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EFFECTS OF TURBULENCE IN FE MODEL OF HUMAN VOCAL FOLDS SELF-OSCILLATION

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Abstract: *The purpose of the study is to determine whether a turbulence model in fluid flow calculation affects the vocal folds (VF) vibration and the acoustics of human vocal tract (VT). The objective is examined using a two-dimensional (2D) finite element (FE) model of the fluid-structure-acoustic interaction for self-sustained oscillations of the VF. The FE model consists of the models of the VF, the trachea and a simplified model of the human VT. The developed FE model includes large deformations of the VF tissue and VF contact interrupting the airflow during glottis closure. The airflow is modelled by the unsteady viscous compressible Navier-Stokes equations, without and with the Shear Stress Transport (SST) turbulence model. Fluid-structure interaction (FSI) and morphing of the fluid mesh are realized using Arbitrary Lagrangian-Eulerian (ALE) approach. The method is applied on the FE model of the VT shaped for the Czech vowel [a:]. Also effect of varying stiffness of the superficial lamina propria (SLP) is analyzed. The numerical simulations showed that considering of the turbulence affects mainly higher frequencies apparent in a frequency spectrum of the VT acoustics.*

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

1. Introduction

Relatively large number of computational models were recently published in literature, however many of them do not cover the complete fluid-structure-acoustic interaction. FE model of the interaction between structure and airflow created by Alipour et al. (2000) was one of the first partial differential equation based models. The model was modified later to comprise acoustics of the vocal tract (Alipour et al., 2015). Zhang et al. (2004) take into account interaction between airflow and acoustics resolved by Ffowcs-Williams-Hawkings method. The fluid-structure-acoustic interaction is usually solved in two ways. Coupling of a structure and incompressible fluid flow solutions with acoustic analogy is more common (Link et al., 2009), on the other side if compressible fluid is considered (Suh et al., 2007), the acoustic solution can be obtained directly from the pressure field.

Previous studies of the authors concern of numerical simulations of self-sustained VF vibration (Švancara at al., 2011; Švancara at al., 2014) with emphasis on material properties of lamina propria (Hájek et al., 2016a; Hájek et al., 2016b). In this study a new FE model is presented and the solution of fluid flow without the turbulence model is compared to the solution with included SST turbulence model, one of the most advanced in the group of RANS (Reynolds-averaged Navier-Stokes) flow models.

2. Methods

The 2D FE model was created in the program system ANSYS 15.0 and is composed of 14389 linear elements; see Fig. 1a. Geometry of the four layered VF was created according widely used Scherer's M5

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geometry (Scherer et al., 2001). Young's modulus of VF layers were used as follows: epithelium 25000 Pa, SLP 2000 – 5000 Pa, ligament 8000 Pa and muscle 65000 Pa. Poisson's ratio of 0.49 was considered for all layers except the muscle with 0.40. The material density of 1040 $kg \cdot m^{-3}$ was used for all layers. Geometry of the VT was converted from magnetic resonance images (Radolf, 2010). Material properties of air corresponding to the human body temperature were used: density 1.205 $kg \cdot m^{-3}$, fluid viscosity $1.81351 \cdot 10^{-5}$ $kg.m^{-1} \cdot s^{-1}$, speed of sound 353 $m \cdot s^{-1}$. Boundary conditions of the structural (VF) and fluid (VT and trachea) part of the model are shown in the Fig. 1a together with position of evaluation points. Other details of the model can be found for example in Hájek et al. (2016b).

At first VF are set to phonatory position by pushing them slightly into the contact. Solution algorithm for fluid-structure interaction is based on explicit coupling scheme with separate solvers for the structural and fluid part. More details can be found in Švancara et al. (2014). Computational algorithm of airflow with SST turbulence model is given in Fig. 1b.

