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FE MODEL OF THE HUMAN VOCAL FOLDS CONSIDERING FLUID-STRUCTURE INTERACTION

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Summary: *The study presents three-dimensional finite element (FE) model of flow induced oscillations of the human vocal folds in interaction with acoustic processes in the simplified vocal tract model. The FE model includes vocal folds pretension before phonation, large deformations of the vocal fold tissue, vocal folds contact, fluid-structure interaction, morphing the fluid mesh according the vocal folds motion, unsteady viscous compressible airflow and airflow separation during the glottis closure. Fluid-structure interaction is solved using partitioned approach, where the results of solution for the flow are transferred as loads on the vocal folds surface, then the vocal folds motion is computed and then again the equations for the flow are solved. Numerical results confirmed that the developed model can be used for simulation of the vocal folds self-oscillations, and especially for numerical simulations of quantities that are difficult to measure in clinical research.*

1. Introduction

Voice production is result of the flow-induced vibration of the vocal folds interacting with acoustic spaces of the vocal tract. For understanding the mechanism of phonation for healthy as well as for pathological voices it is important to study this problem as the fluid-structure-acoustic interaction problem. Recently, several computational and experimental models of this interaction have been published in literature. Main limitations of experimental techniques (Titze, 2006; Šidlof et al., 2008) are in difficulties to obtain detailed spatial and time information on quantities such as the acoustic pressure generated inside the larynx, intraglottal pressure, impact stress etc. Developed computational models include reduced-order models (Story & Titze, 1995; Horáček & Švec, 2002), models of flow (Zhao et al., 2002) and finite element (FE) models. Various FE models are developed for studying the vocal folds vibration (Alipour et al., 2000; Thomson et al. 2005), because they are able to deal with complex vocal folds models and acoustic spaces geometries, and ability to solve fluid-structure interaction.

In recent works of the authors (Švancara et al., 2008; Švancara et al., 2009) a preliminary three-dimensional (3D) FE model of flow induced oscillations of the vocal folds in interaction with acoustic spaces of the vocal tract was developed. This model includes fluid-structure interaction, large deformations of the vocal folds tissue, vocal folds pretension before phona-

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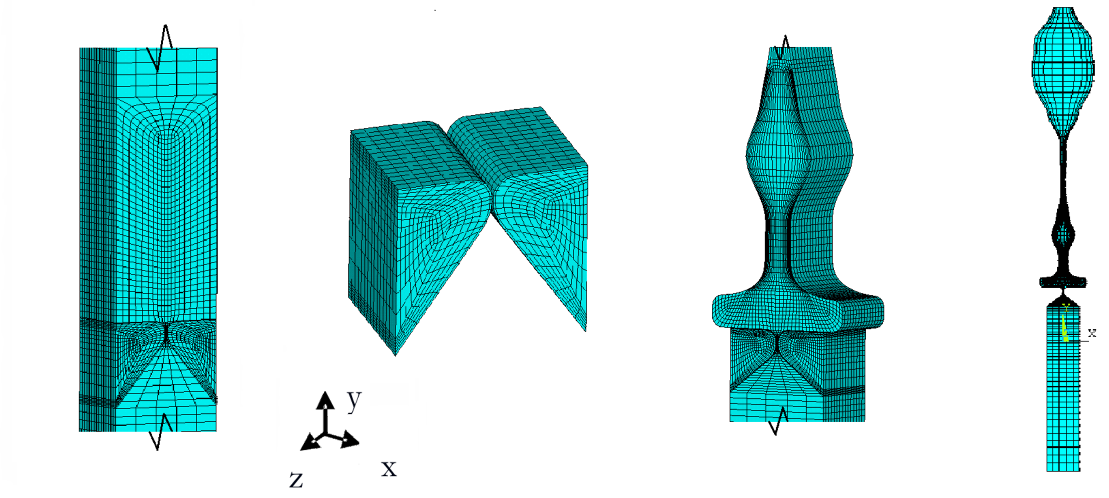
tion, vocal folds contact, morphing the fluid mesh according the vocal folds movement, unsteady viscous compressible airflow and airflow separation. Only one driving parameter of this model is the constant inflow velocity of the air supplied by the lungs. In the present paper the algorithm of fluid mesh morphing was improved and includes new procedures for flow field computation as remapping, smoothing and Arbitrary Lagrangian-Eulerian (ALE) approach. To study the effect of real vocal tract shape on acoustic processes, new FE model with a 3D shaped vocal tract was developed and preliminary results are presented.

