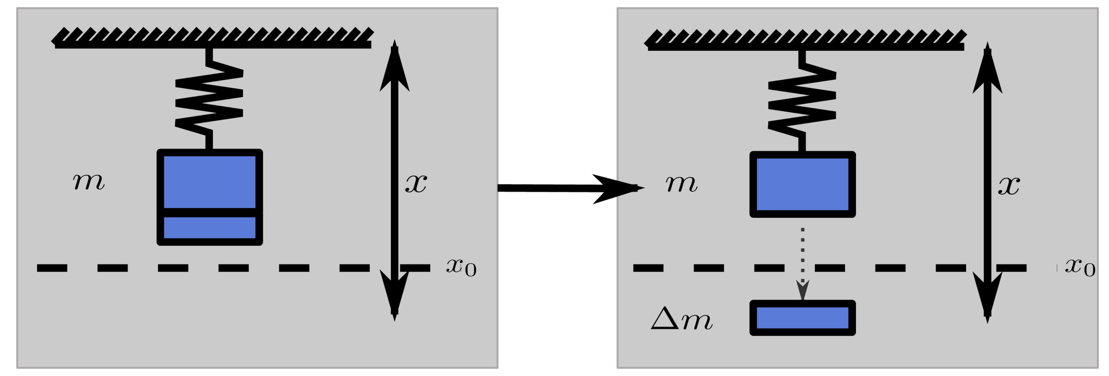
A Dynamics-Inspired Model for Phonation-Induced Aerosolization

Corey Lynn Murphey[1], Allison Hilger[2], and Elizabeth Bradley[1,3]

1. Department of Computer Science, University of Colorado - Boulder
2. Department of Speech Language and Hearing Science, University of Colorado - Boulder
3. Santa Fe Institute

