20th International Conference
ENGINEERING MECHANICS 2014
Svratka, Czech Republic, 12 – 15 May 2014

NUMERICAL SIMULATION OF VIDEOKYMOGRAPHIC IMAGES FROM THE RESULTS OF THE FINITE ELEMENT MODEL

P. Švancara[*], **J. Horáček**[**], **T. Martínek**[***], **J. G. Švec**[****]

Abstract: *The study presents a two-dimensional (2D) finite element (FE) model of the fluid-structure-acoustic interaction during flow induced self-oscillation of the human vocal folds. The FE model combines the FE models of the vocal folds, the trachea and the simplified human vocal tract shaped for phonation of vowel [a:]. The fluid-structure interaction is solved using explicit coupling scheme with separated solvers for structure and fluid domain. The developed FE model comprises large deformations of the vocal-fold tissue, vocal-fold contact, fluid-structure interaction, morphing the fluid mesh according to the vocal-fold motion (Arbitrary Lagrangian-Eulerian approach), solution of unsteady viscous compressible airflow described by the Navier-Stokes equations and airflow separation during the glottis closure. The effect of lamina propria thickness and material properties on simulated videokymographic (VKG) images of vocal-fold vibrations are analyzed. Such variation of the lamina propria properties can be caused by certain vocal-fold pathologies such as Reinke's edema. The developed FE model can be used to study relations among pathological changes in vocal folds tissue, the resulting VKG images and the produced sound spectra.*

Keywords: Biomechanics of voice, Videokymography, Simulation of phonation, Fluid-structure-acoustic interaction, Finite element method.

1. Introduction

Human voice production should be considered as a fluid-structure-acoustic interaction problem, where acoustic waves propagating through the vocal tract are generated by the flow-induced vibrations of the vocal folds. In literature some experimental models of this problem have been published (Titze, 2006). Published computational models include reduced-order models (Horáček et al., 2005), models of flow (Zhao et al., 2002) and finite element (FE) models (Zheng, at al., 2011). Advantage of FE models is their ability to deal with complex geometry of the vocal folds and vocal tract and ability to solve fluid-structure-acoustic interaction.

In recent works of the authors (Švancara et al., 2011; Švancara et al., 2012) a 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 paper presents newly developed 2D FE model of phonation using in literature widely used M5 geometry of the vocal folds (Scherer et al., 2001), four-layers vocal fold structure, much finer FE mesh for the airflow modelling and construction of VKG images resulting from this 2D FE model. Videokymography is a high-speed imaging technique for investigation of vocal folds vibrations, which is widely used in clinical practise (Švec and Schutte, 1996).

2. Method

The 2D FE model was developed using the program system ANSYS 14.5. The geometry of the left vocal fold according Scherer's M5 geometry is shown in Fig. 1a. Model allows variation of lamina propria

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[*] Ing. Pavel Švancara, PhD.: Institute of Solid Mechanics, Mechatronics and Biomechanics; Brno University of Technology; Technická 2896/2; 616 69, Brno; CZ, svancara@fme.vutbr.cz

[**] Ing. Jaromír Horáček, DSc.: Institute of Thermomechanics; Academy of Sciences of the Czech Republic; Dolejškova 1402/5; 182 00, Prague; CZ, jaromirh@it.cas.cz

[***] Ing. Tomáš Martínek: Institute of Solid Mechanics, Mechatronics and Biomechanics; Brno University of Technology; Technická 2896/2; 616 69, Brno; CZ, y107940@stud.fme.vutbr.cz

[****] RNDr. Jan G. Švec, PhD.: Department of Biophysics; Palacky University Olomouc; 17. listopadu 12; 771 46, Olomouc, CZ, svecjang@gmail.com.cz

thickness (parameter T_{SLP}) in range 0.15-1.8 mm. Fig. 1b shows the FE model of the four layered tissue of the vocal folds. The FE model of the trachea and the simplified acoustic spaces of the human vocal tract shaped for simulation of phonation of vowel [a:] is shown in Fig. 1c. The model of the vocal tract for the Czech vowel [a:] was created by converting data from magnetic resonance images (MRI) (Radolf, 2010). The vocal folds are modelled by a four layered tissue – epithelium, lamina propria, ligament and muscle with homogenous and isotropic material of each layer.

