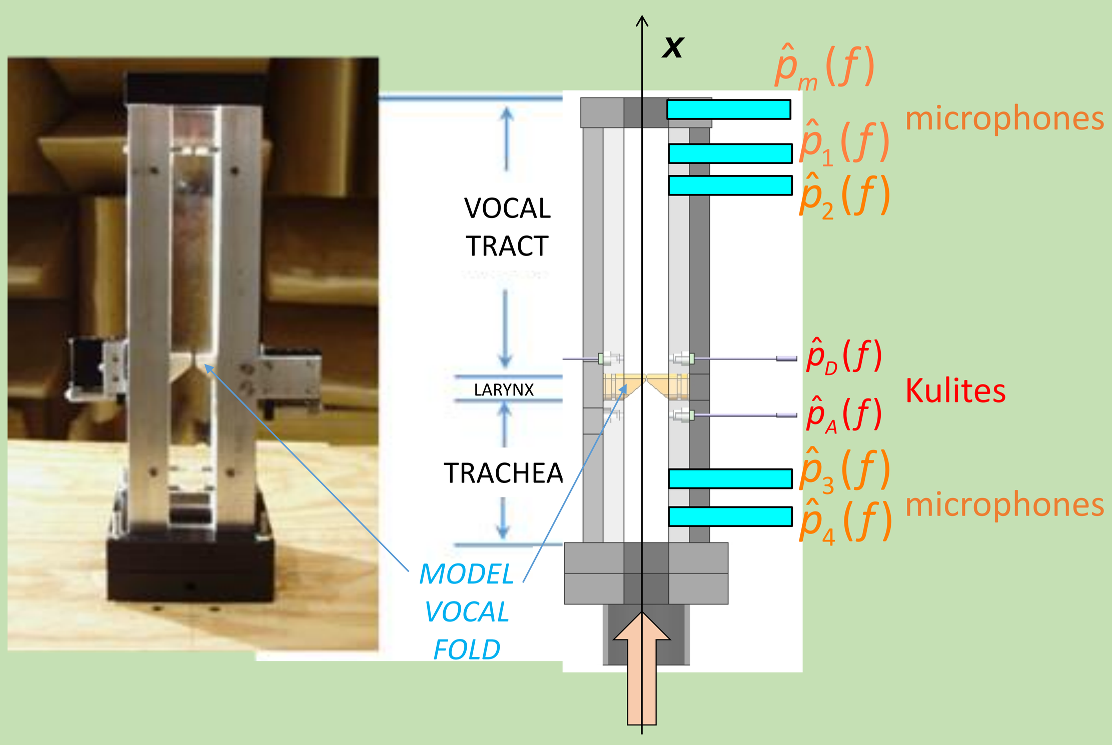
System acoustic efficiency:

$$\eta_{larynx+VT} = \frac{\overline{p_m' Q_m'}}{2 p_L \overline{Q_A} + 2\overline{p_A^{+\prime} Q_A'}}$$

We estimated the work terms used in computing efficiency.

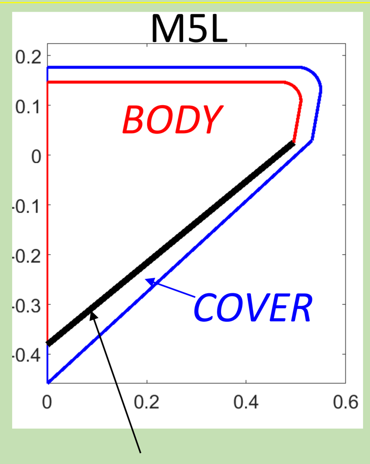
METHODS

Airway Phantom



Vocal fold model

multi-layer silicone rubber/oil mix, molded on ABS bracket



CONUS/LIGAMENT (paper modeled between layers)

Signal processing

We used the measured acoustic pressures $\hat{p}_1, \hat{p}_2, \hat{p}_3, \hat{p}_4$ to estimate the following work terms, which are in the form of variances and covariances:

$$\overline{Q_A'^2} \quad \overline{Q_D'^2} \quad \overline{p_A^{+\prime} Q_A'} \quad \overline{p_D^{-\prime} Q_D'} \quad \overline{p_m' Q_m'}$$