2. Finite element model

The FE model was designed within the program system ANSYS 12.1. First version of the developed complete finite element model is shown in Fig. 1a). The model consists of the vocal fold tissue (see Fig. 1b) and the simplified acoustic spaces of the vocal tract modelled by a rectangular channel. The complete FE model with shaped vocal tract modelling the acoustic spaces for vowel /a/ is shown in Figs. 1c and 1d. The vocal tract was created by converting data from magnetic resonance images (Radolf, 2010). The vocal folds are modelled as symmetric with three layers – epithelium, ligament and muscle (Titze, 2006). ANSYS element type SOLID 185 was used and homogenous and isotropic material of each layer was assumed with Young modulus: $E_{epitel} = 20\ kPa,\ E_{ligament} = 2\ kPa,\ E_{muscle} = 5\ kPa$, Poisson ratio: $m_{epitel} = m_{ligament} = 0.49,\ m_{muscle} = 0.4$ and density: $r_{epitel} = r_{ligament} = r_{muscle} = 1040\ kg.m^{-3}$ Proportional structural damping model is used with damping constants $a = 150$ and $b = 3\times10^{-4}$. Collisions of the vocal folds during phonation are modelled by the symmetric surface to surface contact pair elements on faces of the vocal folds (types CONTA174 and TARGE 170). The flow of air is modelled as unsteady viscous compressible and laminar using the element type FLUID 142. Material properties used: speed of sound $c = 343\ ms^{-1}$, viscosity



a) b) c) d)

Figure 1. a) FE model of the vocal folds with a rectangular model of the vocal tract, b) detail of the FE model of the tissue of the vocal folds, c) and d) FE models of the vocal folds together with the FE model of the acoustic spaces of the vocal tract for vowel /a/.

$n = 1.8135\times10^{-5}\ kg.m^{-1}s^{-1}$, density $r = 1.205\ kg.m^{-3}$. FE model consists of 7920 structural elements and 18960 fluid elements.

Before the fluid-structure interaction simulation starts the vocal folds are prolonged in the longitudinal direction by 25% of original length and pushed slightly into the contact. This is performed as static analyses in several steps taking into account the large deformations and contact. Fluid domain mesh is morphed in each time step depending on the vocal folds movement. For this purpose a special procedure was developed that is similar to arbitrary Lagrangian-Euelerian (ALE) approach. The fluid elements are switched to the solid elements of a very soft material and the nodes on vocal folds boundaries are loaded by computed displacements of the vocal folds. The mesh of the fluid elements is then updated according to the computed deformed mesh of the soft solid elements. If the distance between the faces of the vocal folds exceeds a defined minimal value, the mesh is not more deformed at these nodes and flow velocity is set to zero. In this paper new remapping procedure of flow quantities from the old fluid mesh to the new (rezoned) fluid mesh was added. It’s based on piecewise linear function interpolation and smoothing algorithm.

Fluid-structure interaction is solved in ANSYS by partitioned solution procedure. The results of the flow solution are transferred as loads on the vocal folds surface, then the vocal folds motion is computed and then again the fluid flow is solved. This process is iteratively repeated until a needed convergence limit is matched. Vocal folds tissue motion is solved by transient analysis using ANSYS/Structure environment with time step $\Delta t = 1{,}5.10^{-4}$ s taking into account large deformations and vocal folds contact during collision. For transient analysis of unsteady viscous compressible laminar flow the ANSYS/Flotran CFD code is used with the same time step. As a driving parameter a constant airflow velocity at the entrance to the subglottal space is prescribed ($v_y = 0.3\ ms^{-1}$ used here). Zero acoustic pressure is prescribed on the upper side of the vocal tract mesh to simulate radiation into the open space.

3. Mathematical formulation

Using final element method (FEM) the equations of motion for the structure of the vocal folds tissue can be written as

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{f}_a(t), \tag{1}$$

where **M**, **C**, **K** are structural mass, damping and stiffness matrices, $\ddot{\mathbf{u}}$ is nodal acceleration vector, $\dot{\mathbf{u}}$ is nodal structural velocity vector, $\mathbf{u}$ is nodal displacement vector and $\mathbf{f_a}$ is applied load vector. Newmark time integration method was used for solution of equation (1) (including an improved algorithm called HHT - Chung and Hulbert). Large deformations of the structure of the vocal folds are assumed and the contact problem is solved.

