High-resolution CFD simulation of flow in glottis using LES

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Objectives

- High-resolution CFD simulation of airflow during human phonation
- Simple 3D glottal channel geometry and parametrizable vocal fold motion
- Focus on the fluid dynamics

Main goal: assess what level of detail is necessary and how much do the fine turbulent structures influence the aeroacoustic sources and voice generation

Introduction

Numerical simulation of the unsteady separated airflow in glottis during phonation is a challenging issue:

- Airflow most likely laminar in trachea
- Undergoes transition to turbulence within or upstream of the glottis

Numerical modeling

- Laminar model: introduces inaccuracy – neglects turbulent momentum transfer
- Reynolds-Averaged Navier-Stokes (RANS) models: inappropriate for aero-acoustic simulations – provide only mean flow solution with turbulent fluctuations averaged out
- Direct Numerical Simulation (DNS): currently unfeasible due to enormous computational cost

→ **The most promising approach seems to be Large Eddy Simulation (LES)**

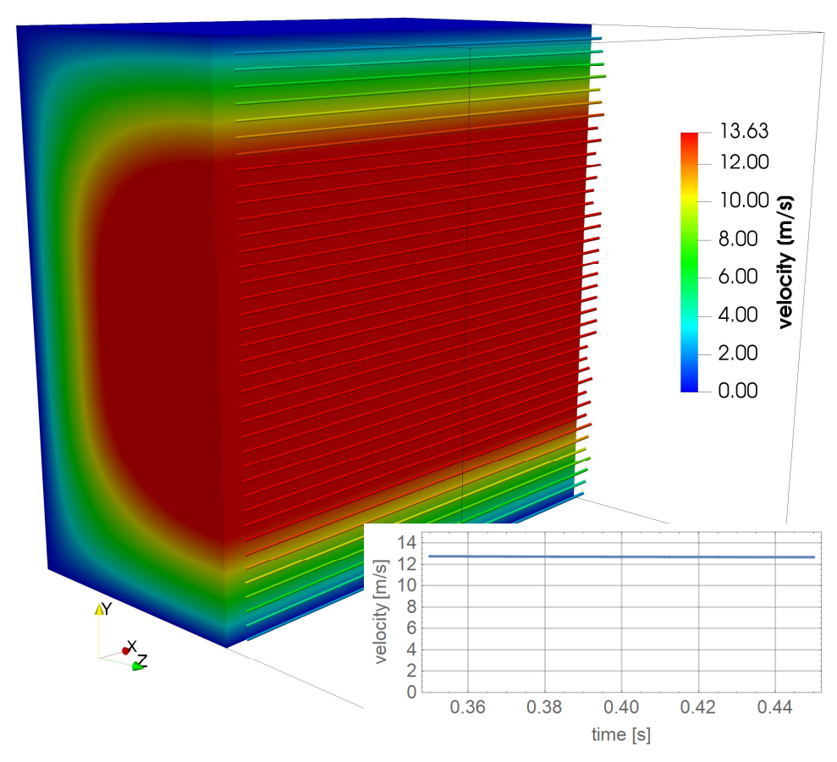


Figure 1. Laminar flow (velocity field and time history)

