23rd International Conference
ENGINEERING MECHANICS 2017
Svratka, Czech Republic, 15 – 18 May 2017

COMPUTATIONALLY EFFICIENT MODEL OF THE HUMAN VOCAL FOLD

J. Štorkán*, T. Vampola**, J. Horáček***

Abstract: *One mass model of the vocal folds with three degrees of freedom in 2D space was created and used to simulate the movement of the vocal folds. Vocal folds are modeled as a solid mass stored flexibly in 2D. The model is excited by aerodynamic forces. The flow is solved by analytical model incompressible and non-viscous fluid with constant flow. In case of close of the glottis are aerodynamic forces replaced by Hertz model of the contact forces. Movement equations are solved by numerical method. The model allows to solve the movement of the vocal folds in the time domain, pressure field acting on the vocal folds or contact pressures.*

Keywords: Simulation of vocal folds, Ideal fluid flow, Nonlinear vibration, Self-exciting vibration, Bio-acoustic, Hertz contact, Aerodynamics forces.

1. Introduction

Vocal folds (VF) are a fundamental part of the human vocal tract. They create a source voice that is modulated in the vocal tract. This creates a human voice. That's one theory of phonation (Fant, 1970). VF are also one of the main source of voice failures. They are mechanically strong and cyclically loaded. VF are sensitive to wear and pathological changes. That is one reason why they are intensively investigated. Research of VF may in the future allow the production and implementation of synthetic VF to human larynx. This will improve the lives of people with voice disorders.

VF research began in middle of the last century the first successful mathematical models are dual mass models. Dual mass models are simple they have 2 DOF and are used today. Team of authors (Horáček et al., 2002) created the single body model with 2 DOF (transverse displacement and rotation) his advantage is a fully parametric geometry of VF profile. Allows to study the influence of geometry on mechanical properties. This mechanical model is linear and does not allow to study the self-excited oscillations. In 2005 was model generalized to enable simulation of nonlinear self-excited oscillation. This work is based on the work (Horáček et al., 2005) in order to generalize the mechanical model by adding a longitudinal movement (3 DOF).

2. Model of VF

Single body model is composed of a body in 2D space (Fig. 1). The shape of the body is defined by independent function a(x) that defines the profile. The body is flexibly attached to the frame by springs and dampers. The springs and dampers are placed in the center of mass of the profile. This makes the stiffness and damping matrix diagonal. Mass characteristic are determined by direct integration profile. The values of stiffness and damping may be prescribed directly or prescribe natural frequency and the width of the resonance peaks and that define the stiffness and damping.

$$\boldsymbol{M}\ddot{\boldsymbol{V}} + \boldsymbol{B}\dot{\boldsymbol{V}} + \boldsymbol{K}\boldsymbol{V} = \boldsymbol{F}, \quad (1)$$

* Ing. Jaroslav Štorkán, Department of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering, Czech Technical University in Prague. Technicka 4, Praha 6, Czech Republic, jaroslav.storkan@fs.cvut.cz

** Prof. Dr. Ing. Tomáš Vampola, Department of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering, Czech Technical University in Prague. Technicka 4, Praha 6, Czech Republic, tomas.vampola@fs.cvut.cz

*** Ing. Jaromír Horáček, Drc, Institute of Thermodynamics, Academy of Sciences of the Czech Republic. Dolejšova 1402/5 Praha 8 Czech Republic, jaromirh@it.cas.cz

where

$$\boldsymbol{M}=\begin{bmatrix} m & 0 & 0\\ 0 & m & 0\\ 0 & 0 & I\end{bmatrix}, \boldsymbol{B}=\begin{bmatrix} b_x & 0 & 0\\ 0 & b_y & 0\\ 0 & 0 & b_t\end{bmatrix}, \boldsymbol{K}=\begin{bmatrix} k_x & 0 & 0\\ 0 & k_y & 0\\ 0 & 0 & k_t\end{bmatrix}, \boldsymbol{V}=\begin{bmatrix} x_T\\ y_T\\ \varphi\end{bmatrix}, \boldsymbol{F}=\begin{bmatrix} F_x\\ F_y\\ M\end{bmatrix}.$$

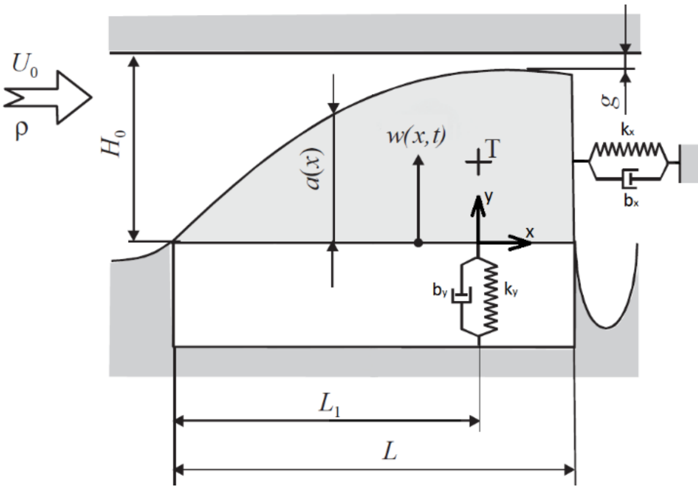

Fig. 1: Solved mechanical model of VF with 3 DOF.

