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USING THE PROPER ORTHOGONAL DECOMPOSITION ANALYSIS FOR DETECTING PATHOLOGIC VOCAL FOLD VIBRATION

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Abstract: *A three-dimensional (3D) finite element (FE) fully parametric model of the human larynx based on computer tomography (CT) measurements was developed and specially adapted for numerical simulation of vocal folds vibrations with collisions. The complex model consists of the vocal folds, arytenoids, thyroid and cricoid cartilages. The vocal fold tissue is modeled as a four layered material where part of the cover was substituted by a liquid layer modelling the superficial layer of lamina propria. The proper orthogonal decomposition (POD) analysis of the excited modes of vibration was used for detecting changes in vibration properties of the vocal folds caused by pathologic changes of vocal fold structure (vocal nodule).*

Keywords: biomechanics of human voice, 3D FE model of human larynx, finite element method, proper orthogonal decomposition analysis

1. Introduction

Human voice plays an important role in society enabling interpersonal communication. Understanding the basic principles of voice production is important for better interpretation of clinical findings, detection of laryngeal cancers or other pathologies and for treatment of voice disorders.

Voice production is a complex physiological process, which involves several basic factors like airflow coming from the lungs, vocal folds (VF) vibration and acoustic resonances of the cavities of the vocal tract, see e.g. Fant (1960).

Design of more exact 3D computer models of the human VF folds enables modelling of some pathological situations. Changes in the structural and geometric properties are related to the changes of the vibratory properties of the vocal folds. In this contribution, the proper orthogonal decomposition method (POD) is used for predicting of the human vocal fold damage.

2. FE model of the human larynx

The geometry and relations between the arytenoids, thyroid and cricoid cartilages was derived from CT images. The geometry of the vocal folds was derived from the CT images registered during phonation of a female subject. The 3D complex dynamic FE model of the human larynx was developed by transferring the raw CT image data into volume models. After meshing of the volume models, the 3D FE model of the complete larynx was constructed within the framework of the program ANSYS (Vampola et al. 2015), see Fig. 1.

The frequency-modal properties and the results of the numerical simulation of the vocal fold oscillations with and without the VF nodule, excited by a prescribed periodic intraglottal aerodynamic pressure, are presented. For simplicity, no fluid structure interaction is considered here, and the primary focus is concentrated on the proper orthogonal decomposition (POD) analysis of the excited modes of vibration and on comparison of the vibration patterns in the vocal fold models.

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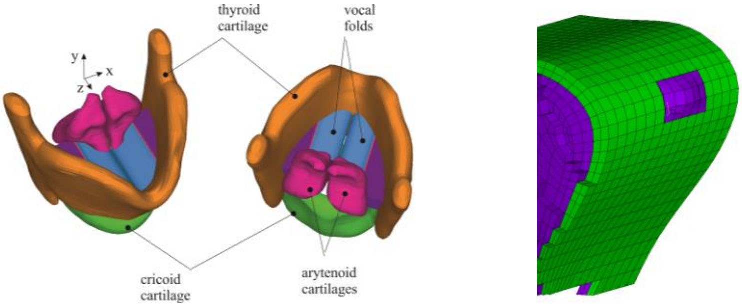

Fig. 1. The 3D FE model of the human larynx with the vocal folds fixed to the arytenoid and thyroid cartilages. False vocal folds were not considered in this study. The vocal fold nodule model (right).

The nonlinear elasticity theory for large-strain deformations with linear strain-stress relationship was implemented. The linear transversal isotropic material model was used for the vocal fold tissue. The tissues material constants for cover, ligament and muscle vocalis considered are summarized in Table 1. An incompressible liquid was included in the superficial layer of lamina propria and modelled by structural finite elements considering the bulk modulus of water (k_L =2.1*10^6 kPa). The VF nodule was modelled by an additional volume 2x1x0.5 mm^3 located in the lamina propria (see Fig. 1) with the material parameters of about 10% higher than the ligament parameters.

