Numerical study of the acoustic sources inside the human larynx by the Finite Element Method

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Introduction

Human phonation is the result of the interaction of different physical fields. Fluid flow through the trachea generates vibrations of the vocal folds, which are positioned inside the larynx. Therewith, fluid flow as well as mechanical vibrational induced sound is generated.
A numerical scheme based on the 2d Finite Element (FE) method will be presented, which allows to reveal the different mechanisms of voice production. Our investigations prove that the main parts within the primary acoustic signal are generated by fluid flow. The vibration induced sound generated by the oscillations of the vocal folds plays a minor role. Concerning the flow induced sound, we may distinguish between the pulsating flow driven by the vocal folds oscillations and strong variations of fluid flow velocities due to the Coanda effect. The first phenomena induces a tonal signal, whereas the second phenomena generates vortices of different scales producing a broadband acoustic signal.

Physical fields

The computational model and the physical fields are summarised in Fig. 1 which has been implemented into the research code CFS++ [1]. We will shortly introduce

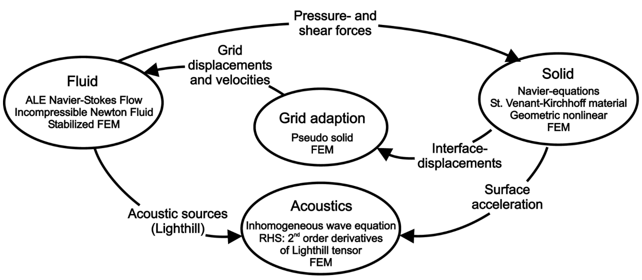

Figure 1: Physical fields for simulating the human phonation with its coupling.

the underlying equations and their couplings; a detailed approach can be found in [2].

Fluid mechanics

We assume that the air flowing through the larynx is occurs at a Mach number smaller than 0.3, hence to describe the fluid flow we apply the incompressible Navier Stokes equations given by

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho(\vec{v} \cdot \nabla)\vec{v} + \nabla p - \mu \Delta \vec{v} = 0 \, , \tag{1}$$

$$\nabla \cdot \vec{v} = 0 \tag{2}$$

with $\vec{v}$ the flow velocity, ρ the fluid density, p the hydrodynamic pressure and μ the dynamic viscosity.

Structural mechanics

As a result from the air flow through the larynx the vocal folds start to vibrate which is described with the help of the partial differential equation of linear elasticity

$$\mathcal{B}^T [c] \mathcal{B} \vec{u} = \rho_\mathrm{s} \frac{\partial^2}{\partial t^2} \vec{u}, \tag{3}$$

where $[c]$ is the tensor of elasticity, ρ_s the density of the solid, $\vec{u}$ the mechanical displacement and $\mathcal{B}$ is the differential operator which results in the 2d plane case as

$$\mathcal{B} = \begin{pmatrix} \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{pmatrix} .$$

Fluid–Solid interaction

Assuming the fluid adheres at the body, fluid velocity v must coincide with the displacement velocity which results in

$$\vec{v} = \frac{\partial}{\partial t} \vec{u} \qquad \text{on } \Gamma_\mathrm{fs} \, . \tag{4}$$

This condition holds only on the common interface Γ_fs, with the displacement given by $\vec{u}$. Furthermore, the fluid stress $[\sigma_\mathrm{f}]$ and solid stress $[\sigma_\mathrm{s}]$ have to coincide in normal direction, resulting in

$$[\sigma_\mathrm{s}] \cdot \vec{n} = [\sigma_\mathrm{f}] \cdot \vec{n} \qquad \text{on } \Gamma_\mathrm{fs}. \tag{5}$$

The fluid stresses can be written explicitly by the hydrodynamic pressure p and fluid velocity $\vec{v}$ as

$$\vec{\sigma}_\mathrm{f} = \rho_\mathrm{f} \underbrace{\int_{\Gamma_\mathrm{fs}} -pI \cdot \vec{n} \, \mathrm{d}x}_{\text{pressure}} + \underbrace{\int_{\Gamma_{fs}} \mu \left(\nabla \vec{v} + (\nabla \vec{v})^T \cdot \vec{n} \right) \, \mathrm{d}x}_{\text{shear}} \, . \tag{6}$$

Acoustic field

Acoustic wave propagation is given by the wave equation

$$\frac{1}{c^2}\frac{\partial^2 p'}{\partial t^2} - \Delta p' = \nabla \cdot (\nabla \cdot \mathbf{T}) \,, \tag{7}$$

where p' is the acoustic pressure and c the speed of sound inside the medium. The inhomogeneity arises from the sound sources in this case the fluid induced sound which is calculated by the Lighthill analogy given by the Lighthill tensor T (for details see [3]). For vibrational acoustics, mechanical velocity and acoustic particle velocity need to be identical in normal direction. This continuity is expressed by the following

$$\frac{\partial}{\partial n} p' = -\rho_{\mathrm{f}} \frac{\partial^2}{\partial t^2} \vec{u} \cdot \vec{n} \qquad \text{on } \Gamma_{\mathrm{fs}} \tag{8}$$

at a common interface Γ_{fs} For a detail discussion we refer to [1].