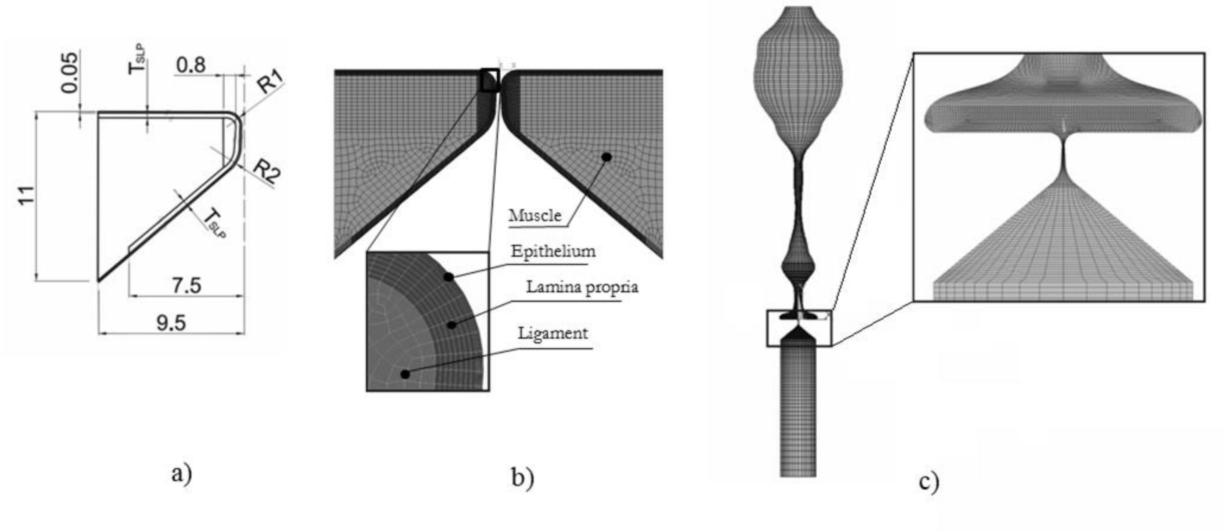

Fig. 1: a) Geometry of the left vocal fold; b) FE model of the four layered tissue of the vocal folds; c) FE model of the acoustic spaces of the trachea and the vocal tract for Czech vowel [a:].

FE model consists of 4014 linear 3-node and 4-node structural elements and 11206 linear 4-node fluid elements. Before the fluid-structure interaction simulation starts the vocal folds are pushed slightly into the contact. Contact of the vocal folds was modelled by the symmetric surface to surface contact pair elements on faces of the vocal folds. Proportional (Rayleigh) structural damping with dimensionless coefficients $\alpha = 110$ and $\beta = 3x10^{-4}$ was used for all layers.

