THREE-DIMENSIONAL FINITE ELEMENT MODELLING OF VOCAL FOLDS VIBRATION IN THE HUMAN LARYNX

T. Vampola¹, J. Horáček², I. Klepáček³
¹ Department of of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering, Czech Technical University in Prague, Czech Republic
² Institute of Thermomechanics, Academy of Sciences of the Czech Republic, Czech Republic
³ 3rd Faculty of Medicine, Charles University, Prague, Czech Republic

Abstract: 3D FE model of the larynx including the vocal folds, arytenoid, thyroid and cricoid cartilages was developed. The vocal fold tissue is modeled as a three layered material representing the epithelium vocal ligament and muscle. First, the frequency modal analysis of the model was performed for nonlinear material characteristics and increasing pre-stress of the vocal folds. Then the results of numerical simulation of the vocal folds oscillations excited by a prescribed aerodynamic pressure loading the surface of the tissue is presented. The FE contact elements are used for modeling the vocal folds collisions.

Keywords: Biomechanics of human voice, parametric FE model of the human larynx, numerical simulation of the vocal folds vibration.

I. INTRODUCTION

Design of a model of the human vocal folds, which would enable to model some pathological situations and voice disorders, is becoming an important part of the voice research. Having in mind an intention, to estimate vocal fold tissue damage from the changes in vibration regimes of the vocal folds, a new three-dimensional fully parametric finite element (FE) volume model of the larynx was developed. The model respects the phonation position of the vocal folds and enables easily to vary their geometrical configuration, the longitudinal tension (pre-stress) and the nonlinear material properties of the individual vocal fold tissue layers. The geometry and relations between the arytenoids, thyroid and cricoid cartilages was derived from CT images of a physical enlarged resin model of the human larynx from the collections of the Anatomical Institute of the 3rd Medical Faculty of the Charles University in Prague and on the bases of the book [6]. This model is a copy of the original physical model from Germany (Deutches Hygiene-Museum, Institute für biologisch-anatomische Anschauungsmaterialen, Dresden).

II. METHODS

A. FE model

The 3D complex dynamic FE model of the human larynx was developed by transferring the CT image data from the DICOM format to the FE mesh. The geometrical configuration of the cross-section of the vocal fold was taken from Hirano [3] and three layers of the vocal fold tissue are considered: epithelium, vocal ligament and muscle with different physical and material properties (see Fig. 1). Full parameterization of the model enables to vary the thickness and material properties of the individual layers.

Fig. 1 Schema of the vocal fold with three layers.

The model enables to take into account longitudinal tension (pre-stress) and adduction of the vocal folds by positioning of the arytenoids and thyroid cartilages—see Fig. 2. The initial position corresponds to the original CT images of the physical model. The model was
created by 3D quadratic volume and shell finite elements.

**B. Material parameters**

The ligament layer consists of the tissue fibers that are oriented in the longitudinal direction \( z \) between the arytenoids and thyroid cartilages. The stiffness of the vocal fold tissue in this direction is substantially higher than the stiffness in the perpendicular direction \( x \). This is the reason why a plane orthotropic model was used [1], where the matrix of the elastic constants is defined as

\[
C = \begin{bmatrix}
E_p^{-1} & -\mu_p E_p^{-1} & -\mu_p E_l^{-1} & 0 & 0 & 0 \\
-\mu_p E_p^{-1} & E_p^{-1} & -\mu_p E_l^{-1} & 0 & 0 & 0 \\
-\mu_l E_p^{-1} & -\mu_l E_p^{-1} & E_l^{-1} & 0 & 0 & 0 \\
0 & 0 & 0 & G_p^{-1} & 0 & 0 \\
0 & 0 & 0 & 0 & G_l^{-1} & 0 \\
0 & 0 & 0 & 0 & 0 & G_l^{-1}
\end{bmatrix},
\]

where \( E_p \) is Young modulus, \( \mu_p \) is Poisson number and \( G_p \) is shear modulus in perpendicular direction \( x \) to the ligament fibers. Analogical constants are denoted by the index \( l \) for the longitudinal direction \( z \). The cartilages were modeled by an isotropy material. For a loose connective tissue between the vocal fold muscle and the thyroid cartilage a model of an incompressible material was used. The material constants considered for the tissues are summarized in Tab. 1.