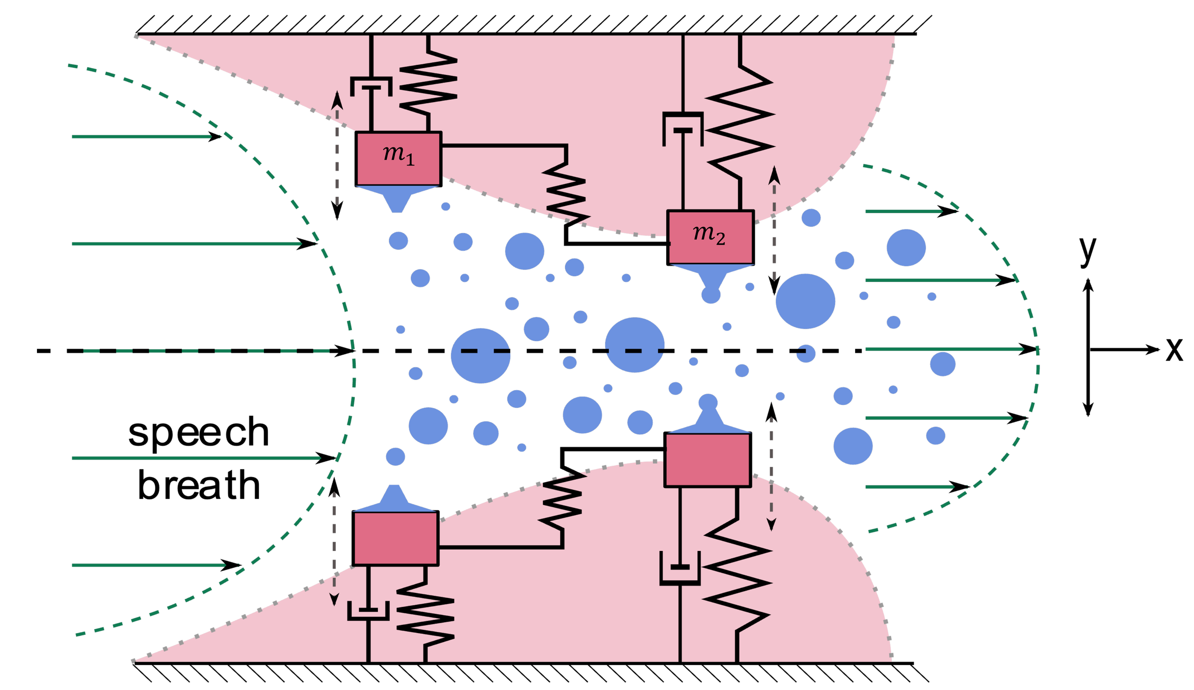
Highlights

- Exhaled aerosols originate in three locations: the lungs, the larynx, and the mouth.
- Vocal-fold oscillation models eject aerosol particles from 0 - 35 μm diameter.
- **Geometry Matters:** mass, stiffness, and damping of the tissue affect the ejection process.
- ***Validation is important but difficult…***



In 1984, Robert Shaw modeled a leaky faucet as a harmonic oscillator ejecting some mass, Δm, with each oscillation. This model **inspired** our model for droplet ejection.