Table 1. Nominal values of material constants of individual tissue layers according to Luo et al. (2008)

	Cover	Ligament	Muscle
G_p [kPa]	0.53	0.87	1.05
G_l [kPa]	10	40	12
μ_p	0.3	0.3	0.3
$E_l(\varepsilon)$ [kPa]	26	104	31
ρ [kgm^{-3}]	1020	1020	1020

3. Frequency – modal characteristic of the models

The first fourth eigenfrequencies and the eigenmode shapes of vibration of the right vocal fold of the FE models for the model without the nodule are presented in Fig. 2. Because the vocal folds are not perfectly symmetric, the fundamental eigenfrequencies for the left and right vocal fold are slightly different, however the mode shapes are very similar. The influence of the VF nodule on the first four eigenfrequencies and the eigenmodes was found negligible.

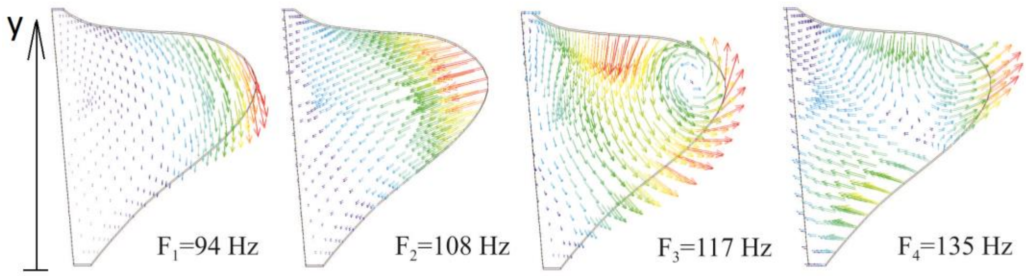

Fig. 2. First four eigenfrequencies and eigenmodes of vibration of the vocal fold model without the nodule.

4. Numerical simulation of vocal folds vibration

The self-sustained vibrations with collisions of the 3D vocal folds models were numerically simulated by using a prescribed intraglottal pressure given by a periodic function in the time domain. Transient analysis was used for simulation of the vocal folds vibration in time domain.

The intraglottal pressure loading of the vocal fold surface was generated by the 2D aeroelastic model of the VF self-oscillations developed by Horáček et al. (2009). The intraglottal pressure was calculated during the VF self-oscillations for the airflow rate Q=0.15 l/s, the prephonatory glottal half-gap g_0=0.2 mm and the subglottal pressure P_{sub}=270 Pa. The intraglottal periodic pressure $p(y,t)$, simulated by the 2D aeroelastic model, and used for excitation of the 3D FE models of the vocal folds is shown in Fig. 3.

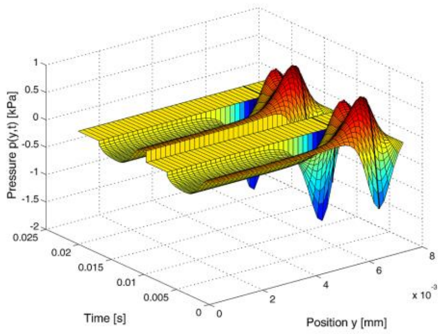

Fig. 3. Two periods of the intraglottal pressure pulses p(y,t) loading the vocal folds surface presented in the time-space domain.

5. Proper orthogonal decomposition analysis of the vocal fold vibration

The proper orthogonal decomposition (POD) is useful tool in analyzing vibration of the flexible structures, see e.g. Feeny & Kappagantu (1998). By means of the POD eigenvalues the amount of the energy in the POD modes can be evaluated. In this contribution we tested the hypothesis if the POD analysis can be used for prediction of the vocal fold damages.

For application of POD method it is necessary to assemble the displacement-history array in the N time snaps for displacements along *x*,*y* and *z* coordinates u_j, v_j, w_j (j=1,2,…,M):

$$\mathbf{D} = [\mathbf{d}(t_1), \mathbf{d}(t_2), \cdots, \mathbf{d}(t_i), \cdots, \mathbf{d}(t_{\mathrm{N}})] \tag{1}$$

An oscillatory component matrix **R** represents the time-varying displacements about the dynamic equilibrium of the system, can be separated from the **D** matrix where the MATLAB functions *mean*(**D**,2) and *ones*(1,N) were used.

$$\mathbf{R} = \mathbf{D} - mean(\mathbf{D},2)\ ones(1,\mathrm{N}) \tag{2}$$

The covariance matrix $\mathbf{C} = \mathbf{R}^T\mathbf{R}/\mathrm{N}$ is then formed. The eigenvectors and eigenvalues of the covariance matrix can be computed by means of singular value decomposition method ($\mathbf{C} = \mathbf{U}\,\mathbf{S}\,\mathbf{V}^T$). The normalized POD modes (also so called toposes) are then derived in the form

$$\boldsymbol{\varphi}_i = \mathbf{C}\,\tilde{\mathbf{u}}_i / \left\|\mathbf{C}\,\tilde{\mathbf{u}}_i\right\|, \quad i = 1, 2, \cdots, \mathrm{N}_{POD.} \tag{3}$$