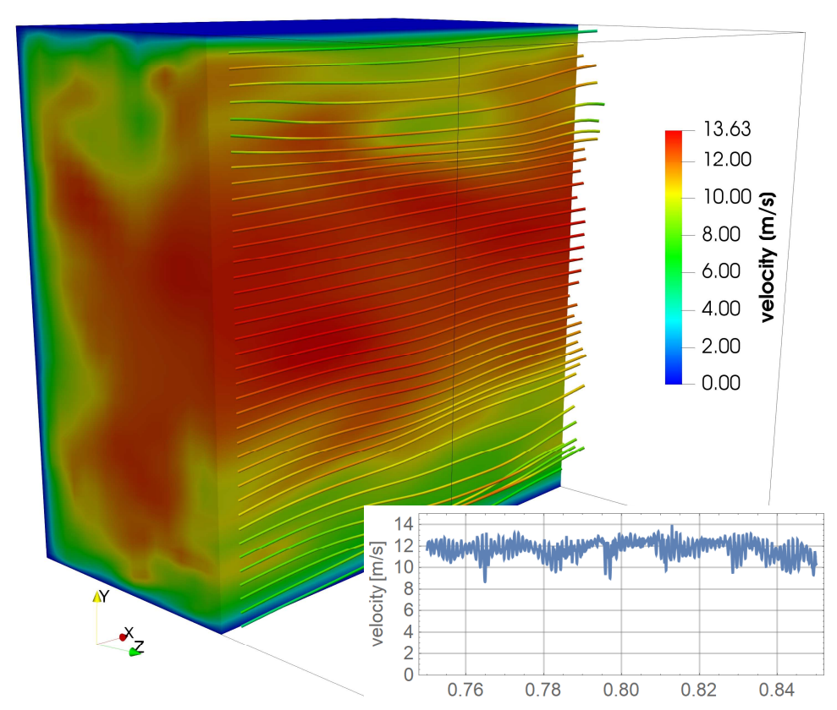


Figure 2. Turbulent flow (velocity field and time history)

Methods

- simplified 3D model of glottis with forced convergent-divergent motion of vocal folds
- geometry of vocal folds based on M5 model by Scherer et al. [3], ventricular folds modeled according to data by Agarwal et al. [4]
- unstructured prismatic and block-structured hexahedral meshes capturing the boundary layer, 2 – 20 million elements

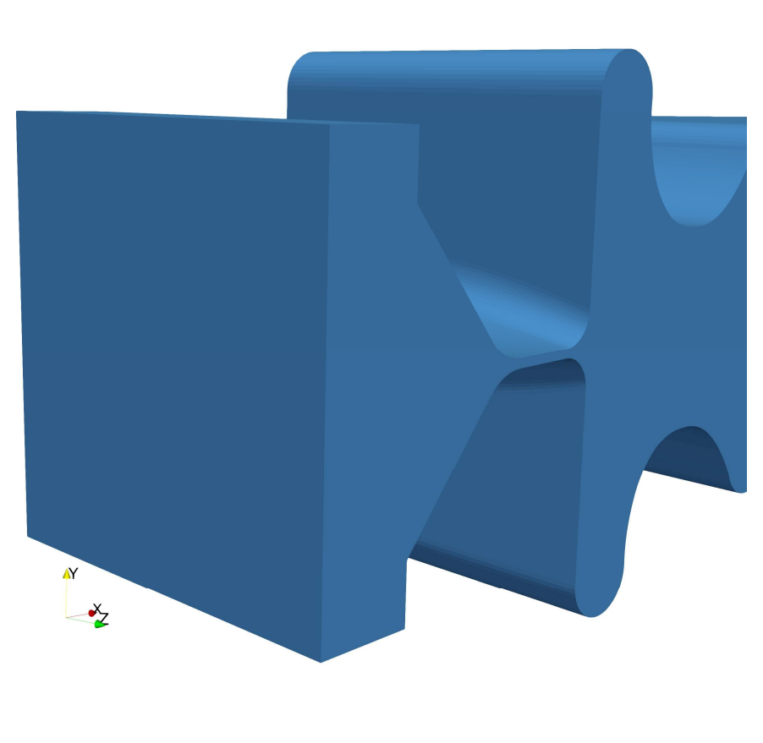


Figure 3. Geometry of the computational domain (part near the glottis)