We tailor Shaw's model to account for:
- free parameters
- acceleration normal to gravity
- fluid-structure interaction

Vibration-Induced Atomization Model



Two-mass Vocal Fold Oscillation Model [2]

$$\begin{cases} m_1\ddot{x}_1 + \beta_1\dot{x}_1 + k_1x_1 + \hat{k}_{ij}(x_1 - x_2) = f_1 \\ m_2\ddot{x}_2 + \beta_2\dot{x}_2 + k_2x_2 + \hat{k}_{ij}(x_2 - x_1) = f_2 \end{cases}$$

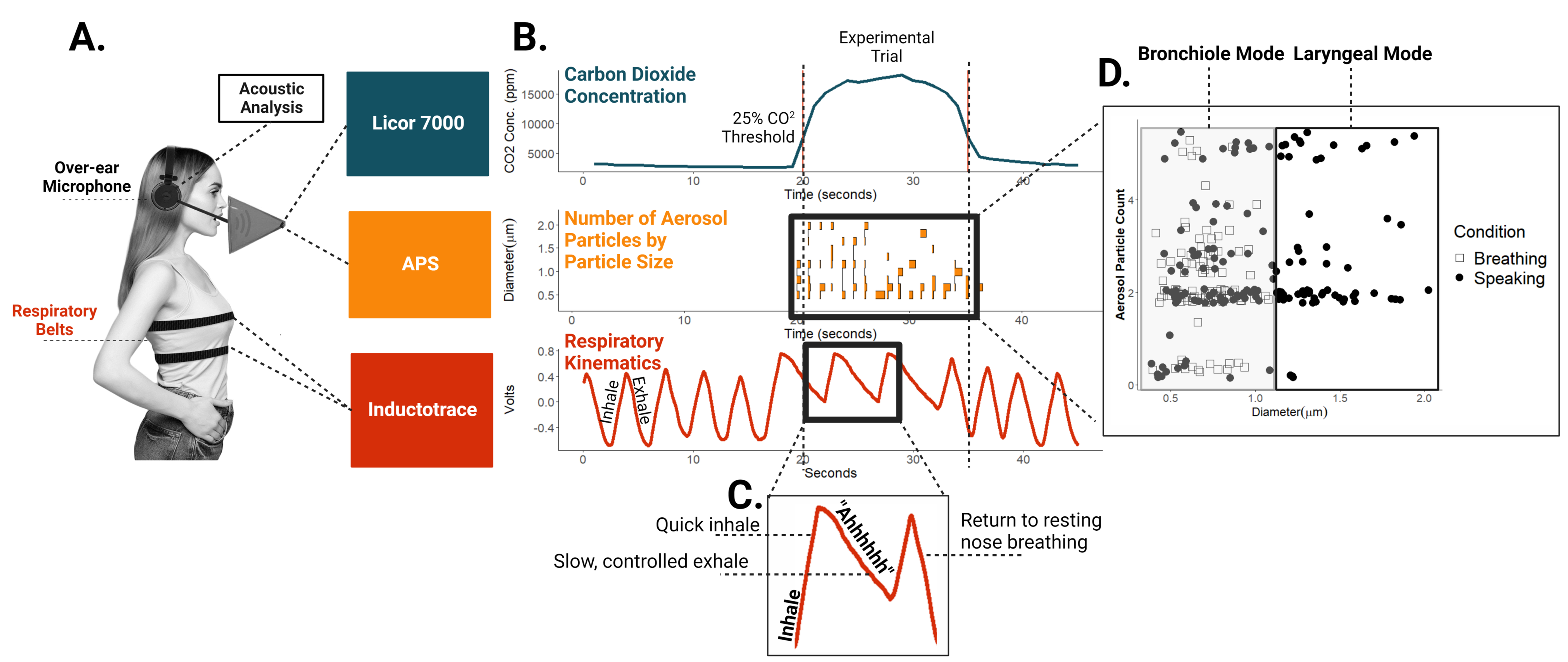
Vibration-Induced Droplet Ejection Model [3]