The unsteady compressible Navier-Stokes equations for the air flow, the energy, species transport and turbulence equations can be written in the form of a scalar transport equation (Ansys Inc., 2006)

$$\frac{\partial}{\partial t}\left(rC_a a\right)+\frac{\partial}{\partial x}\left(rv_x C_a a\right)+\frac{\partial}{\partial y}\left(rv_y C_a a\right)+\frac{\partial}{\partial z}\left(rv_z C_a a\right)= \\ \frac{\partial}{\partial x}\left(\Gamma_a\frac{\partial a}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_a\frac{\partial a}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma_a\frac{\partial a}{\partial z}\right)+S_a \tag{2}$$

where

a is variable quantity (part of the velocity vector, kinetic energy etc.)

C_a is transient and advection coefficient

Γ_a is diffusion coefficient

S_a is source term.

Using FEM discretization process consists of deriving the element matrices to put together the matrix equation

$$\left(\mathbf{A}_e^{Trans}+\mathbf{A}_e^{Advect}+\mathbf{A}_e^{Diff}\right)\boldsymbol{\alpha}_e=\mathbf{S}_e^a\ , \tag{3}$$

where $\mathbf{A}_e^{Trans}$ is element matrix contributions from the transient term

$\mathbf{A}_e^{Advect}$ is element matrix contributions from the advection term

$\mathbf{A}_e^{Diff}$ is element matrix contributions from the diffusion term

$\boldsymbol{\alpha}_e$ is the vector of the considered variables

$\mathbf{S}_e^a$ is the vector of the source terms.

Galerkin method of weighted residuals is used for forming the element integrals. The process called global iteration is used for solving all the equations. Pressure equation is solved by the segregated velocity-pressure solution algorithm (Ansys Inc., 2006). In this approach, the Navier-Stokes equations are used to generate an expression for the velocity in terms of the pressure gradient. This is used in the continuity equation after it has been integrated by parts. This nonlinear solution procedure used in ANSYS/Flotran belongs to a general class of Semi-Implicit Method for Pressure Linked Equations (SIMPLE). The global iteration procedure consists of this steps:

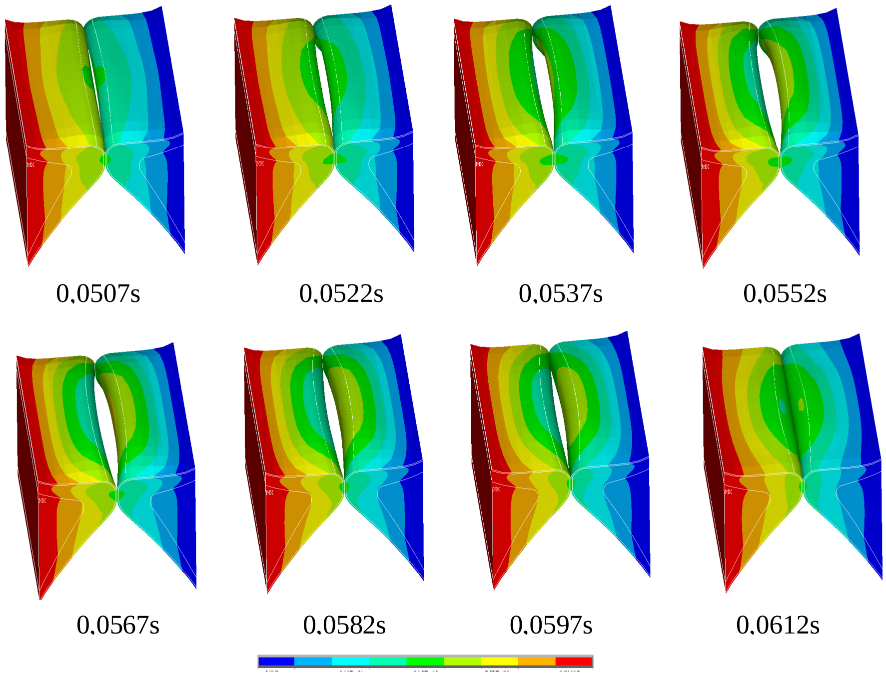
- Formulate and solve v_x equation approximately.
- Formulate and solve v_y equation approximately.
- Formulate and solve v_z equation approximately.
- Formulate pressure equation using, v_x , v_y and v_z
- Solve pressure equation for p .
- Update velocities based on, v_x , v_y, v_z and p .
- Formulate and solve energy equation for temperature T.
- Update temperature dependent properties.
- Solve turbulence equations for kinetic energy *k* and dissipation rate *ε*.
- Update effective properties based on turbulence solution.
- Check rate of change of the solution.
- End of global iteration.