The reflection coefficients at microphones 2 and 3 are estimated from the G_{ij} cross-spectra of the pressures measured by microphones :

$$R_3 = \frac{\frac{G_{34}}{G_{33}} - e^{-ik(x_4 - x_3)}}{e^{+ik(x_4 - x_3)} - \frac{G_{34}}{G_{33}}}, \quad R_2 = \frac{\frac{G_{21}}{G_{22}} - e^{-ik(x_4 - x_3)}}{e^{+ik(x_4 - x_3)} - \frac{G_{21}}{G_{22}}},$$

The reflection coefficients at the locations of interest are then given by:

$$R_A = R_3\, e^{-i2k(x_3 - x_A)}, \quad R_D = R_2\, e^{+i2k(x_D - x_2)}, \quad R_m = R_2\, e^{+i2k(x_m - x_2)}$$

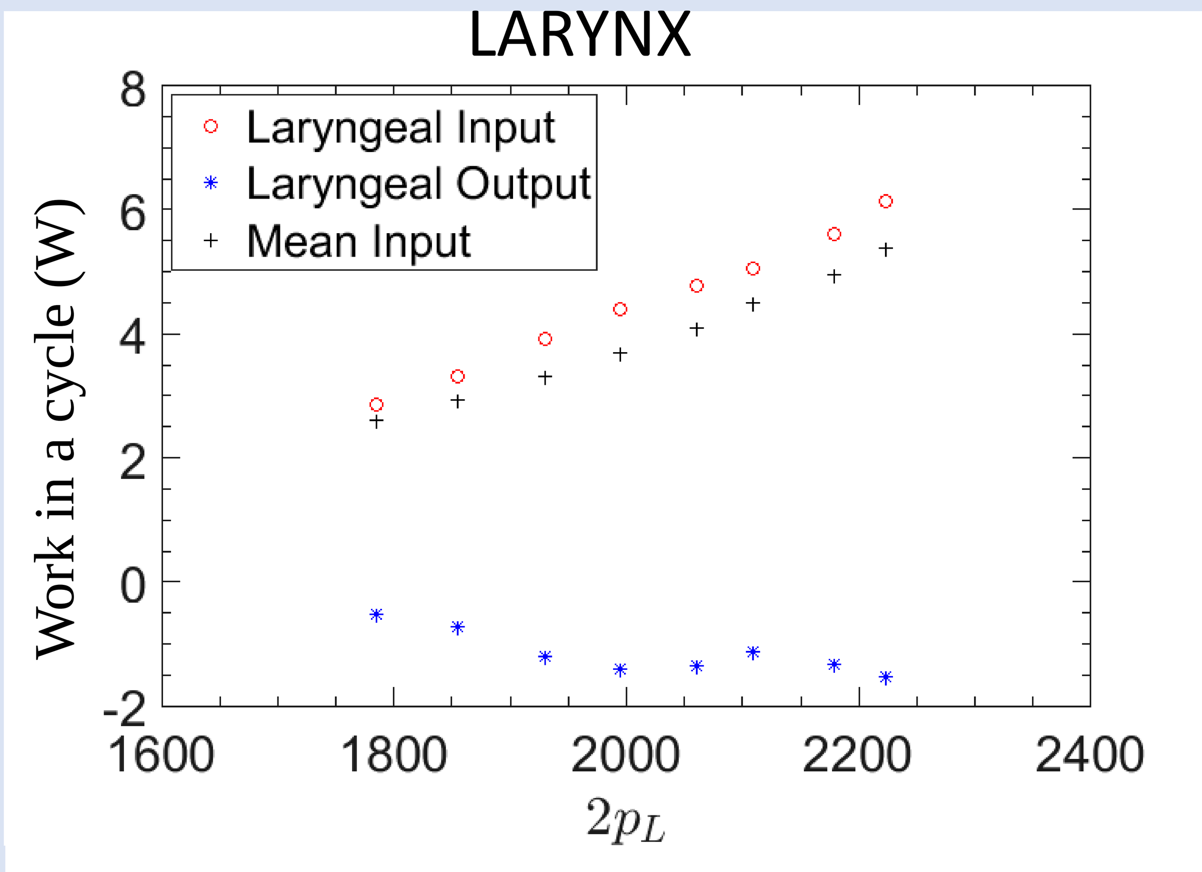
We compute variances, covariances in terms of the autospectra of the measured pressures and the reflection coefficients at the location of interest (Chung and Blaser, 1980a, b, c):

