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Numerical Simulation of Glottal Flow in Interaction with Self Oscillating Vocal Folds: Comparison of Finite Element Approximation with a Simplified Model

P. Sváček[1,*] and J. Horáček[2]

[1] *Department of Technical Mathematics, Faculty of Mechanical Engineering, Czech Technical University in Prague, Karlovo nám. 13, Praha 2, 121 35, Czech Republic.*
[2] *Institute of Thermomechanics, Academy of Sciences of the Czech Republic, Dolejškova 5, Praha 8, Czech Republic.*

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Abstract. In this paper the numerical method for solution of an aeroelastic model describing the interactions of air flow with vocal folds is described. The flow is modelled by the incompressible Navier-Stokes equations spatially discretized with the aid of the stabilized finite element method. The motion of the computational domain is treated with the aid of the Arbitrary Lagrangian Eulerian method. The structure dynamics is replaced by a mechanically equivalent system with the two degrees of freedom governed by a system of ordinary differential equations and discretized in time with the aid of an implicit multistep method and strongly coupled with the flow model. The influence of inlet/outlet boundary conditions is studied and the numerical analysis is performed and compared to the related results from literature.

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1 Introduction

The flow induced vibrations of structures can be important in various situations and technical applications, for an overview see e.g. [3]. The research focuses on problems of fluid-structure interactions (FSI) in aero-elasticity and hydro-elasticity [9]. Recently, the numerical methods for solution of FSI problems become important also in biomechanics. One approach in speech modelling is to model the interaction of the vocal folds using a

*Corresponding author. *Email addresses:* Petr.Svacek@fs.cvut.cz (P. Sváček), jaromirh@it.cas.cz (J. Horáček)

simplified model, cf. [17], based on a simplified description of both fluid and structure dynamics. Recently, simplified methods for numerical analysis of interactions of glottal flow with vocal folds vibrations were used e.g. in [14, 16]. Even if for these approaches a simplification of the flow problem was used, e.g. potential flow or Bernoulli equation, such simplified models are able to quantify many fundamental physical parameters characterizing the human voice production known in phoniatrics – see e.g. applications of the developed aeroelastic model [15] in simulations of phonation [1] and the vocal folds loading [12, 13]. The reality is much more complex: the air flow coming from lungs accelerates in the narrowest glottal part causing the vibrations of the vocal folds compliant tissue. The glottis is almost (or completely) closing during vibrations and the vocal folds collide generating the sound. The modelling of such a complex phenomenon encounters many difficulties as it is a result of coupling complex fluid dynamics and structural behaviour including contact and acoustic problems. Recently, more accurate flow descriptions were used to improve flow calculations, cf. [20]. Particularly, the interaction of air flow in human vocal tract with the vibration of the vocal folds was considered in [18].

Nevertheless, the application of simplified mathematical models can provide valuable information as well as better understanding of the phenomena. Particularly, the numerical simulations are considered as important tool in biomechanics, where experimental in-vivo studies are problematic. In this paper the coupled FSI problem of air flow through model of the vibrating glottal region is numerically approximated in a simplified geometrical domain. The results are compared to the relevant results obtained by a simplified flow model and attention is paid to the comparison of approximate solutions of the coupled fluid-structure interaction problem to the outcomes of a simplified aeroelastic model. Similar comparisons were published in [8], where the finite volume approximations of Navier-Stokes equations on Cartesian grids were coupled with a two-mass dynamical model, cf. [17]. Here, the 2D finite element approximations of Navier-Stokes equations are coupled with the elastic structure vibrations described by a mechanically equivalent two degrees of freedom system. Such a problem was analyzed in [14], [16] using a simplified 1D flow model allowing the self-sustained vibrations (i.e. the critical flow velocity for which the system becomes unstable by flutter type of instability).

The flow is described by the incompressible Navier-Stokes equations (flow velocities in the human glottal region are lower than 100 m/s and the influence of compressibility on the flow induced instability can be neglected). The flow problem is numerically approximated by the finite element (FE) method stabilized by Galerkin-Least Squares (GLS) method, cf. [6, 10], and modified for the application on moving domains, cf. [21]. Furthermore, the time and space discretized linearized problem of the large system of linear equations needs to be solved in a fast and efficient manner. The application of direct solvers as UMFPACK (cf. [7]) leads to a robust method, where different stabilization procedures can be easily applied even on anisotropically refined grids. The system of ordinary differential equations describing the structure motion is discretized in time by higher order backward difference formulas (2nd or 4th order). The fluid and structure are coupled by the interface conditions enforced by a coupling algorithm. The described