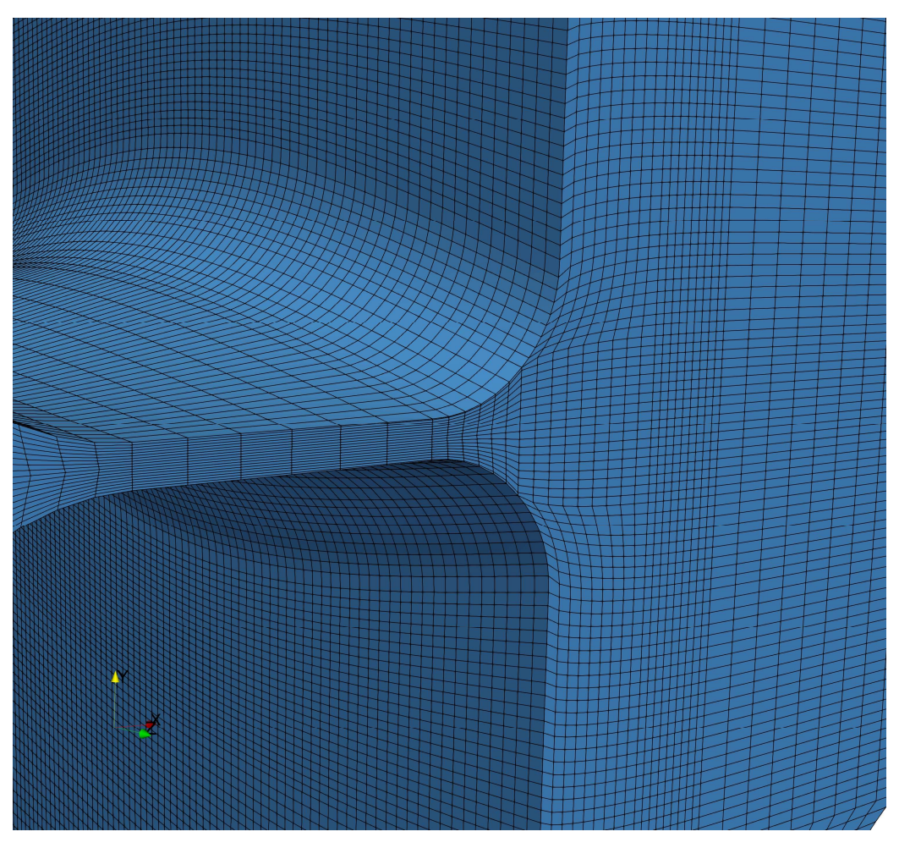


Figure 4. Fully connected block-structured hexahedral mesh with boundary layer refinement (2.2M elements)

