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NUMERICAL SIMULATION OF VIDEO-KYMOGRAPHIC RECORDS OF THE VOCAL FOLD VIBRATION

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Abstract: *The reconstruction of the video-kymographic records from the numerical simulation of the vocal fold vibration is used for prediction of the type of vocal fold damaged. Three-dimensional (3D) finite element (FE) fully parametric model of the human larynx was developed and used for numerical simulation of stresses during vibrating vocal folds with collisions. The complex model consists of the vocal folds, arytenoids, thyroid and cricoid cartilages. The vocal fold tissue is modeled as a three layered transversal isotropic material. The results of numerical simulation of the vocal folds oscillations excited by a prescribed intraglottal aerodynamic pressure are presented. The FE contact elements are used for modelling the vocal folds collisions and the stresses in the vocal fold tissue are computed in time domain. The damaged of the ligament tissue is simulated by the modification of the modulus of elasticity. The video-kymographic records are reconstructed for health and damaged vocal folds. The results show significant dynamic stresses in all there directions (horizontal, vertical and anterior-posterior).*

Keywords: Biomechanics of human voice, 3D FE model of human larynx, Vocal fold vibration, Video-kymographic record.

1. Introduction

With regard to the clinical practice, when basic investigative techniques include video-kymographic, the question arises of whether the character of vibration recorded by the high-speed camera can be used for prediction of the damage to the vocal cords. Therefore, the computer model of the human vocal folds was designed enabling to model some pathological situations and voice disorders. Some simplified lumped mass dynamic models of phonation can be used for a rough estimate of the impact stress or acceleration level depending on various phonation parameters like e.g. prephonatory glottal gap, subglottal pressure and fundamental frequency (Horáček et al., 2005). Because the mechanical loading of vocal fold self-oscillations with collisions is caused by a combination of the aerodynamic, inertial and impact forces and moreover, regarding the complicated three-dimensional (3D) structure and material properties of the living tissue, is necessary assembled more sophisticated models based on Finite Element (FE) modelling enable us to estimate all main normal and shear stresses in the different vocal fold tissue layers in all three directions, even if the computational demands on computers and computer time needed are much higher and still limited. These models can be used for the evaluation of the correlation between the deformation and stresses fields of the vocal fold tissues with the video-kymographic records of the vocal folds vibrations.

2. Methods

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 according to Hirano (1975). Three layers of vocal fold tissue are considered (Titze, 2006): epithelium, vocal ligament and muscle with different physical and material properties - see Fig. 1.

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The developed fully parameterized 3D FE model enables to vary the thickness and material properties of the individual layers and to take into account longitudinal pretension and adduction of the vocal folds by positioning of the arytenoids and thyroid cartilages – see Fig. 1.