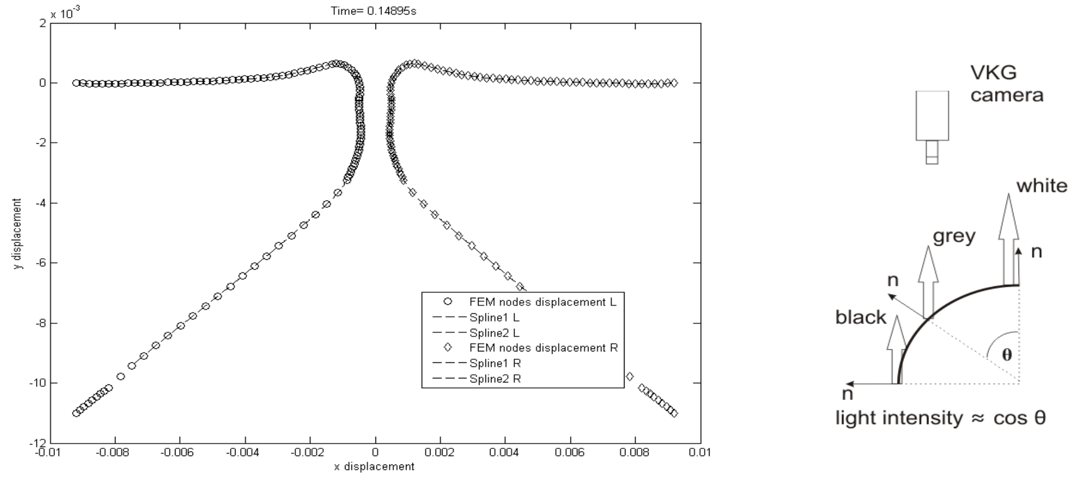

Fig. 2: Interpolation of computed positions of FE nodes by splines (left) and a schematic of the reflected light intensity using a cosine emission law (right- according to Horáček et al., 2009).

The fluid-structure interaction is solved using explicit coupling scheme with separated solvers for structure and fluid domain. The results of the airflow solution are transferred as loads on the vocal folds surface, then the vocal folds motion is computed, then the fluid mesh is morphed according to the vocal fold movement and then again the fluid flow is solved. For solving the moving boundaries of the fluid domain the Arbitrary Lagrangian-Eulerian (ALE) approach is used. The vibrations of the vocal folds was computed by a transient analysis with a time step $\Delta t = 1.5x10^{-4}\,s$, taking into account the large deformations of the vocal fold tissue and vocal fold collisions. The airflow was solved as unsteady viscous compressible and laminar flow using transient analysis with the same time step as vocal folds movement solution. For modelling the acoustic wave propagation in fluid domain, the compressible Navier-Stokes equations were utilized. A constant airflow velocity at the entrance to the subglottal space was prescribed as driving parameter and zero acoustic pressure was prescribed on the upper end of the vocal tract in order to simulate radiation into the open space.

For simulation of VKG images from the results of the FE model, a special program was developed in Matlab. The program first interpolates computed positions of FE nodes on vocal folds surface by splines to achieve better spatial resolution (see Fig. 2). A shape-preserving piecewise cubic interpolation is used with spatial resolution $1x10^{-5}\,m$. And then the emission cosine law is used for computation of light intensity reflected from the visible vocal-fold surface depending on the surface angle.

3. Results and Discussion

Fig. 3 shows an example of computed displacements in *x* and *y* directions of selected nodes on the face of the left and right vocal fold for the model with thickness of lamina propria T_{SLP}=1.35 mm. The first nodes were located on the top margin of the vocal folds and the second ones on the bottom margin. From the results we can see that oscillations of the vocal folds are symmetric and are stabilized after first few periods of the transient regime. We could also see a phase delay in displacement in *x* direction between the nodes on the top and bottom margins of the vocal folds. It is a result of upward-propagating mucosal wave (Titze, 2006). Displacements in *y* direction for nodes on top margin for the left and right vocal fold are exactly the same so curves in graph lying on each other. Same situation is for the displacements in *y* direction of the nodes on bottom margin.