For solving fluid-structure interaction (FSI) partitioned solution procedure is used (Zhang et al., 2003), where flow equations and the structural equations are solved alternatively with separate solvers, passing the latest solution from one model to another. This procedure in each time step consists of:

- Update the fluid mesh according the movement of the structure.
- Assemble fluid domain matrices as usually performed in fluid-only problem with velocity conditions on FSI boundary according to movement of the structure.
- Solve the fluid equation using direct or iterative solver.
- Calculate the fluid force on FSI boundary.
- Assemble structure domain matrices as usually performed in structure-only problem with adding fluid forces on interface.
- Solve the structure equation using direct or iterative solver.

4. Results and discussion

Fig. 2 shows an example of numerically simulated displacement of the vocal folds in *x* direction during one oscillation period at eight time steps from 0.0507s to 0.0612s.


0,0507s 0,0522s 0,0537s 0,0552s

0,0567s 0,0582s 0,0597s 0,0612s

Figure 2. Computed displacement of the vocal folds in *x* direction at eight time steps during one oscillation period (0.0507-0.0612s).

Fig. 3 shows the numerically simulated airflow velocity on cross-section through the vocal tract during one oscillation period at eight time steps from 0.0507s to 0.0612s.

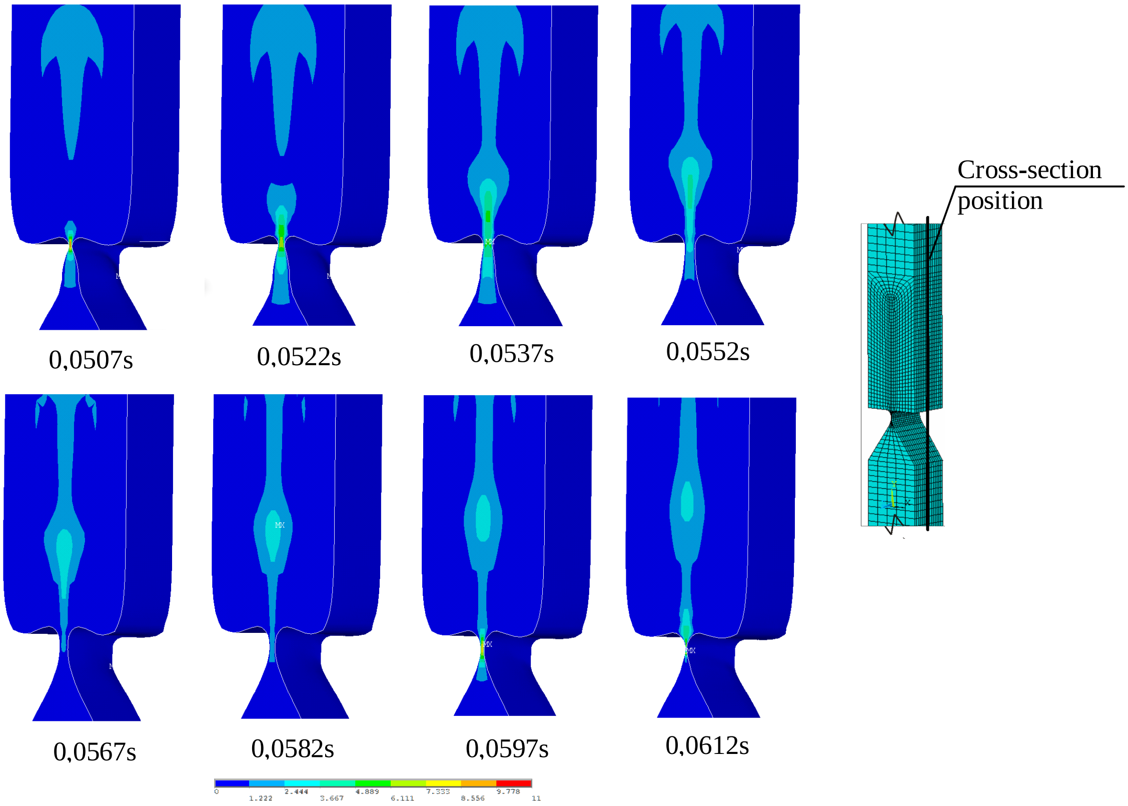


Figure 3. Computed air velocity on cross-section through the vocal tract during one oscillation period at eight time steps from 0.0507s to 0.0612s.