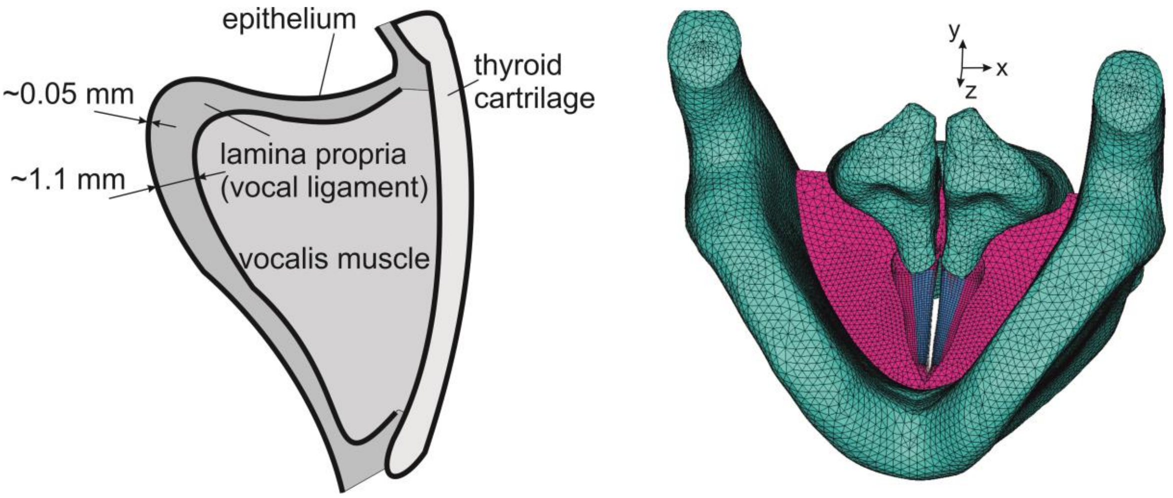

Fig. 1. Schema of the vocal fold with three tissue layers (left), FE model of the human larynx with the vocal folds between the arytenoids and thyroid cartilages (right).

The nonlinear elasticity theory for large-strain deformations with the linear transversal isotropic material model was used for the vocal fold tissue, where the matrix of the elastic constants in strain-stress relations is defined as follows:

$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{xy} \\ \varepsilon_{xz} \\ \varepsilon_{yz} \end{bmatrix} = \begin{bmatrix} E_p^{-1} & -\mu_p E_p^{-1} & -\mu_{pl} E_p^{-1} & 0 & 0 & 0 \\ -\mu_p E_p^{-1} & E_p^{-1} & -\mu_{pl} E_p^{-1} & 0 & 0 & 0 \\ -\mu_{lp} E_l^{-1} & -\mu_{lp} E_l^{-1} & E_l^{-1} & 0 & 0 & 0 \\ 0 & 0 & 0 & G_p^{-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & G_l^{-1} & 0 \\ 0 & 0 & 0 & 0 & 0 & G_l^{-1} \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{xz} \\ \sigma_{yz} \end{bmatrix} \tag{1}$$

where $E_p = 2\, G_p\, (1+\mu_p)$ is the Young modulus, μ_p is the Poisson number and G_p is the shear modulus in perpendicular plane *xy* to the ligament fibers, and analogical constants are denoted by the index *l* for the longitudinal direction *z*. The tissues material constants considered are summarized in Tab. 1.

Tab. 1: Nominal values of material constants of individual tissue layers according to Mital (2008) – E = Epithelium, L = Ligament, M = Muscle, C = Cartilage, LT = Loose connective Tissue.

	E	L	M	C	LT
G_p [kPa]	0.530	0.870	1.050	-	-
G_l [kPa]	10	40	12	-	-
μ_p	0.3	0.3	0.3	0.47	0.4999
$E_l(\varepsilon)$ [kPa]	26	104	31	-	-
ρ [kgm^{-3}]	1020	1020	1020	1020	1020
μ_{lp}	0.3	0.3	0.3	-	-

2.1. Numerical simulation of vocal folds vibration

The motion of the vocal folds was numerically simulated for a prescribed intraglottal pressure given by a periodic function in the time domain. The intraglottal pressure signal loading the vocal fold surface was generated by the 2D aero elastic model (see Horáček et al., 2005) of the vocal folds during the vocal folds self-sustained vibrations for the airflow rate $Q = 0.179$ l/s the prephonatory glottal half-gap $g_0 = 0.2$ mm and the fundamental frequency $F_0 = 100.766$ Hz, that corresponded to the subglottal pressure $P_{sub} = 378.4$ Pa, and the resulted vocal folds vibration were characterized by the open quotient $OQ = 0.725$, defined as the open time of the glottis divided by the period length of the vocal folds vibrations, by the maximum glottis opening $GO = 1.27$ mm and the maximum impact stress estimated by the Hertz theory $IS = 1328$ Pa.

2.2. Computed displacement

The limits of the computed trajectories of the middle cross-section are presented in Fig. 2. These deformations can be used for reconstruction of the video-kymograph records of the human vocal fold vibration see Fig. 3. The damaged of the vocal fold was simulated by the decreasing of the modulus of elasticity of the ligament tissue about 20%.

