

Computational Modeling of Fluid-Structure-Acoustics Interaction During Voice Production

Weili Jiang, Xudong Zheng, and Qian Xue

Mechanical Engineering Department, University of Maine

Abstract

The paper presented a three-dimensional, first-principle based fluid-structure-acoustics interaction computer model of voice production which employed a more realistic human laryngeal and vocal tract geometries. Self-sustained vibrations and important convergent-divergent vibration pattern of the vocal folds were captured by the model. Proper orthogonal decomposition analysis demonstrated the 1:1 entrainment of the two dominant vibratory modes. Several voice-quality associated parameters of the glottal flow waveform were found to be well within the normal physiological ranges. The analogy between the vocal tract and a quarter-wave resonator was demonstrated. The acoustic perturbed flux and pressure inside the glottis were found to be at the same order with their incompressible counterparts, suggesting strong source-filter interactions during voice production.

Keywords: fluid-structure-acoustic interaction, acoustic coupling in voice production

1. Introduction

Voice production is a complex three-way interaction process between the glottal flow dynamics, vocal fold vibrations and vocal tract acoustics. During voiced speech, the forced air from the lungs interacts with the adducted vocal folds to initiate self-sustained vibrations. This creates a pulsatile jet in the larynx which is the sound source. The jet then passes through the supraglottal vocal tract which primarily serves as an acoustic resonator to reshape the spectrum of the sound source. The acoustic pressure in the vocal tract can also propagate back to the larynx to affect glottal flow dynamics and vocal fold vibrations.

The objectives of the current study were to: (a) develop a first-principle based computational model of voice production which could faithfully model the fluid-structure-acoustics interactions with more realistic larynx and airway geometries; (b) to analyze the flow waveform, vocal fold vibrations and acoustic dynamics predicted by the model and compare them to the established data; (c) to investigate the effect of acoustic coupling on voice production.

2. Computational method and simulation setup

The computational solver was built upon our previous immersed-boundary-finite-element method based fluid-structure interaction solver (Zheng et al., 2010). The glottal airflow was governed by the three-dimensional, unsteady, viscous, incompressible Navier–Stokes equations. A hydrodynamic/acoustics splitting method based acoustics solver was integrated to realize the three-way interactions (Seo and Moon, 2006; Seo and Mittal, 2011). The acoustics field was modeled by the linearized perturbed compressible equation (LPCE). Further details of this model can be found in

Seo and Mittal (2011). With this splitting method, the total velocity/pressure of the flow would be the sum of the incompressible flow velocity/pressure and acoustic velocity/pressure perturbation.

The coupling process of the simulation is shown in Table 1. The fluid, structure and acoustics solvers were explicitly coupled through a Lagrangian interface where vocal tract and vocal folds contacted. In each iteration, the incompressible flow was marched by one step with the existing deformed shape and velocities of the solid tissue as the boundary conditions. The acoustic solver was then marched with the updated incompressible flow field as well as the existing deformed shape and velocities of the solid tissue as the boundary conditions. The forces at the vocal fold surface was then calculated with the new incompressible flow pressure and acoustic perturbation pressure. At last, the solid solver was marched by one step with the updated surface traction. The deformation and velocities on the solid grid were then transferred to the vocal fold surface, so that the fluid/solid interface can be updated.

Table 1. *The coupling process of the flow, acoustics and solid solvers*

Step	Procedure
1	Flow solver, get the incompressible flow pressure and velocity
2	Acoustics solver, get the compressible flow perturbed pressure and velocity
3	Update the traction on the vocal folds
4	Solid solver, get the tissue displacement and velocity
5	Deform lumen and update the lumen boundary condition
6	Go to Step 1

The geometric model of the simulation is shown in Fig.1. The geometry of the larynx was roughly reconstructed from a thin-slice CT scan of the larynx of a 30-year-old male subject (Zheng et al., 2009). The geometry of the vocal folds was constructed based on the mathematical model proposed by Titze and Talkin (1979), which has considered the three-dimensional shape of the vocal fold including the anterior-posterior variation. The cross-section area of the supraglottal vocal tract was taken from an in-vivo based neutral vowel model proposed by Story (2005), and it was superimposed onto a realistic airway center line from the in-vivo MRI measurement (Story et al., 1996) to generate the supraglottal tract model. The length of the supraglottal tract was 17.4cm and the length of the subglottal tract was 3.05cm. The vocal tract generally did not move except the place that contacted with the vocal folds.