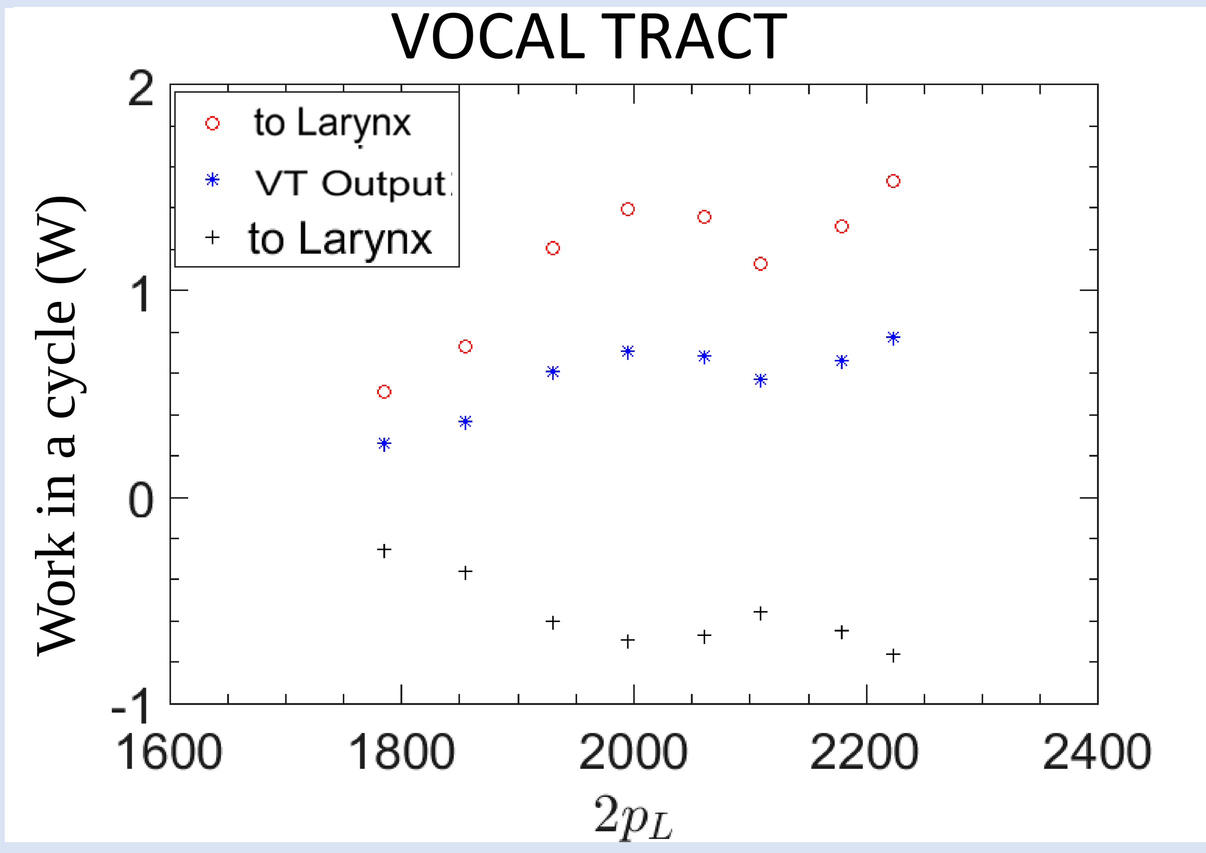
$$\overline{p_A^{+\prime} Q_A'} = 2\frac{S}{\rho_0 c}\int_0^{+\infty} \mathrm{Re}\left(G_{33}\frac{1}{1+R_A}\right)df, \quad \overline{Q_A'^2} = 2\left(\frac{S}{\rho_0 c}\right)^2 \int_0^{+\infty} G_{33}\,\mathrm{Re}\left(\frac{1 - 2\ \mathrm{Im}\{R_A\} - |R_A|^2}{|1+R_A|^2}\right)df$$

$$\overline{p_D^{-\prime} Q_D'} = 2\frac{S}{\rho_0 c}\int_0^{+\infty} \mathrm{Re}\left(G_{22}\frac{1}{1+R_D}\right)df, \quad \overline{Q_D'^2} = 2\left(\frac{S}{\rho_0 c}\right)^2 \int_0^{+\infty} G_{22}\,\mathrm{Re}\left(\frac{1 - 2\ \mathrm{Im}\{R_D\} - |R_D|^2}{|1+R_D|^2}\right)df$$

