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Numerical Simulation of Fluid–Structure Interaction in Human Phonation

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ABSTRACT

The human voice originates from the larynx which is located in the neck. Vocal folds inside the larynx vibrate and modulate the airflow from the lungs, giving rise to acoustic energy, i.e. sound which is further modified in other parts of the vocal apparatus (lips, tongue, nasal cavity etc.) Increasing knowledge about the complex fluid–structure interaction in the larynx is important to identify voice disorders and in the future to simulate larynx surgery.

Several difficulties are involved herein. We are dealing with a flow at high Reynolds number and low Mach number, interacting with an inhomogeneous anisotropic nonlinear structure undergoing large deformations where the stress response depends on the strain history. The description of biomaterials is by no means simple and relies heavily on empirical data. We want that our model will be able to capture the effect of self-sustained oscillations of vocal fold tissue due to the interaction with the air flow. Our goal is to compute the acoustic field radiated from the larynx using direct numerical simulation. Since we are interested in the generation and propagation of sound in the airways, our starting point is the compressible Navier–Stokes equations. We consider fluid–structure interaction in 2D, but the goal is to move to 3D at a later stage. We assume a Newtonian fluid obeying the perfect gas law.

A compressible Navier–Stokes solver has previously been implemented and verified for external flows with aeolian tones. In order to obtain the energy estimate required for strict stability, the solver utilizes a summation by parts operator, which corresponds to a sixth order finite difference scheme in the interior and a third order difference method near the boundaries, cf. [4][3]. The strict stability property is extremely important for long time integration. When used with the simultaneous approximation term technique to implement the fluid–structure coupling, the strictly stable finite difference method will guarantee stability of the coupled system. Using the classical fourth order explicit Runge–Kutta method, the solution is advanced in time. The equations are expressed in a perturbation formulation to minimize cancellation errors caused by computing small changes of the variables in low Mach number flow. A characteristic-based treatment and an exit zone are employed at the outflow boundary. Applying a sixth order explicit filter to the solution at every time step suppresses spurious oscillations. Results for

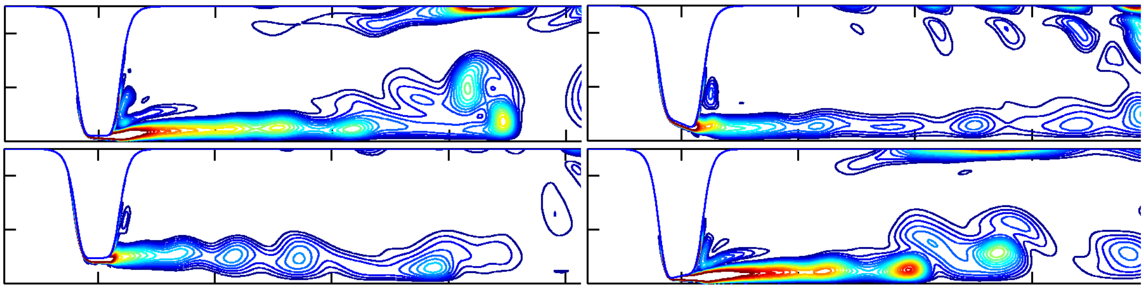

Figure 1: *Vorticity contours near the glottal region at 4 different times for the time dependent geometry:* $t = 1.0\,T_0$ *upper left,* $t = 1.3\,T_0$ *upper right,* $t = 1.6\,T_0$ *lower left, and* $t = 1.9\,T_0$ *lower right, where* T_0 *is the period of the forcing motion.*

the 2D and axisymmetric airflow in the larynx for a stationary grid as well as an imposed wall motion geometry [1] have been qualitatively verified by comparison with [2].

For the structure part of the simulation, we consider a nearly incompressible neo-Hookean elastic material undergoing large deformations. Viscous damping is governed by the Kelvin model of viscoelasticity. We shall make use of measurements of the viscoelastic shear properties of vocal fold tissues.

The coupling between fluid and structure is accomplished via the arbitrary Lagrangian–Eulerian (ALE) approach where we let the solution from the structure domain (i.e. the coordinates and velocities of the material particles) alter the boundaries for the fluid domain. The boundary conditions for the fluid are then the usual viscous no-slip condition and the continuity of normal stresses across the fluid–structure interface.

So far, we have obtained results for a stationary geometry in two different configurations (i.e. converging/diverging glottis, corresponding to different shapes of the vocal folds during the glottal oscillation) and a moving geometry with imposed wall motion. Both axisymmetric and 2D flow have been considered for all the different cases. Figure 1 shows vorticity contours for the flow case with the 2D time dependent geometry at 4 different times [1]. The vortex shedding is more pronounced for the diverging glottis shape at $t = 1.9\,T_0$, cf. the lower right plot in Fig. 1, than for the converging glottis shape at $t = 1.3\,T_0$, cf. the upper right plot in Fig. 1, where T_0 is the period of the forcing motion. All results have been computed on a 480×120 grid. The goal for the final paper is to have a working fluid–structure interaction model and a realistic model for the vocal folds.

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