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NUMERICAL SIMULATION OF THE EFFECT OF STIFFNESS OF LAMINA PROPRIA ON THE SELF-SUSTAINED OSCILLATION OF THE VOCAL FOLDS

P. Hájek*, P. Švancara*, J. Horáček, J. G. Švec*****

A two-dimensional (2D) finite element (FE) model of the fluid-structure-acoustic interaction during self-sustained oscillation of the human vocal folds (VF) is presented in this paper. The aim is to analyze the effect of stiffness of lamina propria on VF vibrations. Such stiffness change can be caused by some VF pathologies. The developed FE model consists of the FE models of the VF, trachea and a simplified human vocal tract. The vocal tract model shaped for simulation of phonation of Czech vowel [a:] was created by converting data from the magnetic resonance images (MRI). The developed FE model includes VF contact, large deformations of the VF tissue, fluid-structure interaction (FSI), moving boundary of the fluid mesh (Arbitrary Lagrangian-Eulerian (ALE) approach), airflow separation during the glottis closure and solution of unsteady viscous compressible airflow described by the Navier-Stokes equations. The numerical simulations showed that higher values of lamina propria Young's modulus (stiffer lamina propria) result in a decrease of the maximum glottis opening. Stiffer lamina propria also requires the use of higher subglottal pressure to initiate self-sustained vibration of the VF.

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

1. Introduction

Production of human voice is a complex fluid-structure-acoustic interaction problem, where the air flow induced self-oscillations of the vocal folds generate acoustic waves propagating through the vocal tract. Besides experimental studies, numerical modelling can be used to investigate this complex phenomenon. Traditional approach is to use low degree of freedom mass models of the vocal fold vibration (Ishizaka & Flanagan, 1972; Story & Titze, 1995; Horáček et al., 2005). Presently higher-level FE models are used. They allow to deal with complex geometry of the vocal folds and vocal tract and allow to solve fluid-structure-acoustic interaction. Xue et al. (2014) used immersed boundary method for solving fluid-structure interaction and studied phonation on three-dimensional human larynx model. Hybrid numerical approach to analyze human voice production was used by Šidlof et al. (2015), where first the fluid flow problem is solved using finite-volume method with prescribed motion of the VF and then Lighthill's acoustic analogy or acoustic perturbation equations are used to solve propagation of acoustic waves in the vocal tract.

In previous works of the authors (Švancara et al., 2011; Švancara et al., 2014) the FE model of flow-induced oscillations of the VF in interaction with acoustic spaces of the vocal tract was developed. In this study a new 2D FE model of phonation was constructed using four-layered VF structure and in literature widely used M5 geometry of the vocal folds (Scherer et al. 2001). Effect of stiffness and damping of

* Ing. Petr Hájek: Institute of Solid Mechanics, Mechatronics and Biomechanics; Brno University of Technology; Technická 2896/2; 616 69, Brno; CZ, y126528@stud.fme.vutbr.cz

* Ing. Pavel Švancara, Ph.D.: 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, DrSc.: Institute of Thermomechanics; Academy of Sciences of the Czech Republic; Dolejškova 1402/5; 182 00, Prague; CZ, e-mail: jaromirh@it.cas.cz

*** RNDr. Jan G. Švec, Ph.D.: Department of Biophysics; Palacky University Olomouc; 17. listopadu 12; 771 46, Olomouc; CZ, e-mail: svecjang@gmail.com.cz

lamina propria on VF vibrations was also studied in previous paper of the authors (Hájek et al. 2016), where the model was excited by constant velocity prescribed at the entrance to the subglottal space. In this study model is excited by the constant lung pressure which corresponds better to real human voice production (Titze, 2006).

2. Methods

The FE model was created using the program system ANSYS 16.2. Fig. 1a) shows the 2D FE model of the four-layered tissue of the vocal folds. The overall dimensions of the one VF are width 9.5 mm and height 11 mm, thicknesses of individual layers are also depicted in Fig. 1. The FE model of the trachea and the simplified acoustic spaces of the human vocal tract shaped for simulation of phonation of the Czech vowel [a:] is shown in Fig. 1 b) together with used boundary conditions and measuring points. Layers of the VF was considered to be homogenous and isotropic with the Young's modulus of 25 kPa for epithelium, 1÷5 kPa for the lamina propria (see Tab. 1), 8 kPa for the ligament and 65 kPa for the muscle. The material density of 1040 kg.m^{-3} was used for all four layers. Poisson's ratio of 0.49 was used for all layers except the muscle with 0.40. Other details of the model can be found in Hájek et al. (2016). The change of lamina propria stiffness was simulated by change of Young's modulus (E_{SLP}) of this layer (see Tab. 1). In order to initiate self-sustained vibrations of the VF for the stiffer lamina propria it was necessary to increase the lung pressure at the entrance to the model of trachea. Three values of the lung pressure (p_{Lu}) were considered: 190 Pa, 275 Pa and 400 Pa.