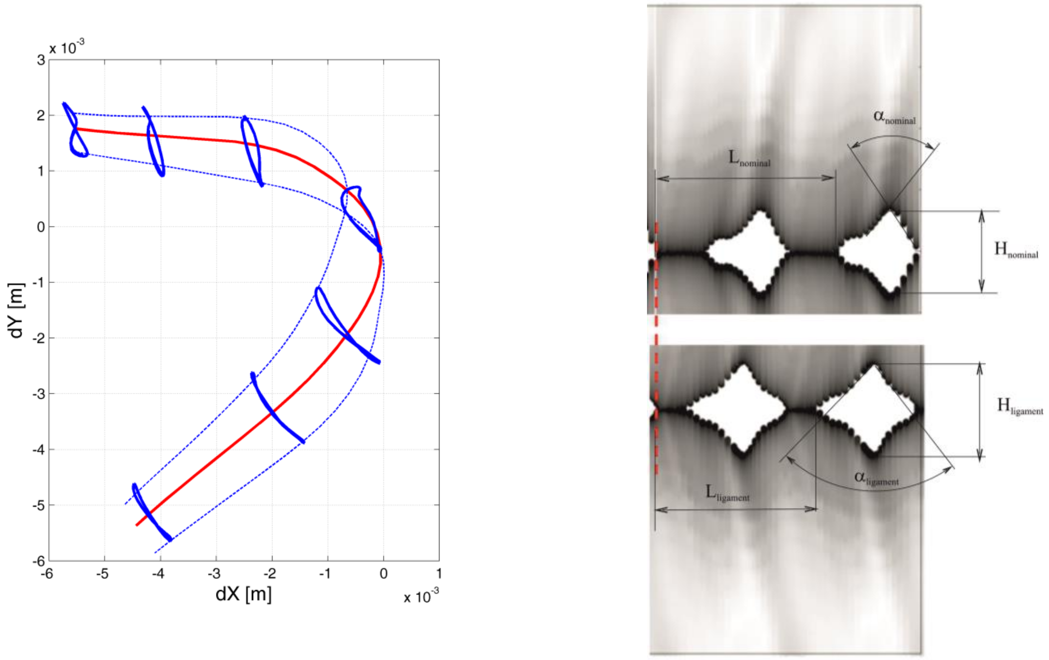

Fig. 2: Nominal shape (red full curve) and maximal deformation (blue dotted curves) in the middle cross-section of the health vocal fold (right), comparison of the reconstructed video-kymograph records for the health and damaged vocal fold (right).

The computed trajectories $u_x(t)$, $u_y(t)$, $u_z(t)$ in the selected nodes of the vocal fold tissue during stabilized oscillation cycles are shown in Fig. 2. A very complicated motion is evident. The mucous Rayleigh type waves are propagating near the vocal fold surface, especially in the upper part of the vocal fold. The maximum value of the peak to peak displacement in the medial (x) direction is about 0.8 mm from and inferior-superior (y) direction is about 1.5 mm. The medial displacement in x direction is limited by the vocal fold collisions. The anterior–posterior vibration amplitude in z direction is negligible. The maximum vibration amplitudes are on the vocal fold surface, the vibration amplitudes are decreasing in the deeper tissue layers.

Tab. 2: Characteristics of vibration for health and damaged vocal fold. OQ=Open Quotient, CQ=Close Quotient, ClQ=Closing Quotient, SQ=Speed Quotient, SI= Speed Index and frequency of vibration for health and damaged vocal fold

	OQ	CQ	ClQ	SQ	SI	f [Hz]
	t_2/t_1	$1-t_2/t_1$	t_2/t_1-1	$t_3/(t_2-t_1)$	(SQ-1)/(SQ+1)	$1/t_1$
health	0.633	0.367	0.212	1.990	0.0828	95.24
damaged	0.724	0.275	0.312	1.319	0.0344	96.9