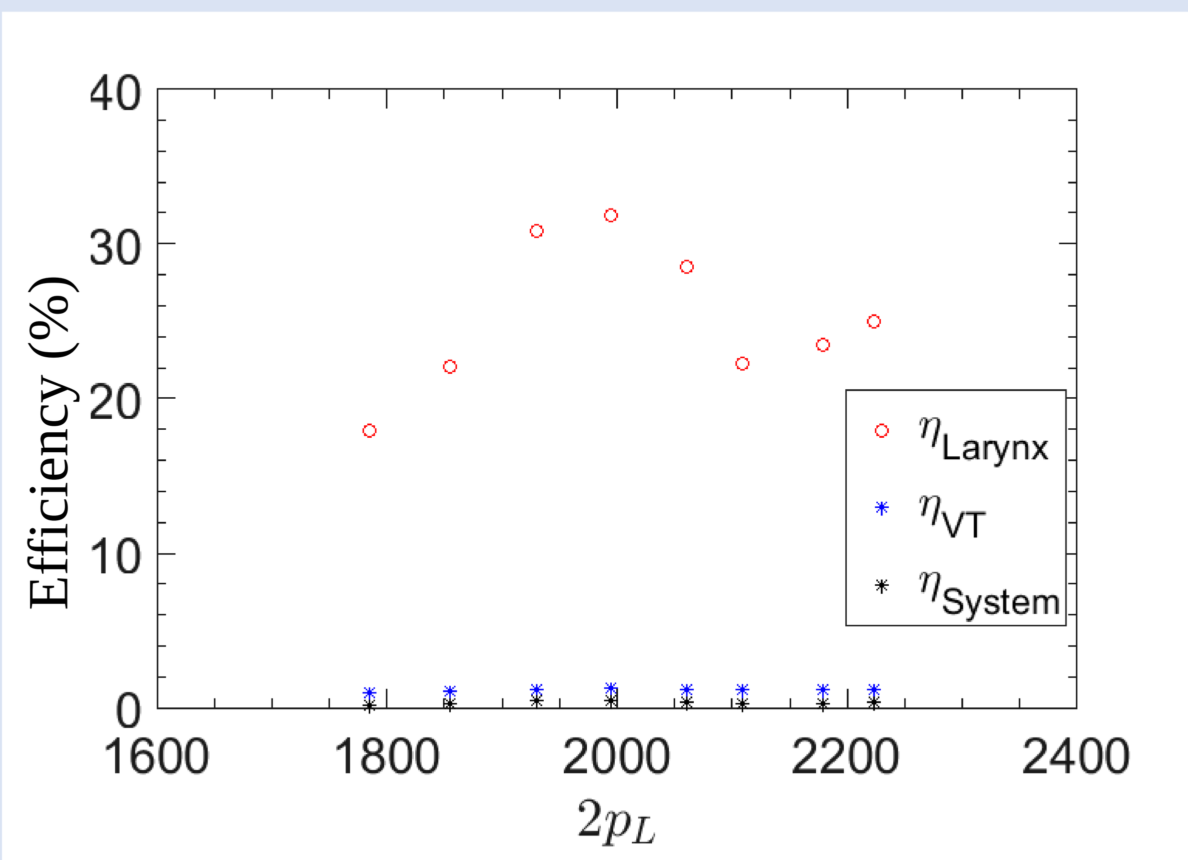
$$\overline{p_m' Q_m'} = 2\frac{S}{\rho_0 c}\int_0^{+\infty} \mathrm{Re}\left(G_{22}\frac{1 + 2\ \mathrm{Im}\{R_m\} - |R_m|^2}{|1+R_m|^2}\right)df$$

RESULTS: Energy Utilization





RESULTS: Efficiencies



SUMMARY

- Defined efficiencies in terms of cycle-averaged terms, guided by control volume analysis
- Inferred necessary pressure, volume flow variances and pressure-volume flow covariances using extension of 2-microphone technique
- Pressure-volume flow covariances comprise the energy transfers relevant for efficiency
- Estimated laryngeal, vocal tract, and system efficiencies for vocal fold vibration in airway phantom

12th ICVPB - Grenoble