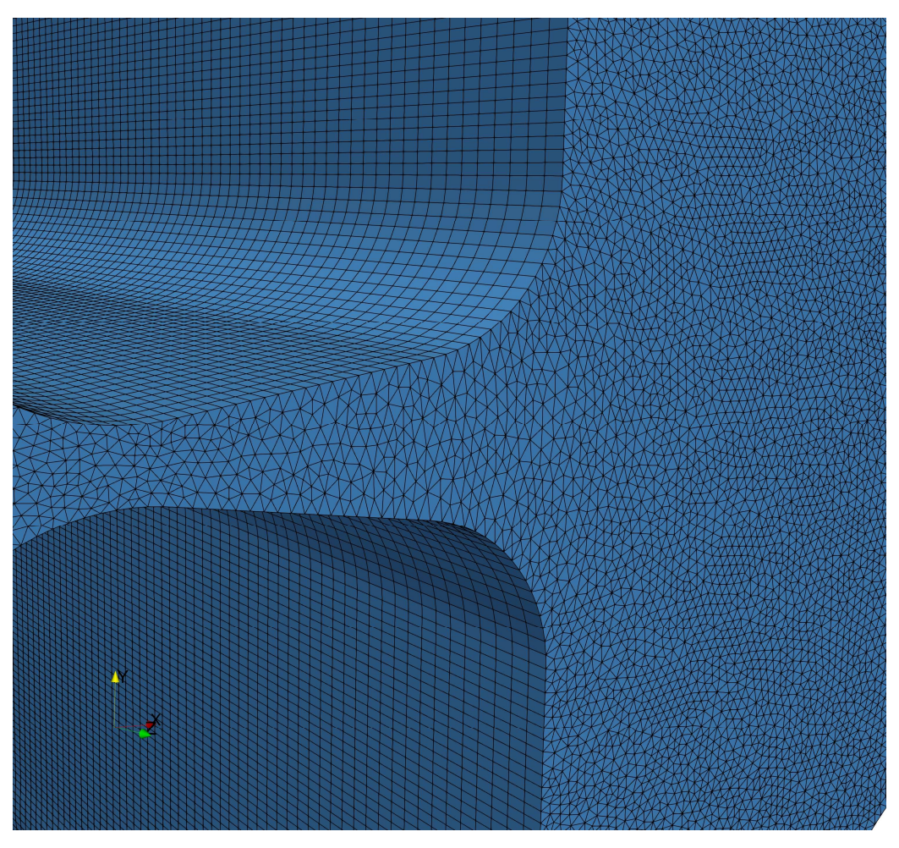


Figure 5. Unstructured prismatic mesh without boundary layer refinement (10M elements)

- CFD model: Large eddy simulation with one-equation sub-grid scale model

$$\frac{\partial \overline{\boldsymbol{u}}}{\partial t} + \nabla \cdot (\overline{\boldsymbol{u}} \otimes \overline{\boldsymbol{u}}) = -\frac{1}{\rho} \nabla \bar{p} + \nabla \cdot (2\nu \overline{\boldsymbol{S}} - \boldsymbol{T}),$$

$$\nabla \cdot \overline{\boldsymbol{u}} = 0, \quad \text{where}$$

$\overline{\boldsymbol{u}}$ and $\bar{p}$	filtered (large-scale) velocity and pressure
ν and ρ	molecular viscosity and density of air
$\overline{\boldsymbol{S}} = \frac{1}{2}(\nabla \overline{\boldsymbol{u}} + \nabla \overline{\boldsymbol{u}}^T)$	large-scale strain rate tensor
$\boldsymbol{T} - \frac{1}{3} tr(\boldsymbol{T})\boldsymbol{I} \approx -2\nu_{SGS}\overline{\boldsymbol{S}}$	deviatoric part of the sub-grid scale (SGS) stress tensor
$\nu_{SGS} = C_K \sqrt{k_{SGS}} \Delta$	SGS viscosity ($C_K = 0.094$ .. constant, Δ .. LES filter width)
k_{SGS}	SGS turb. kinetic energy, calculated from transport equation

- numerical method: finite volume method with 2nd order discretization schemes (implementation in OpenFOAM 5.0)
- parallel CFD simulation of 20 periods of vocal fold vibration, mesh 2.5M elements, 24 CPU cores: about 4000 core-hours (160 hours wall-time)
- aeroacoustics: hybrid formulation with acoustic perturbation equations [5]