Computed aerodynamic pressure at three selected nodes above, between and bellow the vocal folds is shown in Fig. 4. From the results we can see that the fundamental vocal fold oscillation frequency was 48 Hz and maximum subglottal pressure was about 100 Pa.

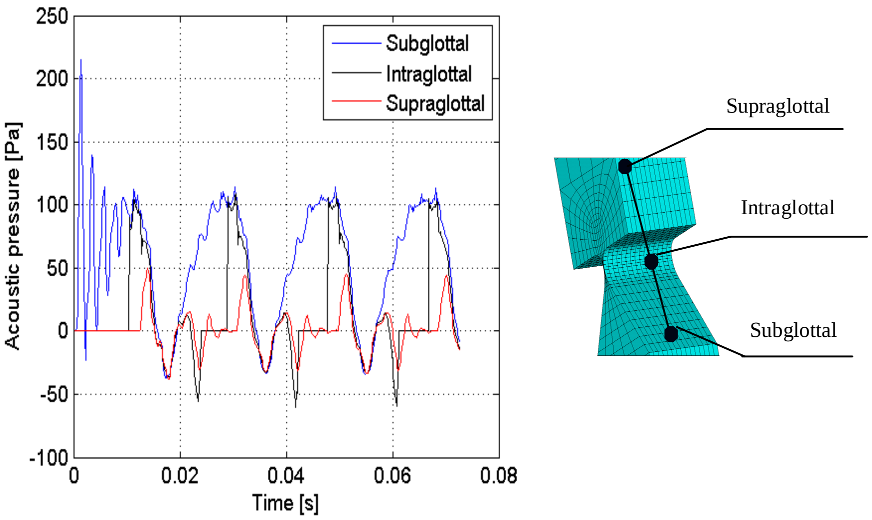


Figure 4. Computed acoustic pressure at three selected nodes.

Fig. 5 shows the computed acoustic pressure at 20 nodes, positioned along the line going from the subglottal to the supraglottal space. We can observe there the changes of the pressure field when passing through the glottis.

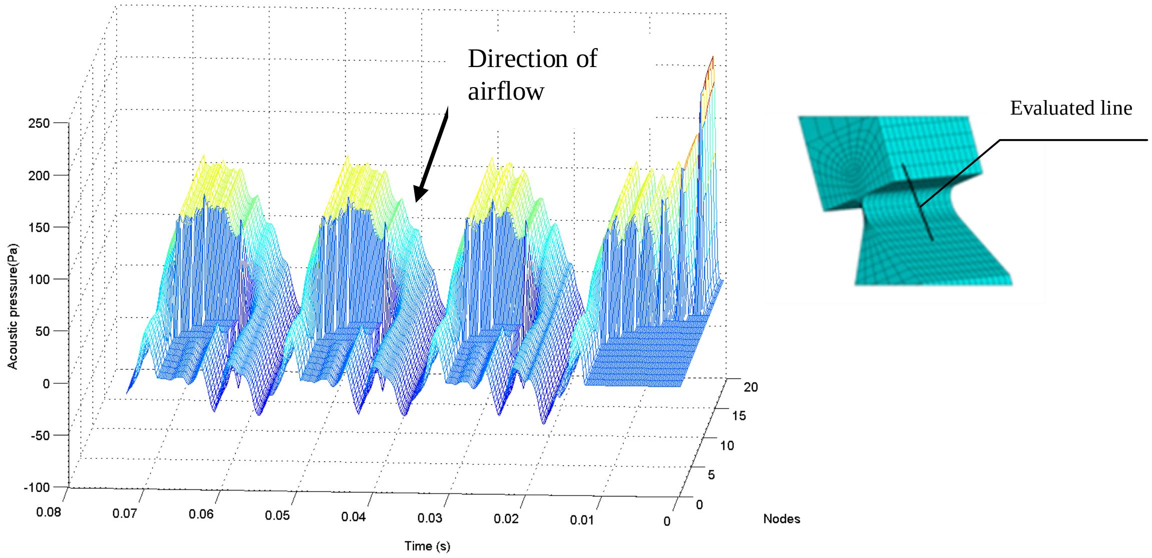


Figure 5. Acoustic pressure computed during first four oscillation periods at 20 nodes, positioned along the line going from the supraglottal to the subglottal space.