The relative amount of energy involved in the POD modes can be expressed from the diagonal of the matrix **S**

$$energy\ [\%] = \left(s_{ii} \Big/ \sum_{i=1}^{3M} s_{ii} \right) 100 \tag{4}$$

Finally the modal assurance criterion (MAC) was used for evaluation a relation of the POD modes with the normal modes of vibration:

$$MAC_{ij}\ [\%] = \frac{(\mathbf{v}_i^T \boldsymbol{\varphi}_j)^2}{(\mathbf{v}_i^T \mathbf{v}_i)(\boldsymbol{\varphi}_j^T \boldsymbol{\varphi}_j)} 100 \tag{5}$$

where $\mathbf{v}_i$, $i=1,2,\ldots,N$ are the normal modes of vibration and $\boldsymbol{\varphi}_j$, j=1,2,…,$\mathrm{N}_{\mathrm{POD}}$ are the POD modes.

The POD analysis was applied on numerically simulated displacements for the FE models with and without the nodule. The results are summarized in Table 2 and in Fig. 4 for first three and two POD modes, respectively. Table 2 presents the MAC values (5) and the relative POD modes energies (4) computed for the first three POD modes (3) for the VF models without and with the VF nodule.

Table 2 shows that up to 97-98 % of the total energy is captured by the first two POD modes in both FE models. However, the main difference between the VF models is in the entrainment of the eigenmodes of vibration. The first POD mode for the VF model without the VF nodule entrains the 1st and 2th eigenmodes while the model with the nodule entrains a combination of the 1st and 3nd eigenmodes.

Table 2 Modal assurance criterion (MAC) coefficients $MAC_{ij}\,[\%]$ *computed for the full FE models of the vocal folds: a) with the nodule and b) without the nodule.*

a)	eigenmode				
POD mode	1	2	3	4	Energy [%]
1	31.04	2.87	41.34	9.91	73
2	37.30	24.85	18.97	1.28	25
3	1.04	0.15	8.97	5.81	0.4
b)	eigenmode				
POD mode	1	2	3	4	Energy [%]
1	36.35	40.78	12.25	0.28	53
2	26.61	0.52	28.92	17.70	45
3	0.41	2.35	9.63	0.001	0.99

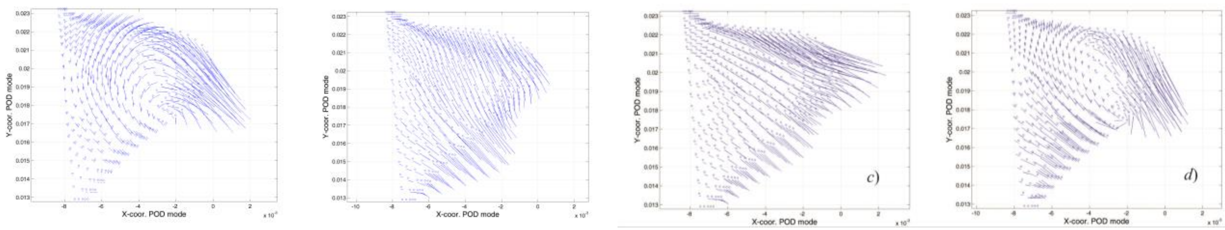

Fig. 4. First two POD modes of vibration computed for the full FE models of the vocal folds with the VF nodule (first and second) and without the nodule (third and fourth). For more clarity, only displacements of the nodes in the middle cross-section of the vocal folds are shown in the figure.

6. Conclusions

The geometry of the parametric 3D FE model of the vocal folds developed as a part of the complex 3D larynx model can be easily modified, enabling tuning and optimization procedures for finding proper geometric and material parameters related to the vocal fold vibration characteristics.

The POD analysis of the VF vibration patterns with and without the nodule proved a sufficient sensitivity of the developed computational VF model to a small variation of the model parameters and therefore the model can be used for prediction of the vocal fold damages.

Acknowledgement

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