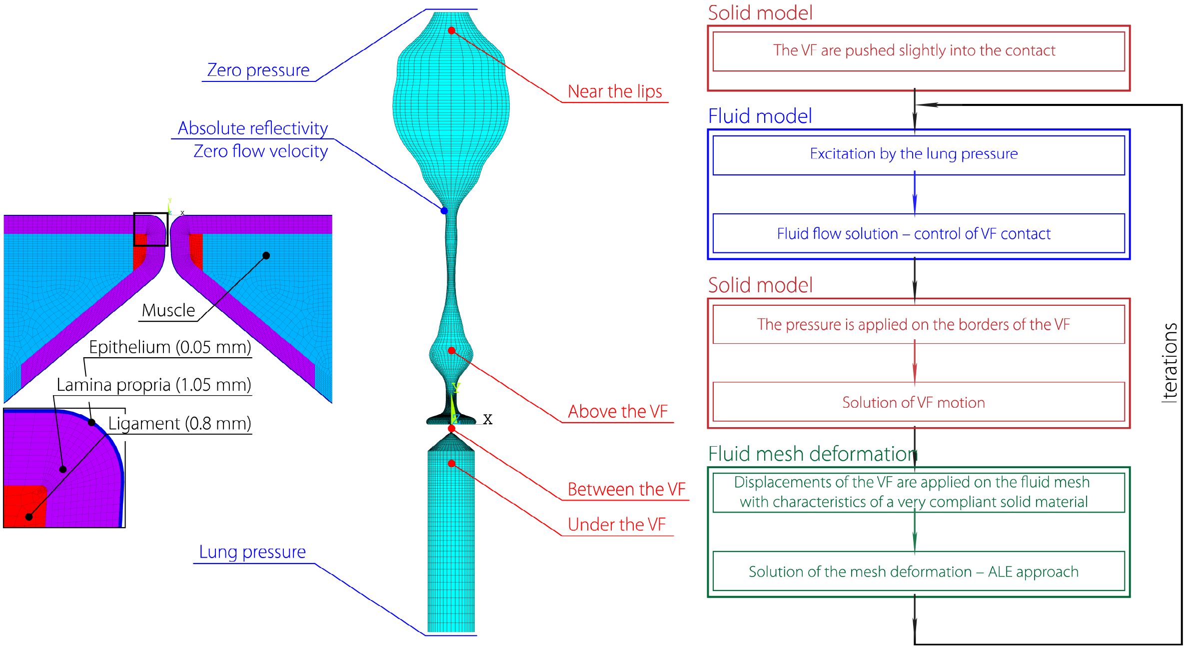

Fig. 1: a) FE model of the four-layered tissue of the VF, b) FE model of the acoustic spaces of the trachea and the vocal tract for the Czech vowel [a:], c) computational algorithm.

In the beginning of the numerical simulation, the VF are pushed slightly into the contact to the phonatory position. Then the fluid-structure interaction is solved using explicit coupling scheme with separated solvers for the structure and fluid domains. Computational algorithm is shown in Fig. 1 c). More details can be found in Švancara et al. (2014). Each computation (up to 0.1 s) took approximately 11 hours on PC with Intel i7–960 3.20 GHz (4 cores / 8 threads) and 12 GB of RAM.

3. Results and discussion

Fig. 2 shows an example of the vocal folds self-oscillations computed for $E_{SLP} = 2$ kPa and $E_{SLP} = 3$ kPa, the thickness of the lamina propria $t_{SLP} = 1.05$ mm and the lung pressure $p_{Lu} = 275$ Pa. Output pressure characteristics and sensitivity of the results on E_{SLP} can be found in Hájek et al. (2016). The oscillations of the VF are stabilized after the first few periods of the transient regime. We can also observe that the stiffer lamina propria (E_{SLP} = 3 kPa) decreased the maximum of the VF displacement in *x* direction and the fundamental frequency – see Tab. 1. For the fluid velocity we can see in Fig. 2 two peaks, the smaller peak is in the initial (opening) phase and the higher peak appears during closing phase of the oscillation period. The maximum magnitude of the fluid velocity remained approximately constant for both E_{SLP} values when the lung pressure was unchanged.

For each variant of the model (changing E_{SLP}) the following parameters widely used in laryngology (Titze, 2006) were then evaluated (see Tab. 1): the maximum glottis width, the open quotient OQ (i.e., duration of open phase divided by cycle duration), the closed quotient CQ (i.e., duration of closed phase divided by cycle duration), the closing quotient ClQ (i.e., duration of closing phase divided by cycle duration), the speed quotient SQ (i.e., duration of opening phase divided by duration of closing phase), the speed index SI (i.e., difference between the durations of the opening and closing phases divided by sum of these) and the fundamental oscillation frequency *f*.