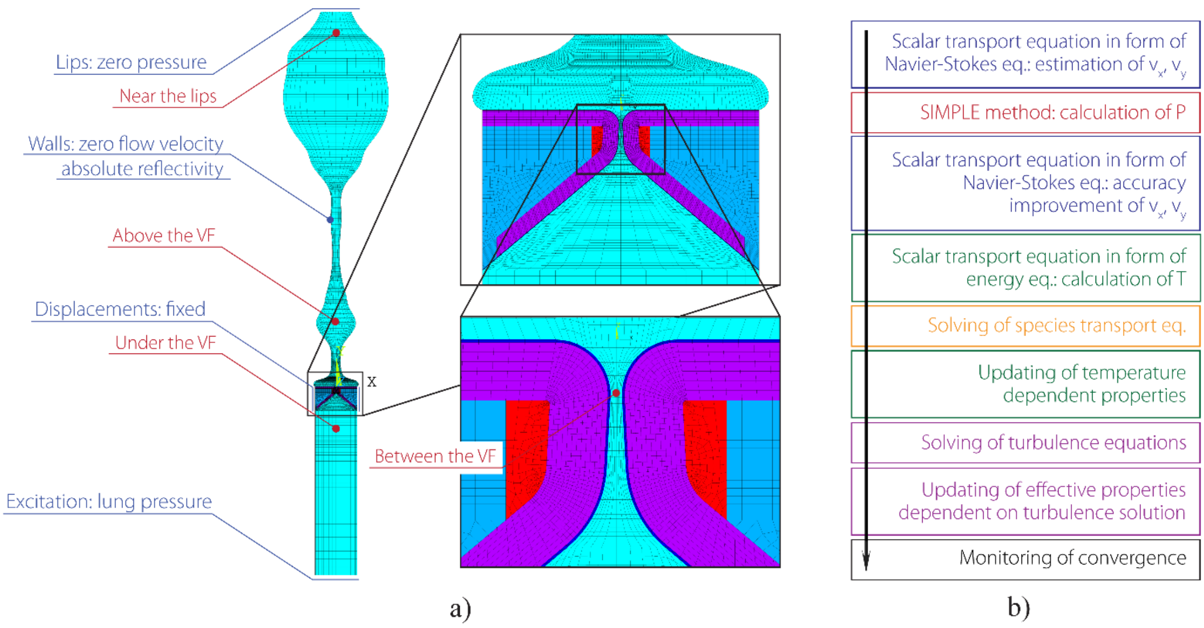


Fig. 1: a) Complete FE model with boundary conditions (blue), evaluation points (red) and with details of FE mesh; b) computational algorithm of airflow with SST turbulence model.

Typical computation of 0.1 s long phonation with turbulence model took approximately 13.5 hours on Intel i7–960 3.20 GHz (4 cores / 8 threads) and 12 GB of RAM. Equivalent solution without turbulence model took 3 hours less on the same PC.

3. Results and discussion

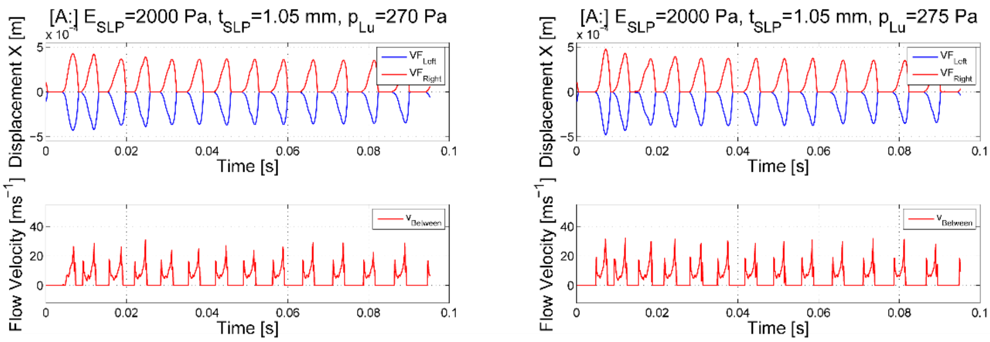
Comparison of the VF oscillation characteristics with and without turbulence model for increasing Young's modulus of the SLP (E_{SLP}) is in Tab. 1. Evaluated parameters of VF oscillations were the maximal width of glottis WG_{max}, the open quotient OQ, the closed quotient CQ, the closing quotient ClQ, the speed quotient SQ, the speed index SI and the fundamental oscillation frequency. The lung pressure p_{Lu} was decreased by 5 Pa for simulations with turbulence model in order to initiate the self-sustained vibrations.

