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Investigation of prescribed movement in fluid–structure interaction simulation for the human phonation process ☆

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ABSTRACT

In a partitioned approach for computational fluid–structure interaction (FSI) the coupling between fluid and structure causes substantial computational resources. Therefore, a convenient alternative is to reduce the problem to a pure flow simulation with preset movement and applying appropriate boundary conditions. This work investigates the impact of replacing the fully-coupled interface condition with a one-way coupling. To continue to capture structural movement and its effect onto the flow field, prescribed wall movements from separate simulations and/or measurements are used.

As an appropriate test case, we apply the different coupling strategies to the human phonation process, which is a highly complex interaction of airflow through the larynx and structural vibration of the vocal folds (VF). We obtain vocal fold vibrations from a fully-coupled simulation and use them as input data for the simplified simulation, i.e. just solving the fluid flow. All computations are performed with our research code *CFS++*, which is based on the finite element (FE) method.

The presented results show that a pure fluid simulation with prescribed structural movement can substitute the fully-coupled approach. However, caution must be used to ensure accurate boundary conditions on the interface, and we found that only a pressure driven flow correctly responds to the physical effects when using specified motion.

1. Introduction

The human voice is the basis for verbal communication, i.e., speech. The primary voice signal is generated in the larynx by the two opposing oscillating vocal folds [8]. The entire process is a complex interaction of fluid mechanics, solid mechanics and acoustics. As the lungs compress, air flows through the larynx and forces the vocal folds to vibrate, which in turn creates a pulsating air stream. Pulsating airflow, vocal fold vibrations, and supraglottal air vortices are the source of the perceived acoustic sound. This phenomena is computed by our research code *CFS++*, which is based on the finite element (FE) method [16]. Thereby, the physical properties, as well as their interactions, are considered: fluid and structural mechanics.

This fully-coupled approach is very costly with respect to computational time. There are several methods to reducing the computational effort. One is to use multi-mass models as developed by Flanagan and Landgraf [9]. The computational costs are extremely low, but an accurate flow field cannot be represented and complex oscillatory modes of the vocal folds are not captured. Therefore, based on continuum mechanics, Alipour et al. [1,3] used a finite element method to simulate the vocal folds, while the flow is based on Bernoulli's equation. However, to determine the phonation threshold pressure, a solution of the Navier–Stokes equations is necessary as suggested by de Vries et al. [7].

A second approach is to reduce the number of unknowns by assuming a 2D computational set-up and exploiting symmetry, as demonstrated by Bae and Moon [4] and Thomson et al. [23]. This approach is referred to as the hemilarynx approach and neglects any asymmetric flow, and therefore certain turbulence effects. Hofmans et al. [13] discussed the admissibility set-up by investigating an experimental set-up of an in vitro larynx model and concluded that turbulence effects take too much time to develop. In phonation situations with closing vocal folds, this argument may hold as the flow has only one cycle to completely develop after a glottis opening. There also exist phonation situations in which the vocal folds do not fully close or touch each other (i.e., glottis closure insufficiency [19]); the assumption of a symmetric flow field is not longer valid during these situations where there is no contact.

To circumvent the costly iteration between fluid dynamics and structural mechanics, Larsson and Müller [15], Luo et al. [17] and

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Zheng et al. [27,28] employed a staggered coupling algorithm[1]. However, as shown by Förster et al. [10] and Causin et al. [6], a staggered coupling Dirichlet–Neumann scheme that couples an incompressible fluid and a flexible structure is not unconditionally stable—known as the artificial added mass effect.

Another method to reduce computational efforts, while still accounting for a realistic flow field, is the simulation of 3D flow with specified movement of the structure. Essentially, the complex coupling is replaced with simple boundary conditions. The consequences, shortcomings, and validity are discussed in this work. This type of approach was chosen by Schwarze et al. [22] and Šidlof et al. [25], but instead of a velocity profile as inflow condition, Šidlof set a fixed pressure at the inflow. A detailed overview over all different methodologies simulating the human phonation process is presented by Alipour et al. [2] and most recently by Mittal et al. [18].

The aim of this study is to analyze the impact on reducing a fully-coupled fluid–structure phenomena to a pure fluid simulation with prescribed structural motion. To achieve this investigation, structural displacements of a fully-coupled simulation are extracted and used as imposed motion for a straight forward flow simulation. Additionally, a number of variations to the pure fluid simulations, which include changes in fluid–structure interface conditions, pressure inlet and geometry, are examined. These variations imitate specific uncertainties or incorrect boundary conditions and are each elucidated in separate sections of the manuscript.

The paper is organized as follows: first, the geometric set-up of the larynx is introduced in conjunction with the multilayer vocal folds. In Section 2 the mathematical models are presented, describing the governing equations of fluid and solid mechanics, as well as the field interactions. For a detailed description of the methods and their implementation to solve the coupled problem by means of the finite element method, we refer to [16], which also covers validation with the experimental set up of [11]. Section 3 presents four different case studies and discusses these by comparing the volume flux through the glottis, as well as the vibration of the vocal folds. In Section 4, the paper closes with a discussion of the results.