Results

In a series of simulations the acoustic field of vibrational and fluid induced sound was compared. This was being done by computing the acoustic with just the fluid induced sound disregarding the boundary sources given in (8). And in a separate computation calculating the acoustic field by employing the homogeneous wave equation, disregarding any fluid induced sources, but satisfying the boundary condition (8) to include the vibrational induced sound. The model setup is depicted in Fig. 2 showing the vocal folds inside the larynx, regarding the three different structural layers and their properties.
As can be seen in Fig. 3 the mechanical induced sound is much smaller than that of fluid induced sound. Comparing this result with a simulation were the glottis width is enlarged to 0.7 mm (see Fig. **??**) it shows that the bigger glottis results in a much broader acoustic frequency spectrum. Furthermore, no dominant frequency component is recognisable as in *Fig.* 3 at about 190 Hz.
These results imply the importance of a proper closing glottis for a clear and healthy voice. Furthermore, they show that the fluid flow is the dominant source of the phonation which is hard to proof by measurements.

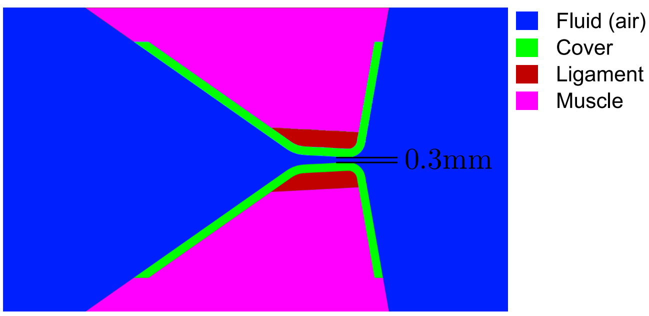

Figure 2: Setup of the simulation model showing the vocal folds inside the larynx with the three different materials.

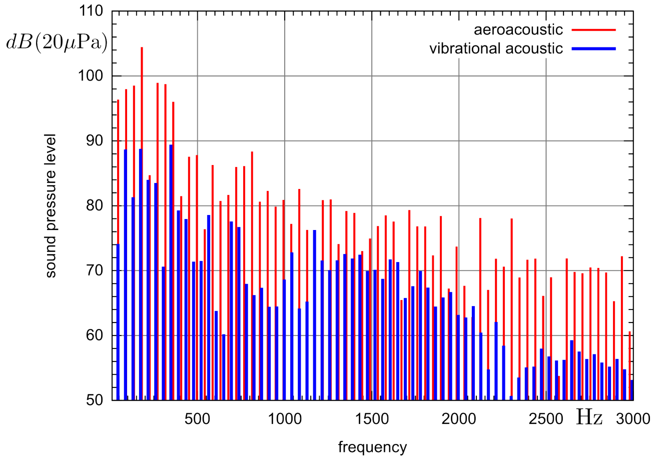

Figure 3: Comparison of acoustic spectra for fluid induced and vibrational induced sound simulation for a glottis width of 0.3 mm.

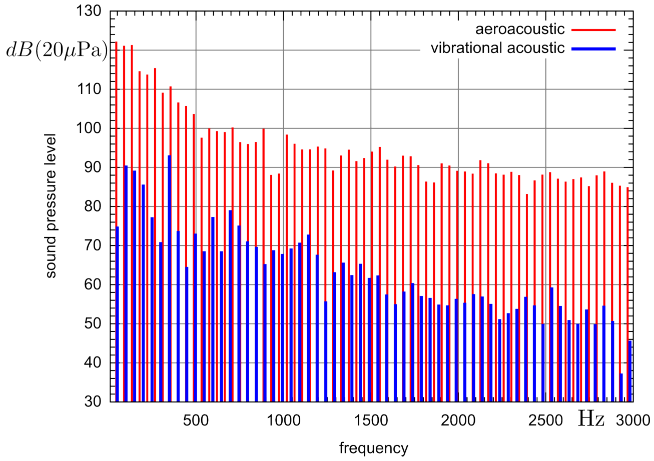

Figure 4: Comparison of acoustic spectra for fluid induced and vibrational induced sound simulation for a glottis width of 0.7 mm.

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