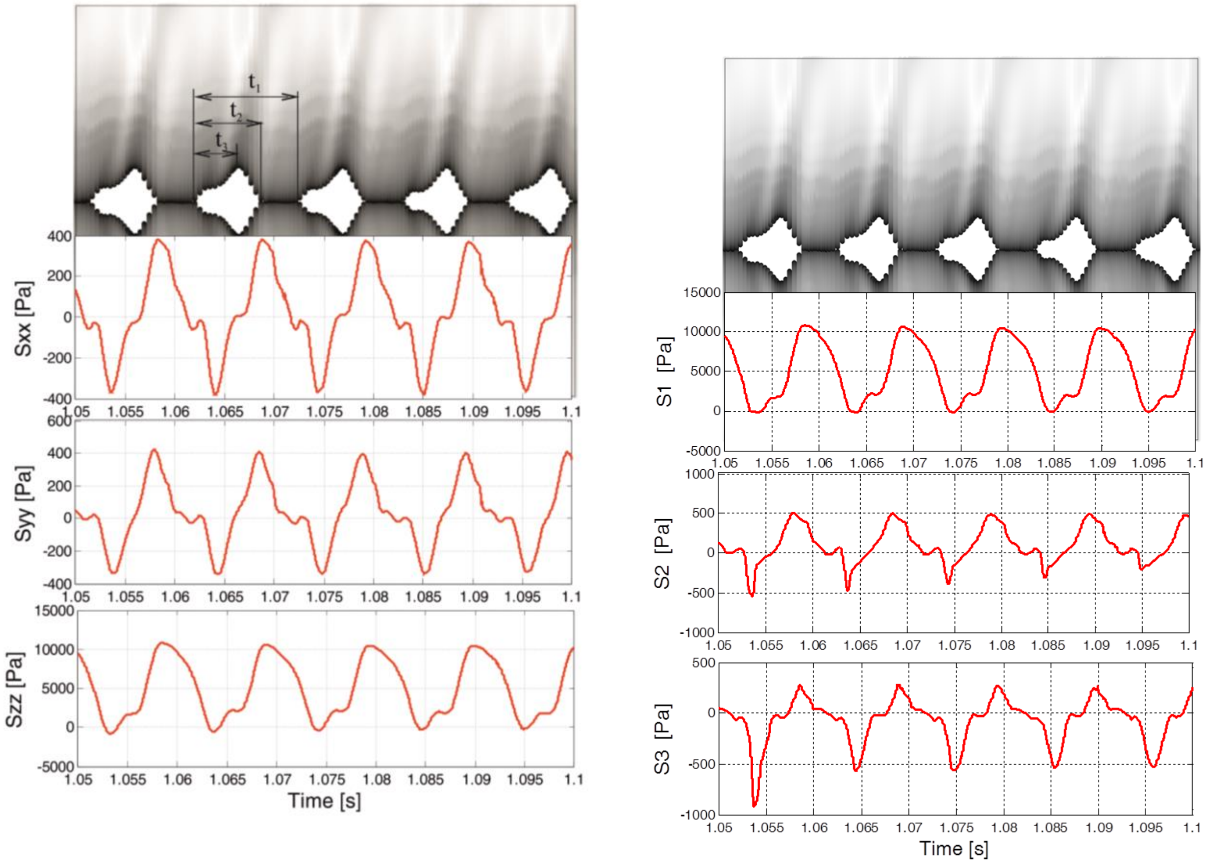

Fig. 3: Reconstruction of the video-kymographic records (top) and the normal stresses and principal stresses (bottom) of the health vocal folds.

3. Conclusions

The geometry of the parametric 3D FE model of the vocal folds developed as a part of the complex larynx model can be easily modified, enabling tuning and optimization procedures for finding proper model geometric and material parameters related to the vocal fold vibration characteristics. The results suggest that the model enables to predict stresses in the layered vocal fold tissue due to the vibration of the vocal folds in phonation regimes with collisions. The motion of the vocal folds excited by periodic intraglottal pressure pulses seems to be qualitatively similar to the vibration patterns known from clinical observations. From the preliminary results can be concluded that the reconstructed video-kymographic records are sensitive enough to the material parameters and geometric reconfiguration of the vocal fold and can be used for prediction of the vocal fold damaged.

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