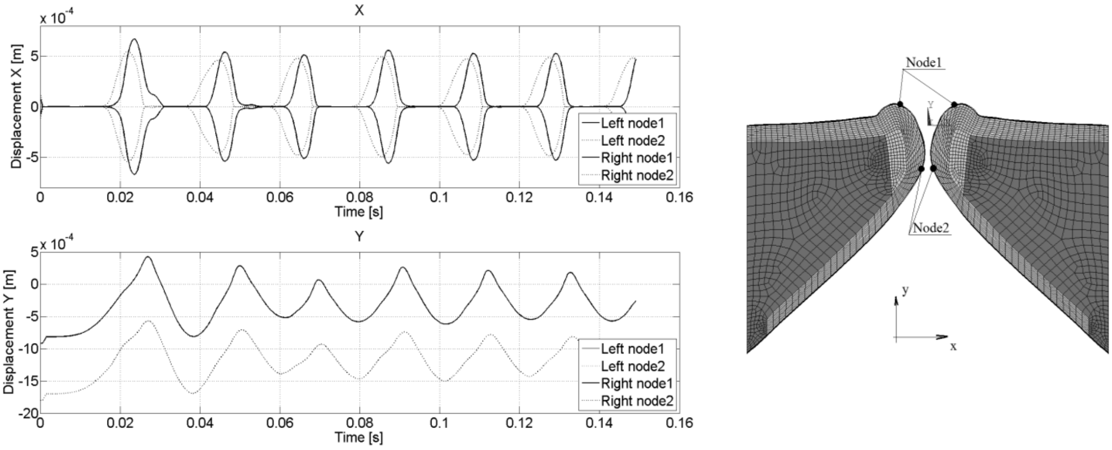

Fig. 3: Computed displacements in x and y directions of selected nodes on the face of the left and right vocal fold.

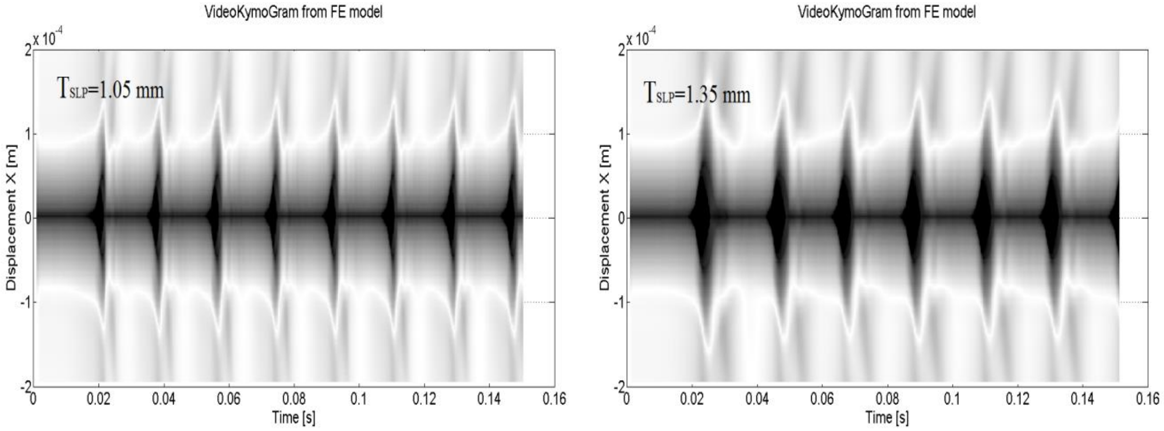

Fig. 4: VKG images created from the FE modelling results for model with thickness of lamina propria 1.05 mm (left) and 1.35 mm (right).

Example of a VKG images created from the results of FE modelling for the model with thickness of lamina propria TSLP = 1.05 mm and TSLP = 1.35 mm is shown in Fig. 4. The results show that with increasing thickness of lamina propria maximum gap between open vocal folds is increasing, time when vocal folds are open (open quotient) is increasing, there is more rounded transition from opening to closing phase and the vocal folds change more clearly their shape from convergent to divergent during one oscillation period. When the Young modulus of the lamina propria and their damping is decreased then more prominent mucosal wave can be observed.

4. Conclusions

A two-dimensional FE model of the vocal fold self-oscillations in interaction with the vocal tract acoustics was created. Computed results showed that prescribed constant airflow velocity at the entrance to the subglottal space produce vocal folds self-oscillations that are symmetric and stabilized after first few periods of the transient regime. The used compressible Navier-Stokes equations capture acoustic wave propagation phenomena in fluid and therefore a complete fluid-structure-acoustic interaction is modelled. Numerically simulated results show very close similarities with real human voice production, i.e. fundamental oscillation frequency, mean subglottal pressure and acoustic resonances corresponding to the formants of the vocal tract cavities. Also VKG images created from the results of FE modelling shows close similarities to those observed laryngoscopially in real human vocal folds.

Acknowledgement

This research is supported by the Grant Agency of the Czech Republic by the project No P101/12/1306 and by the European Social Fund Projects OP VK CZ.1.07/2.4.00/17.0009.

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