Since the airflow is simulated as unsteady and compressible, the pressure waves in the model are travelling with the speed of sound. Fig. 6 shows the computed acoustic pressure at the point above the vocal folds together with the change of the air density at this point. The acoustic pressure changes correspond perfectly to the changes in the air density.

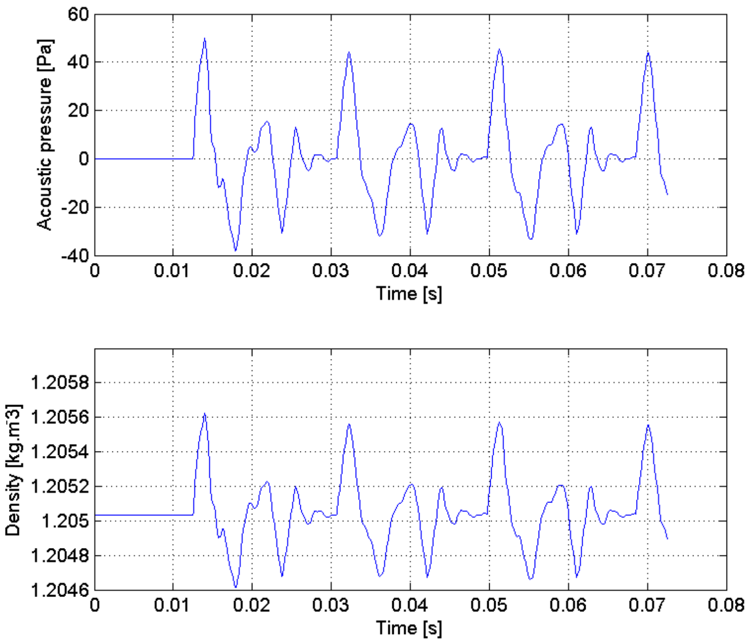


Figure 6. Computed acoustic pressure at point above the vocal folds together with change of the air density at this point.

Computed acoustic pressure at three selected nodes above the vocal folds is shown in Fig.7 for last three computed periods. The speed of sound *343* ms^{-1} for travelling pressure disturbances can be calculated from the marked detail of the second pressure peak taking into account the time delay of the signals and the distance between the nodes.

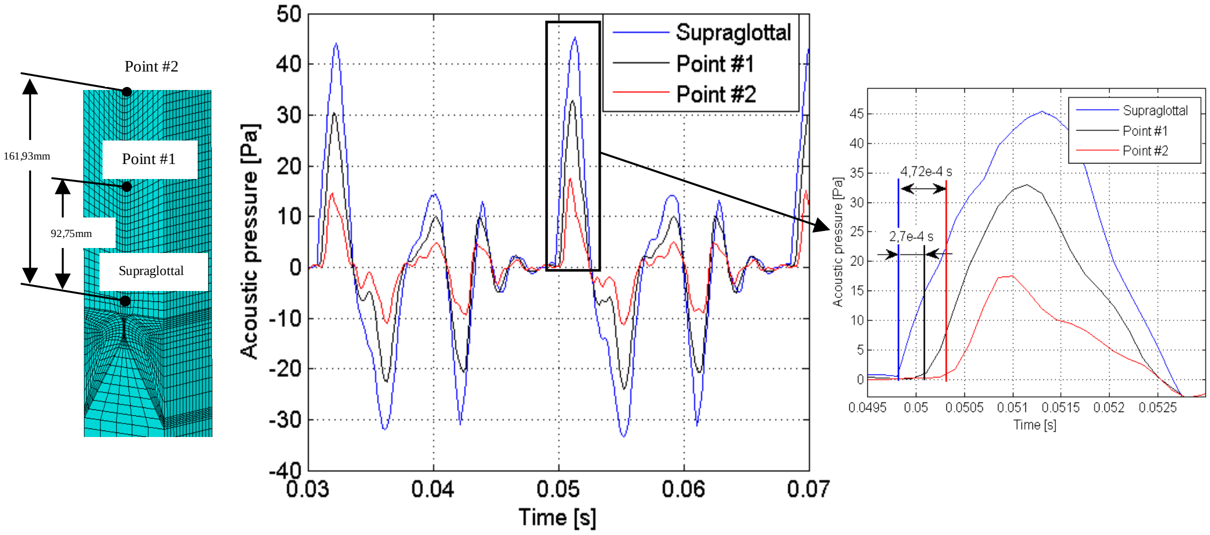


Figure 7. Computed acoustic pressure at three selected nodes above the vocal folds.