$$m_i = f(m_{i,t}, \overline{m_i})$$

$$\dot{m}_i = \begin{cases} 0, & \ddot{x} \le a_c \\ -r(\ddot{x} - a_c), & \ddot{x} > a_c \end{cases}$$

$$m_1 \ge m_2$$

Experimental Validation



Approach

- Evaluate sizes of particles emitted during various phonation tasks.
- Subtract off baseline experimental droplets from respiration
- Compare the experimental histogram of particle sizes to the model outputs (i.e., histogram of modeled particles sizes).

Challenges

- No filtration, deposition, and secondary breakup of particles through the vocal tract.
- Computational model is not patient-specific.
- Many free parameters and poorly understood boundary conditions.

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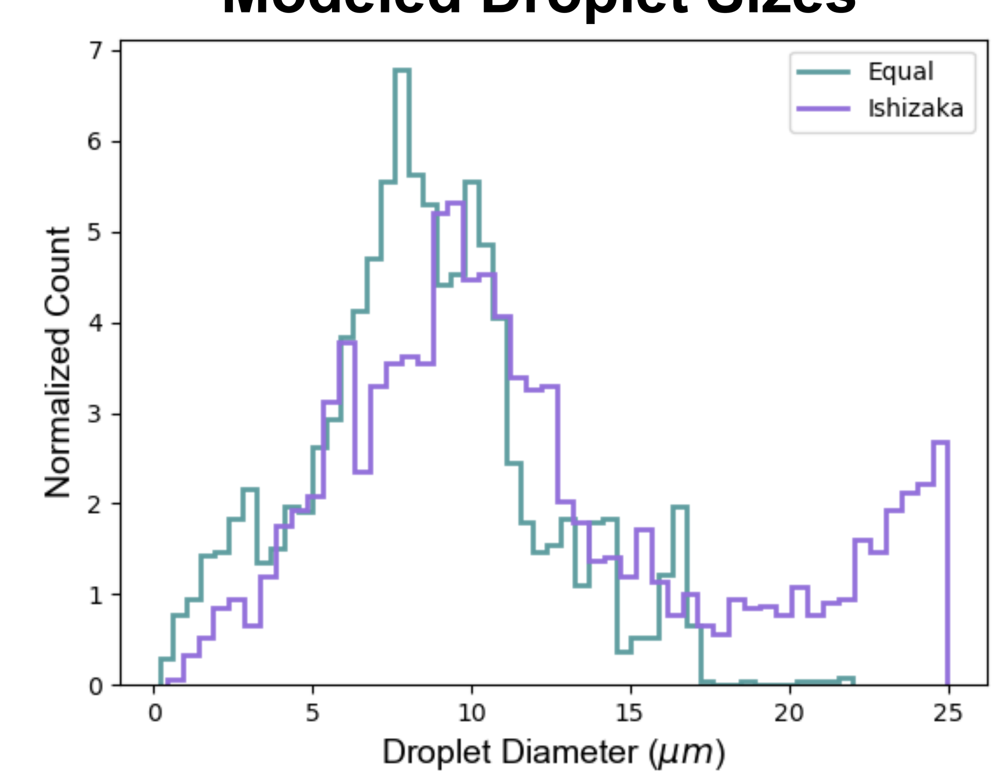
3. James, A. J., Vukasinovic, B., Smith, M. K. & Glezer, A. Vibration-induced drop atomization and bursting. J. Fluid Mech. 476, 1-28 (2003).
4. Faraday, M. On a Peculiar Class of Acoustical Figures; and on Certain Forms Assumed by Groups of Particles upon Vibrating Elastic Surfaces. Philosophical Transactions of the Royal Society of London 121, 299-340 (1831)
5. P. Martien, S. C. Pope, P. L. Scott, and R. S. Shaw, "The chaotic behavior of the leaky faucet," *Physics Letters A*, vol. 110, no. 7, pp. 399-404, Aug. 1985, doi: 10.1016/0375-9601(85)90065-9.
6. R. Shaw, *The dripping faucet as a model chaotic system*. Santa Cruz, CA: Aerial Press, 1984.