2. Model of fluid–structure interaction

2.1. Geometric set-up

The geometric model consists of a simple channel with two elastic bodies inside representing the vocal folds. Through use of magnetic resonance imaging (MRI), Gömmel [12] extracted the geometry of the trachea, which shows that the vibration of the vocal fold covers only a part of the trachea. In our investigations, this is incorporated by narrowing the subglottal channel width as depicted in Fig. 1.

There are two prominent models to compute simulations of the vocal folds: (1) the “M5” model constructed by Scherer et al. [20,21], and (2) the model by Šidlof et al. [26] which uses an ex vivo plaster-casting methodology. A 2D version of the latter model was used in the subsequent simulations due to its complexity and realistic structure. This model has been improved by additionally considering different layers. The muscle, also called body, is at the base, and has a skewed trapezoidal form and supports the ligament. Both, the muscle and the ligament are covered by the lamina propria, which is approximately 1.2 mm thick at the base and reduces to half of its thickness at the tip of the vocal fold.

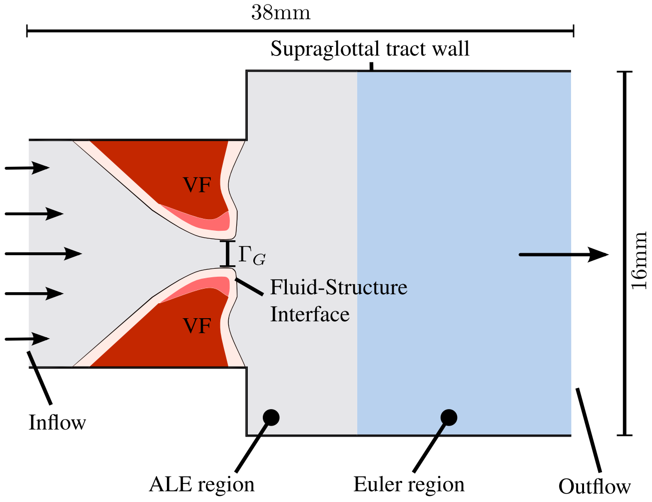

Fig. 1. Fluid regions and boundary conditions. The glottis divides the fluid region into sub- and supraglottal area.

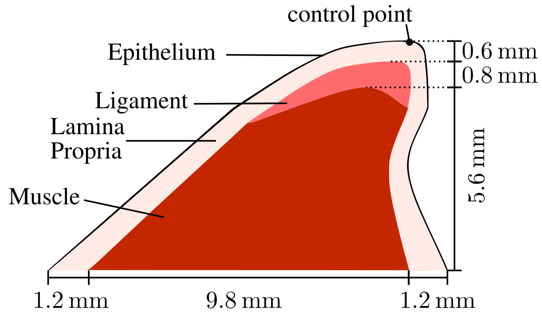

Fig. 2. Geometry and material model of the vocal fold, consisting of four different regions. Dotted lines are reference lines for better readability.

The lamina propria is covered by a very thin tissue (0.05 mm) called epithelium, represented by a thin line in Fig. 2.

Material parameters are still uncertain, as explained by Alipour et al. [2], as the thin and complex structure makes an experimental measurement difficult. Therefore, our material parameters rely on good estimation and comparison with different models. Additionally, an eigenfrequency analysis is done in advance to achieve a realistic vibrational frequency that mimics human phonation (Titze [24]). The elasticity modulus, used in the simulations, are given in Table 1. As 0 Poisson’s ratio a value of 0.45 is taken for all four tissue types.

2.2. Fluid mechanics

The flow can be regarded as incompressible for low Mach numbers (Ma < 0.3), as is the case in human phonation. This sets the fluid density ρ_f to a constant value and results in the incompressible Navier-Stokes’s equations, consisting of the following momentum and mass conservation equations:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \nabla p - \nu \Delta \mathbf{v} = \mathbf{0}, \qquad (1)$$

$$\nabla \cdot \mathbf{v} = 0. \qquad (2)$$

In Eqs. (1) and (2) $\mathbf{v}$ denotes the fluid velocity, p the kinematic pressure $\left(p = \frac{P}{\rho_f}\right)$, and $\nu \left(\nu = \frac{\mu}{\rho_f}\right)$ the kinematic viscosity. To accurately capture the change in the fluid domain due to structural movement, the Arbitrary–Lagrangian–Eulerian (ALE) approach is used. Numerical instabilities, arising by convection dominants, are remedied by

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[1] A staggered approach means that the two physical fields are computed one after another and no iteration in between is applied. In contrast, a strong coupled scheme iterates between the physical fields until an equilibrium is reached within each time step.