Results

CFD simulation

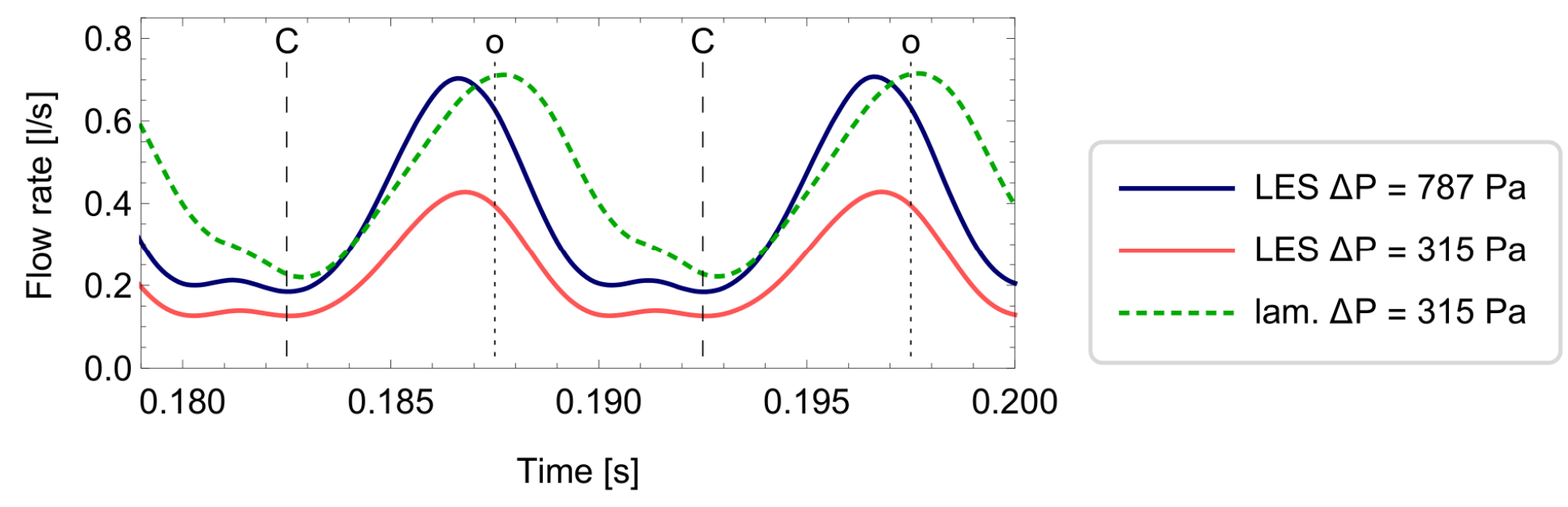


Figure 6. Flow rate waveform simulated by LES, compared to laminar simulation

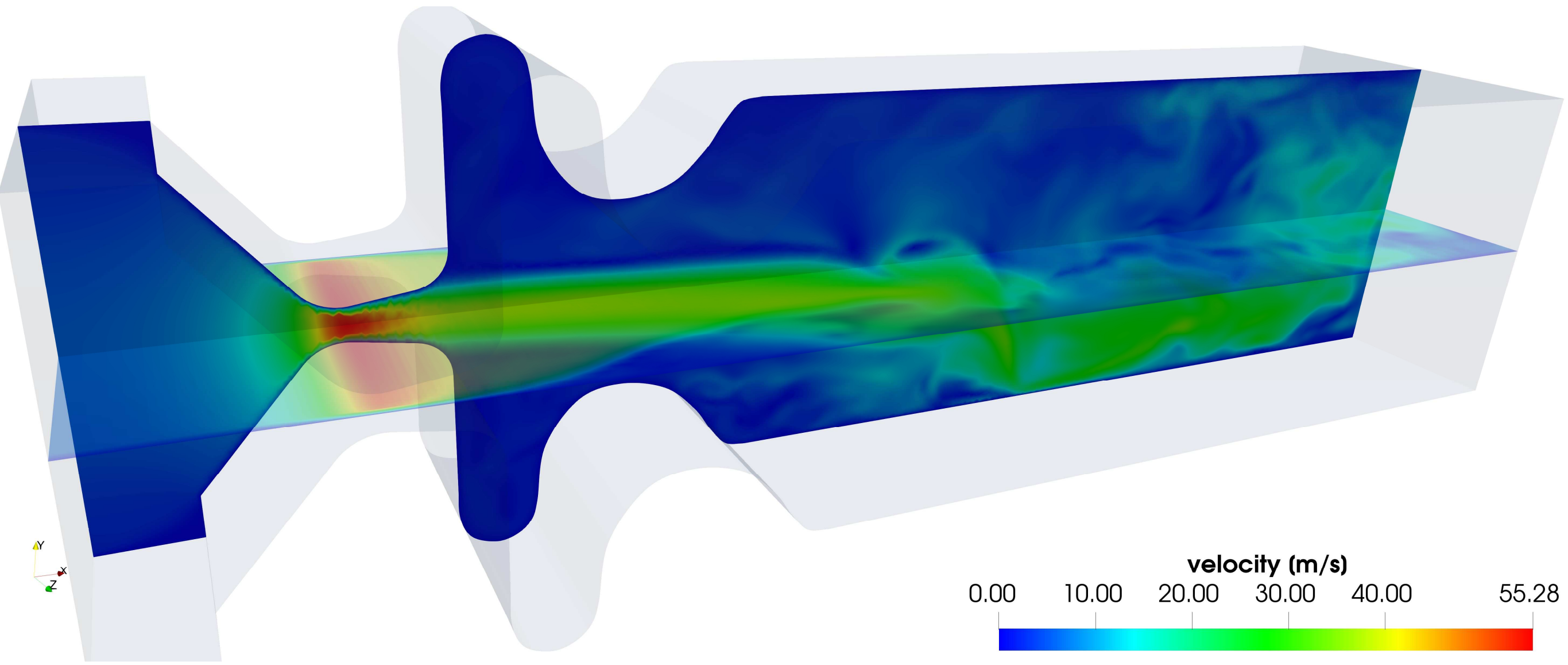


Figure 7. Velocity field in midsagittal and midcoronal planes (end of the opening phase), showing the pulsating