From the results we can be observe the increase of the fundamental frequency for simulations with turbulence model. Maximal width of glottis WG_{max} remains more or less in the same limits. Duration of the open phase is slightly shorter compared to the closed phase when using the turbulence model (see open quotient OQ and closed quotient CQ in Tab. 1). The values of the quotients correspond to clinical results (Lohscheller et al., 2013).

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

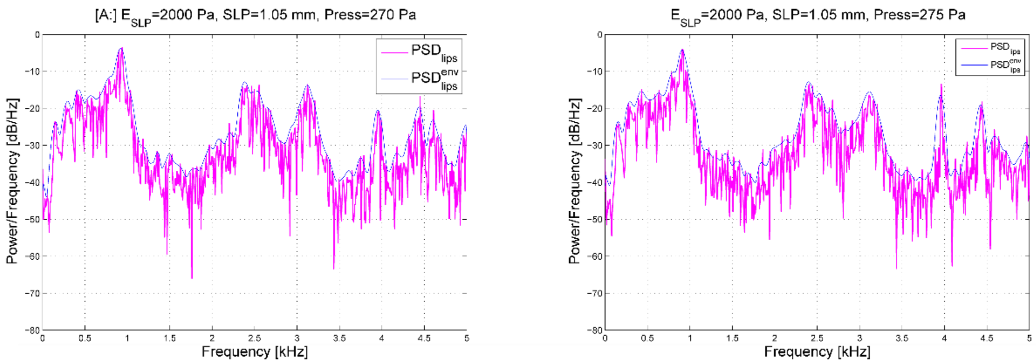
Turbulence model	E_{SLP} [Pa]	p_{Lu} [Pa]	WG_{max} [mm]	OQ [–]	CQ [–]	ClQ [–]	SQ [–]	SI [–]	*f* [Hz]
Yes	**2000**	**270**	0.56	0.38	0.62	0.09	3.14	0.52	132
	2500		0.49	0.46	0.54	0.09	4.00	0.60	132
	3000		0.42	0.50	0.50	0.06	7.20	0.76	122
	3500		0.38	0.57	0.43	0.06	8.83	0.80	97
No	**2000**	**275**	0.55	0.47	0.53	0.07	5.33	0.68	123
	2500		0.48	0.47	0.53	0.09	4.29	0.62	127
	3000		0.42	0.55	0.45	0.07	6.83	0.74	116
	3500		0.38	0.57	0.43	0.07	6.86	0.75	103

Fig. 2 shows an example of the vocal folds self-oscillations that are stabilized after several periods of transient regime both for simulation with and without the turbulence model. Comparing flow velocities in selected node between the VF one can observe a decrease of all peaks for simulation with SST turbulence model. Such a decrease could be caused by energy dissipation due to capturing smaller eddies by turbulence. Power spectral density of acoustic pressure in the node near the lips is not too affected by using the SST turbulence model for frequencies up to 3 kHz, see Fig. 3. For frequencies above 3 kHz, an amplitude decrease of resonance frequencies for simulation with the turbulence model can be observed.



a) b)

Fig. 2: 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: a) with turbulence model; b) without turbulence model.



a) b)

Fig. 3: Power spectral density of acoustic pressure in selected node near the lips a) with turbulence model; b) without turbulence model.

4. Conclusion

The 2D FE model of the fluid-structure-acoustic interaction during self-sustained oscillation of the human vocal folds was created and effect of the SST turbulence model on the VF vibration and the acoustics of the VT was analyzed.

The computed results showed that use of SST turbulence model leads to slightly increase of the fundamental frequency even for smaller lung pressure used for excitation. For simulation with turbulence model also duration of the open phase is slightly shorter comparing to the case without turbulence model. Use of SST turbulence model leads also to decrease of peaks of flow velocities between the VF and to decrease of the peaks of acoustic resonances for frequencies above 3 kHz. Turbulence model is capable of capturing smaller eddies comparing to simulations without any turbulence model. Computation without any turbulence model is able to capture only eddies up to size of an element. Smaller eddies represent additional dissipation of energy in form of acoustic quadrupoles on higher frequencies (Williams, 1969). Larger eddies carry more energy than the relatively small ones (Williams, 1969) and for that reason larger eddies have dominant impact on interaction between fluid and acoustics and affect mainly lower frequencies.

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