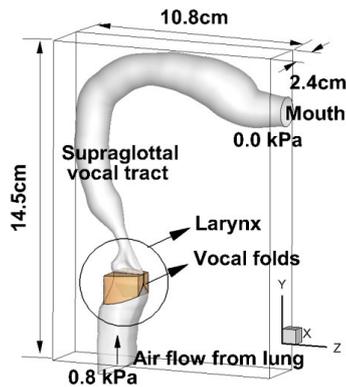


Figure 1. The geometric model of the larynx

3. Discussion and conclusion

Self-sustained vibrations and a reasonable glottal flow waveform were captured by the model and important voice-quality associated parameters were found to be well within the normal physiological ranges. The important convergent-divergent vibration pattern of vocal folds was captured. POD analysis demonstrated the 1:1 entrainment of the two dominant vibratory modes. The analogy between the vocal tract and a quarter-wave resonator was demonstrated.

The simulation result reflected that the acoustic perturbed flux and pressure inside the glottis as well as the supraglottal tract were all at the same order with their incompressible counterparts, suggesting strong source-filter interactions during normal phonation. This effect was associated with the acoustic pressure oscillation associated with the first formant of the supraglottal tract. We speculated that the strong acoustic coupling observed in the current model was mainly due to the inclusion of the effect of unsteady incompressible flow in the supraglottal tract. Different from the one-dimensional wave equation which describes the wave propagation in the stagnant flow, the current model considered the acoustic perturbation along with the unsteady incompressible flow. The velocity and pressure of the incompressible flow can affect the acoustic perturbation through many terms in the perturbation equation, particularly, the time derivative of the incompressible flow pressure which can act as an additional source term to generate strong acoustic waves.

The model demonstrated the capability of providing fully resolved and coupled flow, structure and acoustics solutions in complex laryngeal shapes. Such a model can be very useful for developing and testing simpler models that can be transformed into clinical tools for simulation-guided diagnosis and therapy of voice diseases. It also can be useful for studying the fundamental mechanisms of voice production, especially those related to the source-tract coupling effect, turbulent sound and different voice types. The model will greatly extend the current framework of voice modeling to a wide range of pathological conditions which often involve complex vibration conditions.

4. Acknowledgements

The project was supported by Grant Number 1R03DC014562 from the National Institute on Deafness and Other Communication Disorders (NIDCD). The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIDCD or the NIH.

5. References

- Seo, J. H., Moon, Y. J. (2006). "Linearized perturbed compressible equations for low Mach number aeroacoustics". In: *J. Comput. Phys.*, 218, 702-719.
- Seo, J. H., Mittal, R. (2011). "A high-order immersed boundary method for acoustic wave scattering and low-Mach number flow-induced sound in complex geometries". In: *J. Comput. Phys.*, 230, 1000-1019.
- Story, B. H. (2005). "A parametric model of the vocal tract area function for vowel and consonant simulation". In: *J. Acoust. Soc. Am.*, 117(5), 3231-3254.
- Story, B. H., Titze, I. R., Hoffman, E. A. (1996). "Vocal tract area functions from magnetic resonance imaging". In: *J. Acoust. Soc. Am.*, 100(1), 537-554.
- Titze, I. R., Talkin, D. T. (1979). "A theoretical study of the effects of various laryngeal configurations on the acoustics of phonation". In: *J. Acoust. Soc. Am.*, 66(1), 60-74.
- Zheng, X., Bielamowicz, S., Luo, H., Mittal, R. (2009). "A computational study of the effect of false vocal folds on glottal flow and vocal fold vibration during phonation". In: *Ann Biomed Eng.* 37(3), 625-642.
- Zheng, X., Xue, Q., Mittal, R., Bielamowicz, S. (2010). "A coupled sharp-interface immersed boundary-finite-element method for flow-structure interaction with application to human phonation". In: *J. Biomech. Eng.* 132, 1110003-1-1110003-12.