jet formed by vocal fold oscillation and its interaction with supraglottal turbulent structures

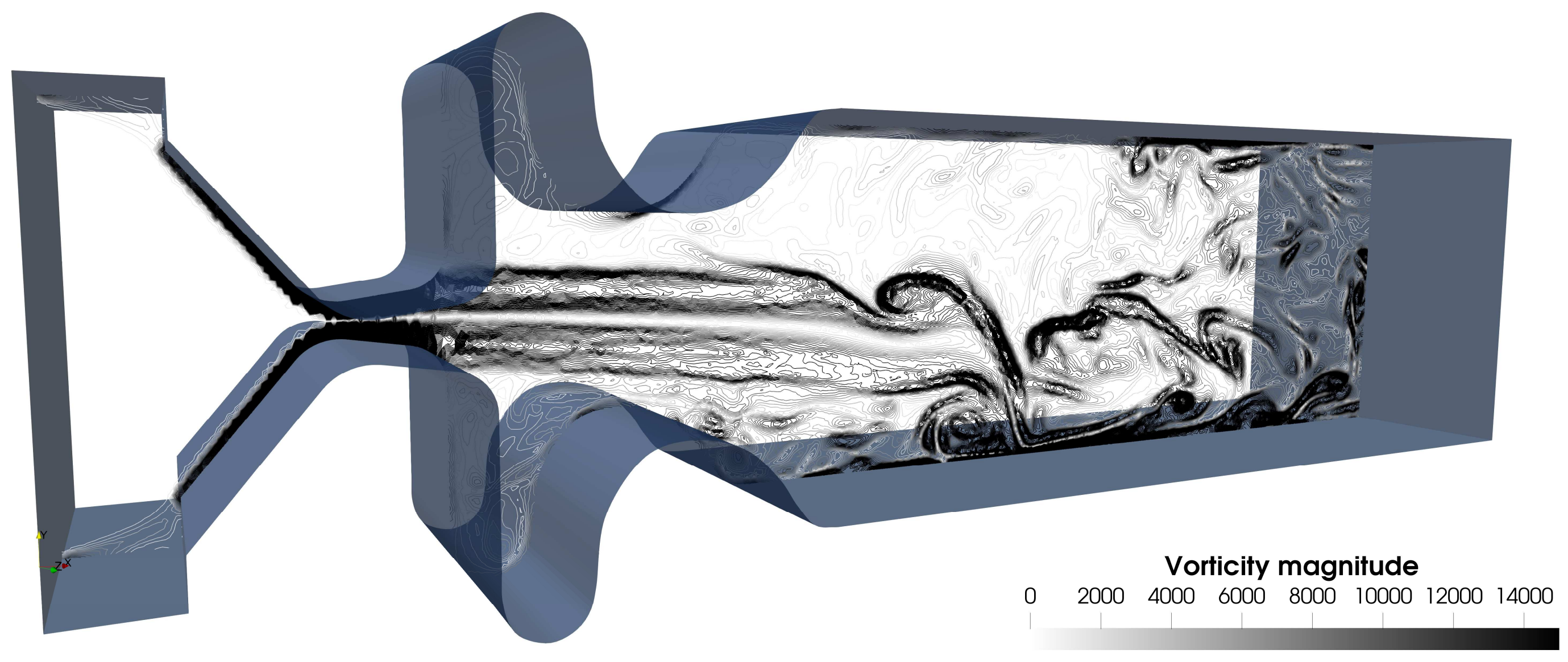


Figure 8. Vorticity isolines in midcoronal plane (end of the vocal fold opening phase), showing the shear layer of the glottal jet and coherent vortex structures