<table>
<thead>
<tr>
<th>( E ) ( \frac{kPa}{L} )</th>
<th>( G_p ) ( \frac{kPa}{L} )</th>
<th>( \mu )</th>
<th>( E_p ) ( \frac{kPa}{L} )</th>
<th>( E_l(\varepsilon) ) ( \frac{kPa}{L} )</th>
<th>( \rho ) ( \frac{kgm^{-3}}{L} )</th>
<th>( \mu_l \equiv \mu_p )</th>
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<td>0.526</td>
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<td>1.052</td>
<td>-</td>
<td>-</td>
<td>0.9</td>
<td>0.9</td>
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<td>0.9</td>
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<td>5</td>
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Orthotropic properties of the three layers of the vocal fold living tissue (epithelium, vocal ligament and muscle) are modeled by respecting the material nonlinearities with increasing prolongation \( \varepsilon \) of the tissue. Nonlinear stiffness of the tissue fibers was considered in the longitudinal direction \( z \). The Young modulus in relation to the strain for all three layers is shown in Fig. 3.

![Fig.3 Young modulus of the epithelium, ligament and muscle versus the strain [4].](image)

### III. RESULTS

The frequency-modal characteristics of the model were computed for increasing tension of the vocal folds and an influence of 20% changes in uncertain values of material characteristics of the tissues was modeled. The frequency-modal properties of the FE model are shown in Tab. 2 and Figs. 4-6.

<table>
<thead>
<tr>
<th>( \varepsilon ) [%]</th>
<th>( F_1 ) [Hz]</th>
<th>( F_2 ) [Hz]</th>
<th>( F_3 ) [Hz]</th>
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<td>130.50</td>
<td>140.41</td>
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<td>15</td>
<td>137.82</td>
<td>154.50</td>
<td>163.44</td>
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<tr>
<td>25</td>
<td>165.68</td>
<td>177.66</td>
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<tr>
<td>35</td>
<td>193.68</td>
<td>201.71</td>
<td>209.24</td>
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<table>
<thead>
<tr>
<th>( \varepsilon ) [%]</th>
<th>( F_1 ) [Hz]</th>
<th>( F_2 ) [Hz]</th>
<th>( F_3 ) [Hz]</th>
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<tr>
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<td>25</td>
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<td>0.282E-04</td>
<td>0.776E-07</td>
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<table>
<thead>
<tr>
<th>( \varepsilon ) [%]</th>
<th>( x )</th>
<th>( y )</th>
<th>( z )</th>
</tr>
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</table>
| Tab.3 Participation factor for \( x \), \( y \) and \( z \) direction for the strain \( \varepsilon=5\% \) and first three eigenfrequencies.

The frequency-modal characteristics of the model were computed for increasing tension of the vocal folds and an influence of 20% changes in uncertain values of material characteristics of the tissues was modeled. The frequency-modal properties of the FE model are shown in Tab. 2 and Figs. 4-6.
A dominant vibration direction for each eigenmode was studied by using the participation factor $\gamma_i$, which is a measure of a coincidence of one selected eigenmode with the forced mode shape of vibration when the structure excited in a given direction:

$$\gamma_i = \frac{\phi_i^T M D}{\max \{\phi_i^T M D\}}, \quad (1)$$

where $\phi_i$ is the eigenmode, $M$ is the mass matrix of the structure and $D$ is the forced mode shape of vibration excited in the direction $x$, $y$ or $z$. The calculated participation factor for first three eigenmodes and all three directions $x,y,z$ are summarized in Tab. 3. The displacements in horizontal and vertical directions $x$ and $y$, respectively, are dominant for the first mode for which a rotation around the longitudinal axis $z$ prevails. The vibration in the horizontal direction $x$ dominates for the second eigenmode, while for the third eigenmode, the vibration amplitudes of the membranous part of the vocal fold tissue prevail in the vertical $y$ direction.

Then the motion of the vocal folds was numerically simulated for a prescribed intraglottal pressure loading the vocal folds by a periodic function in the time domain –see Figs. 7.

The pressure signal loading the vocal fold surface was generated by the aeroelastic model [5] of the vocal folds during self-sustained vibrations for a given subglottal pressure and prephonatory glottal gap. Implementation of the contact elements on the vocal folds surface enabled to model the impact stresses in the vocal fold tissue layers during the vocal folds collision.

The vibration response of the vocal folds after loading the tissue by the prescribed intraglottal pressure is shown in Figs. 8-10.
IV. CONCLUSIONS

The geometry of the model is possible to modify easily as well as to apply optimization procedures for finding proper model parameters of the system in relation to the tuning both the vocal folds vibration characteristics, and the larynx model in general.

The computed fundamental eigenfrequencies and mode shapes of vibration are qualitatively similar like for other simplified models in literature [2,7] and the obtained increase of the eigenfrequencies by increasing the vocal fold tension is also realistic. The considered changes in the material properties, in case of the 20% reduction of the Young modulus of the vocal fold tissue in the longitudinal direction were not found important. The generated motion of the vocal folds seems to be qualitatively similar to a vibration mode known from clinical measurements.

Preliminary results show that model the contact elements on the vocal folds surface enable numerical simulations of the collisions of the vocal folds and to predict stresses in the vocal fold tissue due to the impacts.

ACKNOWLEDGEMENTS

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REFERENCES