Multifield Phenomena Human Phonation: Fully Coupled Fluid-Structure Simulation Compared to Prescribed Movement

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Abstract

The human phonation process is an interaction of fluid dynamics, structural mechanics and acoustics. A fully coupled simulation is expensive concerning computational time. Simplifying the model to a pure fluid simulation and prescribing the vocal fold movement reduces these costs. The movement of the vocal folds may be gained by measurement. In this paper the impact of this simplification will be analysed by studying different test cases. Thereby, the vocal fold motion is extracted from a separate simulation and used as a forced movement for a pure fluid simulation. Additionally, small changes to the vocal folds geometry is made to simulation inaccuracies which occur during measurements. All computations are performed with our Finite Element (FE) based research code *CFS++*. The results showed differences between the fully coupled approach and the prescribed approach. Since the deviation are acceptable to a certain range, the pure fluid simulation is an alternative, to give an insight into a given problem. Thereby, significantly decreasing the simulation time.

Key words: fluid-structure interaction, prescribed boundary conditions, finite element method

1. Introduction

The human phonation is a complex interaction between multiple physical fields. Lungs compress the air which induces an air flow through the larynx and forces the vocal folds to vibrate, which in turn changes the fluid flow and forms a pulsating air stream. Air flow and the vibration of the vocal folds are the source of the perceived acoustic sound. With the help of the Finite Element (FE) method this phenomena is modeled in our research code *CFS++* ([1]). The aim of this study is to investigates the impact of reducing a fully coupled simulation to a pure fluid simulation with prescribed movement. Thereby, a fully coupled simulation is taken as reference, from which the structural displacement is extracted and used as the imposed motion for a pure fluid simulation.

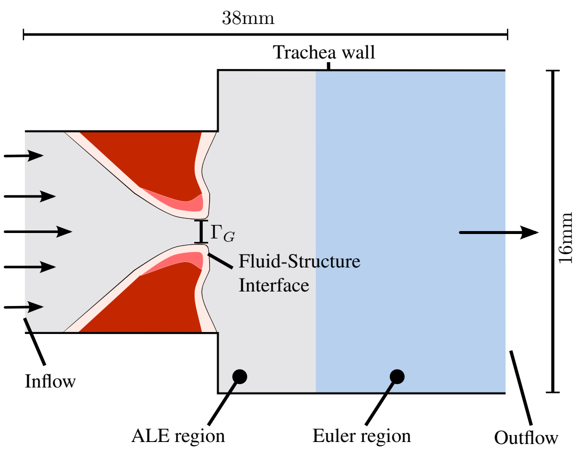

Figure 1: Fluid regions and boundary conditions.

2. Model of fluid-structure interaction

2.1. Geometrical set up

The geometric model is depicted in Fig. 1, which consist of the larynx and the two vocal folds. The vocal fold model is based on Šidlof et al. [2] with additional segmenting the vocal folds into different layers, muscle, ligament, lamina propria and the epithelium – a very thin cover of 0.03 mm (see Fig. 2).

At the inflow a pressure of 1.0 kPa is chosen and 0.0 Pa at the outflow. The larynx wall has no-slip boundary conditions. On the interface of the vocal fold, the fluid velocity must coincide with the structural velocity, enforced by

$$\mathbf{v} = \frac{\partial}{\partial t}\mathbf{u} \qquad \text{on } \Gamma_{\text{fs}} \ . \tag{1}$$

A detailed description of each physical fields and the according mathematical model can be found in [1].

3. Results

A fully coupled simulation is performed on the model as shown in Sec. 2, which is seen as the original model and will be referred to as such. Additionally, a slightly wider vocal fold is generated as depicted in Fig. 2. The movement of the original geometry is then projected on the reformed vocal folds and used as a prescribed movement for a pure fluid simulation. In Sec. 3.2 this case is

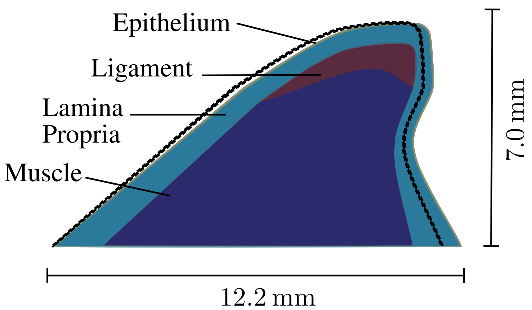

Figure 2: Geometry of reformed vocal fold with material model of the vocal fold, consisting of different regions. Outline of original geometry (dashed line).

further altered by using a fluid inflow profile instead of a fixed pressure.
The idea behind these different scenarios is to simulate and analyse certain approaches which are used to simulate the human phonation process. Thereby, imitating a set up in which measurement data or estimates through observation are used as input for the vocal fold movement.
As comparison the volume flux Q_V at the glottis is used which is calculated by

$$Q_V(t) = \int\limits_{\Gamma_G(t)} \mathbf{v} \cdot \mathbf{n} \, d\Gamma \tag{2}$$

with Γ_G the integration path inside the glottis as depicted in Fig. 1.