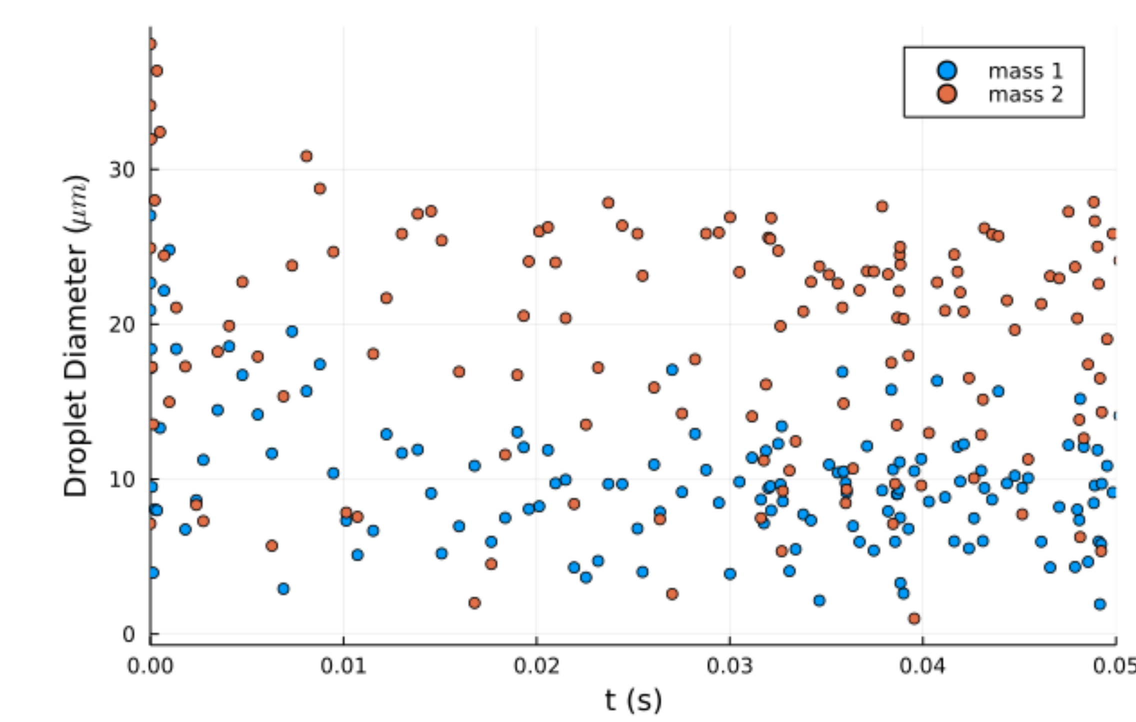
Results

Modeled Droplet Sizes



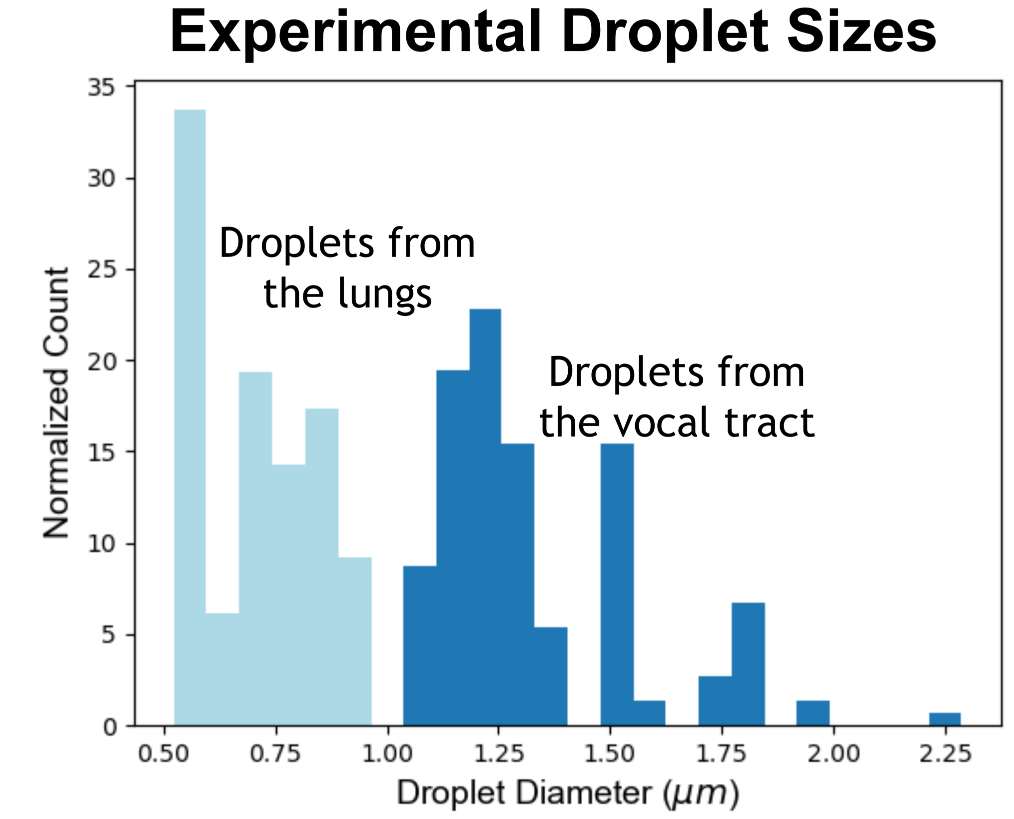
*Droplet size histogram from an equal mass model and a model using parameters from [2].

Modeled Droplet Ejection over Time



*Diameter of droplets ejected over time using parameters from [2].

Experimental Droplet Sizes



While the model yields larger droplets than we see in the experimental results, the model appears to predict the approximate range of droplet sizes we see during experimental phonatory tasks. We expect larger droplets (>5 μm) will deposit out or undergo secondary breakup within the downstream vocal tract. Deposition and secondary breakup are omitted from the current model.

Next Steps

This computational aerosolization framework is a first step toward understanding the physics of aerosol generation during phonation. Inspired by the work of Robert Shaw, the vibration-induced atomization model estimates oscillation accelerations that are sufficient to eject droplets off the surface of the mucosal layer. However, the model's droplet sizes appear to be highly sensitive to geometric parameterization. Parameter tuning and validation remain key challenges in this work. We will extend this computational framework to a multi-mass oscillatory system, adding in unsteady fluids forcing and fluid-structure interaction. We will also validate this approach further by comparing our histogram outputs with experimental aerosol data collected with an aerosol particle sizer during speech trials.

corey.murphey@colorado.edu