Tab. 1: Characteristics of VF oscillation depending on Young's modulus of the lamina propria E_{SLP} and lung pressure p_{Lu}.

E_{SLP} [kPa]	p_{Lu} [Pa]	Max. glottal width [mm]	OQ [–]	CQ [–]	ClQ [–]	SQ [–]	SI [–]	*f* [Hz]
1	**190**	0.53	0.31	0.69	0.07	3.14	0.52	105
1.5		0.42	0.25	0.75	0.04	4.50	0.64	75
2	**275**	0.55	0.47	0.53	0.07	5.33	0.68	123
2.5		0.48	0.47	0.53	0.09	4.29	0.62	127
3		0.42	0.55	0.45	0.07	6.83	0.74	116
3.5		0.38	0.57	0.43	0.07	6.86	0.75	103
4	**400**	0.59	0.52	0.48	0.10	4.33	0.62	164
4.5		0.58	0.55	0.45	0.14	2.88	0.48	179
5		0.56	0.54	0.46	0.11	4.17	0.61	175

Results show that the stiffer lamina propria (higher E_{SLP}) causes a decrease of the maximum of glottal width and in some cases decrease of the fundamental frequency. Same conclusions were observed for the model excited by constant flow velocity (Hájek et al., 2016). Actual model excited by the lung pressure shows the values of the quotients more corresponding to clinical results (Lohscheller, 2013). For example the open quotient is for higher values of E_{SLP} slightly above 0.5. From the results we can also see that the fundamental frequency is increasing with the lung pressure which is also in agreement with clinical data (Titze, 2006). As a next step it is planned to use vocal tract shaped for other Czech vowels, which will allow to analyze the influence of vocal tract geometry on computed results.

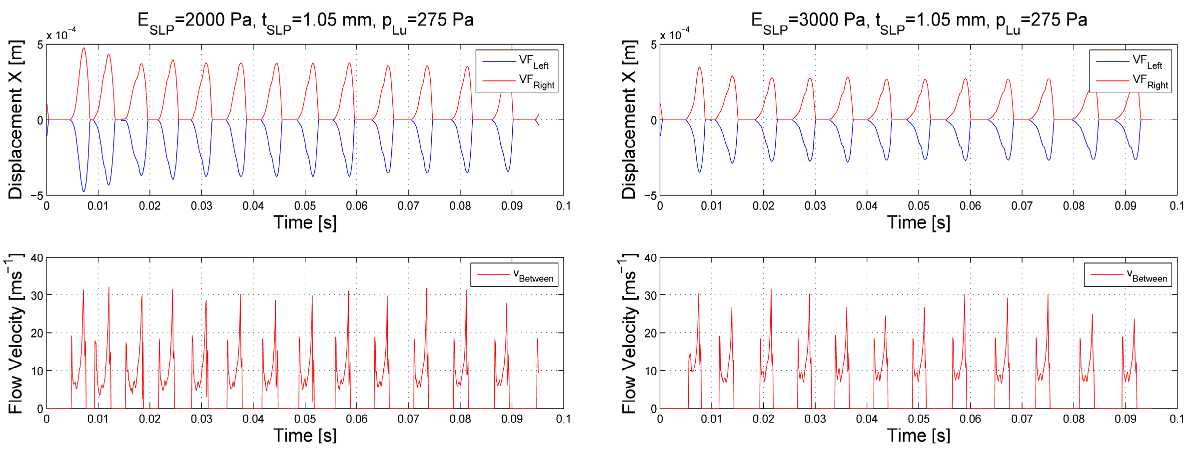

Fig. 2: Computed displacement in x direction of selected nodes on the face of the left and right VF located in the middle of the VF height and flow velocity in selected node between the VF for E_{SLP} = 2 kPa (left graphs) and E_{SLP} = 3 kPa (right graphs).

4. Conclusions

The 2D FE model of the vocal fold self-oscillations in interaction with the vocal tract acoustics was created and the effect of stiffness of lamina propria on the VF vibrations was analyzed. The results of the numerical simulations showed that the excitation of the model by the constant lung pressure produces the VF self-oscillations. Numerically simulated results showed characteristics similar as in human phonation.

The computed results showed that by increasing stiffness of the lamina propria the maximal glottis opening decreases. The lower vibration frequency observed in some cases was probably caused by the fact, that for the lower Young's modulus (E_{SLP}) the lamina propria was vibrating while the muscle remained almost still, whereas for the higher values of E_{SLP} the VF were vibrating as a whole body. The developed model excited by the lung pressure showed that the quotients characterising the phonation regime correspond better to the clinical data comparing to the previous model excited by the constant flow velocity. The numerical simulations also showed that with increasing lung pressure the fundamental frequency increases which is in accordance with clinical results. The developed FE model can be used for simulations how the various pathological changes in VF tissue can change the resulting VF vibrations and the produced sound.

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