3.1. Case Study: Reformed Vocal Folds

The prescribed movement is taken from the original simulation and projected onto the new reformed vocal fold geometry.
In Fig. 3 the volume flux of the fully coupled simulation with original vocal folds and the reformed vocal folds as well as the pure flow simulation with prescribed movement is depicted in the frequency domain. Although, the geometry change is minor there is still an impact to be seen at the two main frequency which are about 7–8% higher for the fully coupled case with reformed vocal folds. For larger geometry changes a much greater difference is to be expected. Nevertheless, the prescribed movement does have the same characteristic peaks as the original fully coupled simulation. Therefore, measurement errors concerning the vocal fold form do not have an significant impact on the volume flux and additionally reducing the simulation time by a factor of three.

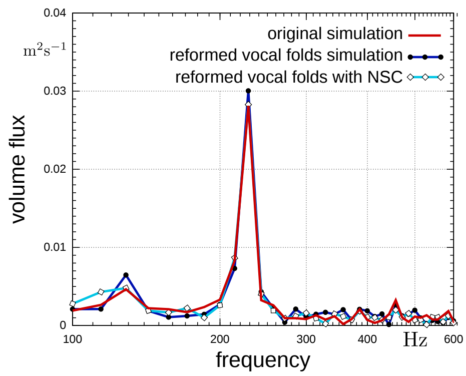

Figure 3: Comparison of volume flux at glottis of original simulation, fully coupled with reformed vocal folds and prescribed movement on reformed vocal folds.

3.2. Case Study: Reformed Vocal Folds with Prescribed Inflow

This case is based on the previous set-up with a further addition, by replacing the pressure inflow condition with a velocity profile.
The velocity profile is extracted from the original simulation and is referred to as “inflow 1”. A further simulation used the inflow profile of the fully coupled simulation with reformed vocal folds and is called “inflow 2”. The results are depicted in Fig. 4 which do not seem to show new findings to previous results. However, it does reveal, that simulations with the same inflow profile have an identical volume flux through the glottis,

whether fully coupled or prescribed is not significant. Visualising a short time excerpt of the volume flux in

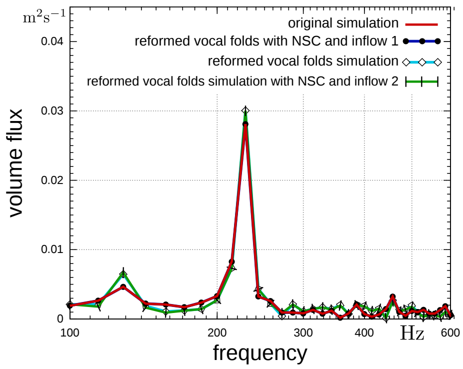

Figure 4: Comparison of volume flux at glottis of original simulation, fully coupled with reformed vocal folds and prescribed movement on reformed vocal folds once with “inflow 1” and once with “inflow 2”.

the glottis (Fig. 5) makes this fact clear. This is especially interesting when the prescribed movement from the original simulation are applied but the inflow condition is extracted from the fully coupled simulation with reformed vocal folds. The results show the same volume flux as the fully coupled simulation with reformed vocal folds although their movement is different. It shows, that the vocal fold movement has no effect on the volume flux through the glottis when velocity profiles are uses as inflow conditions.

If a fully coupled fluid-structure interaction would be taken place, the fluid field would change the vocal fold displacement which in turn effects the flow field. But the movement of the interface is prescribed and a change in the inflow does not change the movement.

4. Conclusion

With specific problems, the pure flow simulation with prescribed movement is a good alternative to a fully coupled simulation, reducing the computational time by a factor of three. If additionally to the prescribed movement the inflow is changed to a velocity profile it showed no back reaction of the vocal fold vibration onto the flow field. This case shows, that the fully coupled simulation is necessary to capture the interaction between both physical fields correctly.

The analysed cases in this work only considered small geometrical changes. The impact on larger deviation, glottis width or channel geometry is still an ongoing work.

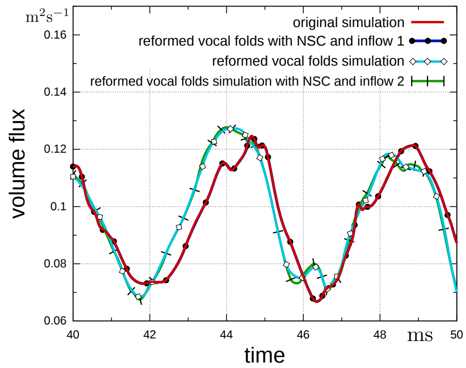

Figure 5: Volume flux through glottis in time domain of of original simulation, fully coupled with reformed vocal folds and prescribed movement on reformed vocal folds once with “inflow 1” and once with “inflow 2”.

5. Acknowledgment

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References

[1] G. Link, M. Kaltenbacher, M. Breuer, and M. Döllinger. A 2d finite-element scheme for fluid-solid-acoustic interactions and its application to human phonation. *Computer Methods in Applied Mechanics and Engineering*, 198:3321–3334, 2009.

[2] P. Šidlof, J. G. Švec, Jaromír, Horáčeke, J. Veselýe, I. Klepáček, and R. Havlík. Geometry of human vocal folds and glottal channel for mathematical and biomechanical modeling of voice production. *Journal of Biomechanics*, 41:985–995, 2008.