IMPACT OF VOCAL FOLD OSCILLATION ON TURBULENT FLOW IN HUMAN PHONATION MODELING

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This study investigates 3D incompressible large-eddy simulations (LES) of laryngeal airflow, followed by subsequent aeroacoustic propagation through the vocal tract and radiation into the free field surrounding the mouth. Even small differences between the subgrid-scale turbulence models employed are manifested in the resulting aeroacoustic frequency spectra.

The performance of two widely used subgrid-scale models, the One-Equation (OE) model and the Wall-Adapting Local Eddy-viscosity (WALE) model, is compared with the Anisotropic Minimum Dissipation (AMD) subgrid-scale model. The AMD model has been relatively recently implemented (as a custom library) [1] and has already proven effective in modeling human phonation, yielding improved spectral characteristics.

To further examine the sensitivity of aeroacoustic spectra to vocal fold kinematics, additional simulations are currently underway. These employ a newly implemented, more physiologically realistic vocal fold motion derived from dynamic MRI measurements of healthy phonation and contrast it with conventional simplified prescribed kinematics. All simulations were performed using the open-source CFD toolbox OpenFOAM.

1 Introduction

Interdisciplinary approaches combining medical applications with mathematical and computational modeling are becoming increasingly prevalent in voice research. Numerical simulations hold significant potential for clinical use, as they enable detailed 3D visualization of laryngeal airflow, localization of aeroacoustic sound sources, analysis of formant patterns for voice disorder classification, and provision of other clinically relevant insights essential for improved diagnosis and treatment of voice pathologies.

2 Methods

The large-eddy simulation of turbulent flow resolves large-scale vortices, while the influence of the subgrid-scale vortices is modeled by a subgrid-scale closure model. The large vortices carrying the most energy in the flow are resolved by Navier-Stokes equations (NSE), whereas the small scales are modeled applying a spatial filter $(\bar{\cdot})$ in NSE

$$\partial_t + \partial_j(\overline{u}_i\overline{u}_j) - \partial_j(\nu\partial_j\overline{u}_i) = -\partial_i\overline{p} - \partial_j\tau_{ij}, \ \ \partial_i\overline{u}_i = 0, \tag{1}$$

where τ_{ij} is subgrid-scale turbulent stress tensor and describes the effect of modelled subgrid-scales on resolved large-scales vortices. To ensure that the turbulent viscosity ν_t is increased locally only as much as necessary to provide sufficient dissipation (i.e., a smooth transition from subgrid-scale effects to the molecular viscosity ν), the following eddy-viscosity relation is used:

$$\tau_{ij} - 0.33\tau_{kk}I_{ij} = -2\nu_t\overline{S}_{ij} = -\nu_t(\partial_j\overline{u}_i + \partial_i\overline{u}_j), \tag{2}$$

where I_{ij} is the identity matrix and $\overline{S}_{ij}$ strain-rate tensor. To guarantee that the kinetic energy of the subgrid scales remains bounded (and decays appropriately), the Poincaré inequality is invoked, leading to the designation of this group of models as minimum-dissipation models. For anisotropic meshes, this approach was extended by [2], with the anisotropic minimum-dissipation (AMD) model, where ν_t is computed as

$$\nu_t = C_A \frac{\max\left\{-(\Delta x_k\partial_k\overline{u}_i)(\Delta x_k\partial_k\overline{u}_j)\bar{S}_{ij}, \ 0\right\}}{(\partial_l\overline{u}_m)(\partial_l\overline{u}_m)}, \tag{3}$$

where Δx_k represents the LES filter width and the model constant $C_A = 0.3$ fitted for a central second-order numerical scheme.

3   Conclusion

Aeroacoustic simulations were performed for cardinal vowels, enabling a comparative evaluation of subgrid-scale models. The key observations are summarized as follows:

1. AMD consistently produced the strongest sound pressure levels (SPL) in higher harmonics up to approximately 2000 Hz across all vowels, whereas WALE dominated in the 2000–3000 Hz range.

2. AMD yielded a stronger second formant (F2), while WALE enhanced the third formant (F3). Note that F3 is generally less relevant for voice diagnostics.

3. The choice of subgrid-scale model had no significant effect on the formant frequency positions.

4. Simulations employing AMD exhibited higher total SPL than those using WALE or OE for all vowels except the front-close vowel /i/.

The AMD model appears highly promising as a successor to the WALE model for laryngeal flow modeling. Its superior prediction of stronger harmonics up to F2 across all studied vowels likely stems from its theoretical advantages: consistency with the exact subgrid-scale stress tensor τ_{ij}, independence from specific filter width approximations, and robustness on anisotropic meshes.

These attributes make AMD particularly well-suited for complex biofluid flows involving vocal fold oscillation. To systematically assess the impact of kinematic realism on turbulent structures and aeroacoustic output, additional simulations are currently underway. These employ a physiologically more realistic vocal fold motion derived from dynamic MRI measurements of healthy phonation and contrast it with conventional simplified prescribed kinematics. This extension is expected to provide deeper insight into how vocal fold oscillation fidelity influences glottal jet turbulence, sound source generation, and the resulting frequency spectra, thereby further improving the reliability of subgrid-scale turbulence modeling in realistic human phonation simulations.

References

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