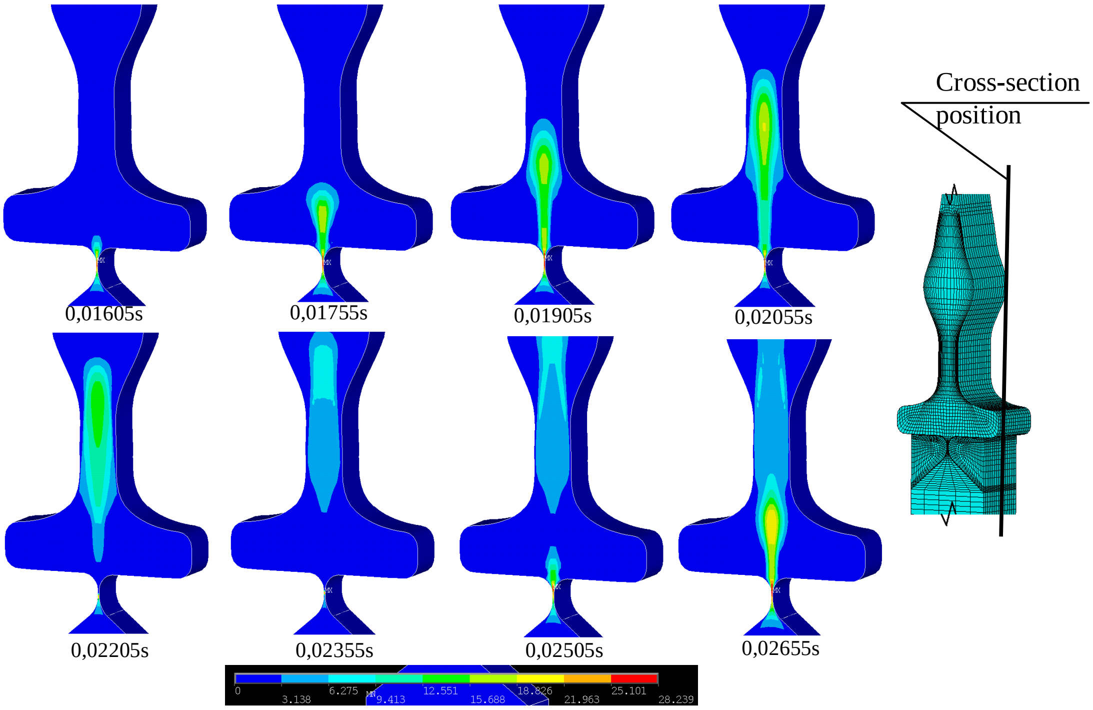


Figure 8. Computed air velocity on cross-section through the 3D shaped vocal tract during one oscillation period at eight time steps from 0.01605s to 0.02655s.

To analyze the effect of real vocal tract shape on acoustic processes, the FE model with a 3D shaped vocal tract modelling the acoustic spaces for vowel /a/ was developed. Preliminary results for this model are not perfectly periodic and the model needs further development. Example of numerically simulated airflow velocity in cross-section of the shaped vocal tract during one oscillation period at eight time steps from 0.01605s to 0.02655s is shown in Fig. 8.

5. Conclussions

Finite element model of the human vocal folds was created that includes the interaction of the oscillating vocal folds with the flowing air and acoustic process in the vocal tract. FE model comprises fluid-structure interaction, large deformations of the vocal folds tissue, vocal folds pretension before phonation, vocal folds contact, morphing the fluid mesh according the vocal folds motion, unsteady viscous compressible airflow and airflow separation during the glottis closure.

Numerical simulations prove that the developed models and algorithms can be used for simulations of interaction between the self-oscillating vocal folds and acoustic processes in the vocal tract. The developed model enables to study influence of some pathological changes in the vocal fold tissue on quality of phonation, and further on, after a FE mesh refinement, to simulate stresses that can result in tissue damages causing various voice disorders.

4. Acknowledgement

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