Aeroacoustic simulation

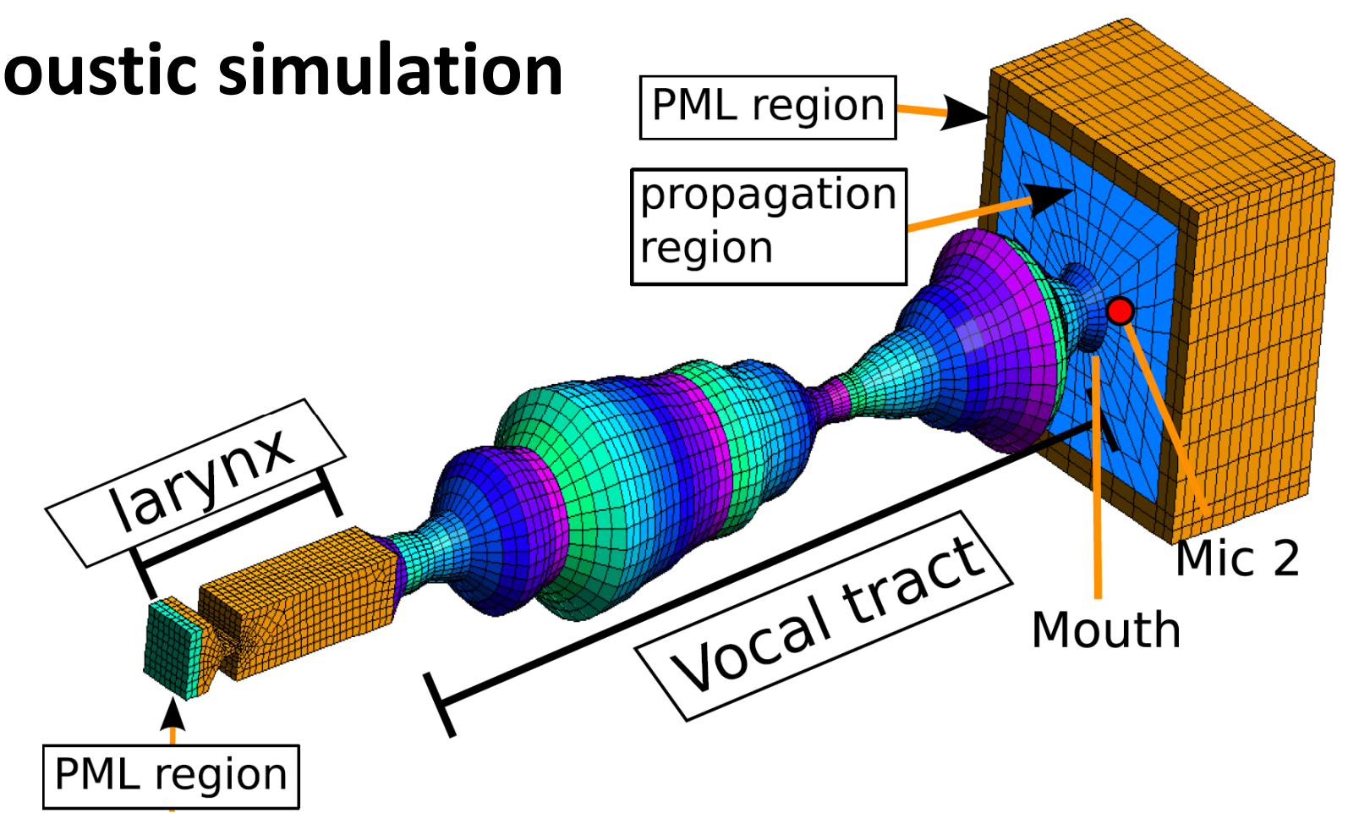
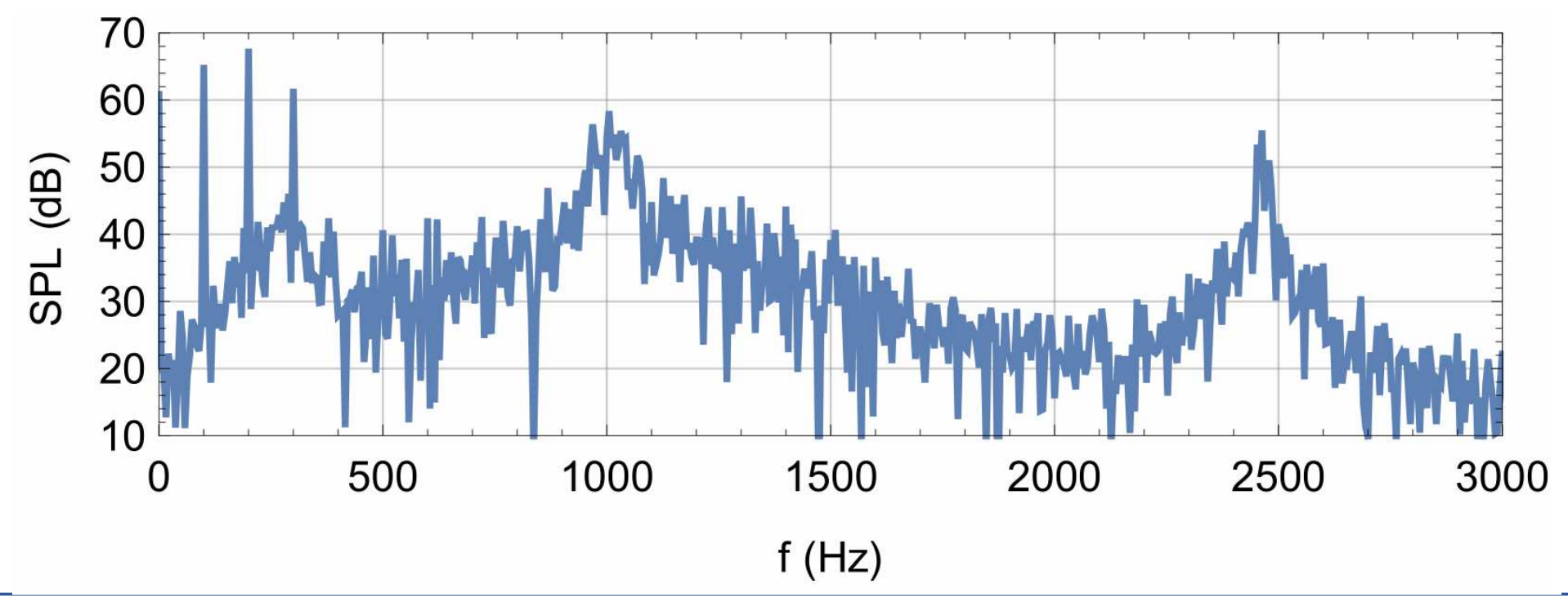


Figure 9. Geometry and acoustic mesh – larynx, vocal tract and propagation region with Perfectly Matched Layer (PML) elements

Realized by Stefan Zörner [5], [6]

Figure 10. Spectrum of the acoustic signal at Mic. 2, showing the fundamental frequency, harmonic freq. up to 400 Hz and formant freq. at 990 Hz and 2400 Hz (geometry corresponding to the vocal tract shape for the vowel /u:/)



Discussion and conclusions

- LES - promising approach for first-principle aeroacoustic simulations of voice
- In some studies [1,2], LES has been already employed. However, a number of open questions still remain
- Subglottal turbulence may significantly affect the flow and acoustic spectra
- SGS model has to resolve properly the boundary layer
- Flow rate waveform simulated by LES is significantly lower than results of a laminar model (due to SGS viscosity)
- The results of aeroacoustic simulations match well the formant frequencies found in human speech

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