2.1. Excitation of model

The main source of excitation VF are aerodynamics forces of the air flow. Aerodynamics forces are determined by integration of pressure field. The air is replaced by an ideal fluid. To obtain the pressure field is needed to get the velocity field. The pressure and velocity fields are divided into time-constant and fluctuation component. Time-constant component can be chosen freely by using relations (3, 5).

$$U(x,t)=\overline{U}(x)+\tilde{u}(x,t) \tag{2}$$

$$\overline{U}(x)=\frac{H_0U_0}{H_0-a(x)} \tag{3}$$

$$P(x,t)=\overline{P}(x)+\tilde{p}(x,t) \tag{4}$$

$$\frac{1}{2}\rho\overline{U}^2(x)+\overline{P}(x)=const \tag{5}$$

The basic equation of fluid mechanics is the continuity equation. For used fluid model and nonstationary channel cross has the form (6). Where U(x,t) is the speed and H(x,t) is the channel height. The height of the channel (7) is derived from the basic height H0, VF profile a(x) and the position of the VF w(x,t). Parameters V_1, V_2, V_3 are the elements of the vector $\boldsymbol{V}$.

$$\frac{\partial H(x,t)}{\partial t}+\frac{\partial (H(x,t)U(x,t))}{\partial x}=0 \tag{6}$$

$$H(x,t)=H_0-a(x)-w(x,t) \tag{7}$$

$$w(x,t)=V_2(t)+V_3(t)(x-V_1(t)) \tag{8}$$

The solution of velocity in the glottis (9) was founded by modifying equations. Elements i_1-i_7 are function of position. Was used boundary condition at the inlet to the larynx $\tilde{u}$ is zero.

$$\tilde{u}(x,t)=i_1V_2+i_2V_3+i_3V_1V_3+i_4\dot{V}_2+i_5\dot{V}_3+i_6V_1\dot{V}_3+i_7V_3\dot{V}_1 \tag{9}$$

The equation of motion for used fluid model is 1D Euler equation (10) is solved after substitution decomposition of pressure and velocity fields. To the solution was used boundary condition $\tilde{p}$ at the output of the larynx is zero. The shape of the solution (11) is formally identical to (9). The solution is the sum of multiply time functions ($\boldsymbol{V_p}(t)$) with space functions ($\boldsymbol{J}(x)$). Both vectors have 39 elements. Column vector $\boldsymbol{V_p}(t)$ containing different combinations of the elements of $\boldsymbol{V},\dot{\boldsymbol{V}},\ddot{\boldsymbol{V}}$. Using a pressure field (11) we can determine the forces and moment acting on the VF.

$$\rho \frac{\partial U(x,t)}{\partial t} + \rho U(x,t) \frac{\partial U(x,t)}{\partial x} + \frac{\partial P(x,t)}{\partial x} = 0 \tag{10}$$

$$\tilde{p}(x,t) = \boldsymbol{J}(x)\boldsymbol{V_p}(t) \tag{11}$$

$$F_x = h \int_{-L_1}^{L-L_1} \tilde{p}(x,t) \frac{da(x)}{dx} dx \tag{12}$$

$$F_y = h \int_{-L_1}^{L-L_1} -\tilde{p}(x,t) dx \tag{13}$$

$$M = h \int_{-L_1}^{L-L_1} \tilde{p}(x,t) \left(\frac{da(x)}{dx} \big(y_T - a(x)\big) - x \right) dx \tag{14}$$

The forces and moment can be formally expressed as (12) only the vector $\boldsymbol{J}(x)$ is changed to constant vectors. If contact occurs between the VF is not used model the aerodynamics forces. When collision is used sub-glottis pressure and hertz (contact) force (16). Where r is radius of curvature, E, μ are elastic constants of the VF and δ is size of penetration.

$$F_{hertz} = \frac{4\sqrt{r}E}{3(1-\mu^2)} \delta^{3/2} \tag{15}$$

2.2. Simulation results

Self-exited vibration was simulated for time interval of one second. The model is fully parametric. VF profile is formed of a part of parabola taken from (Horáček et al., 2005). The flow rate was set Q = 0.11 l/s and gap = 0.2 mm. Natural frequencies was taken from the results (Vampola et al., 2016). Stabilization of the model takes about 0.1 s. Model after stabilization periodically vibrates with the collisions (Fig. 2). Thick marked parts of the graph show the collision. The first harmonic vibration frequency is 105 Hz. Closure of the glottis takes about 30 % of the oscillation period. Frequency spectrum of displacement VF is In Fig. 3. Fig. 4 shows the pressure field acting on the VF in the simulation during the last three periods of movement. Discontinuities in the pressure field are generated by switch aerodynamics forces to the subglottic pressure during VF collision. This pressure field was used for excitation FEM model of the VF. Results of dynamic FEM analysis (Figs. 5 and 6) confirmed the applicability of the model to generate the correct pressure fields. This can save a lot of time in comparison with co-simulation because it is not necessary solve CFD part.

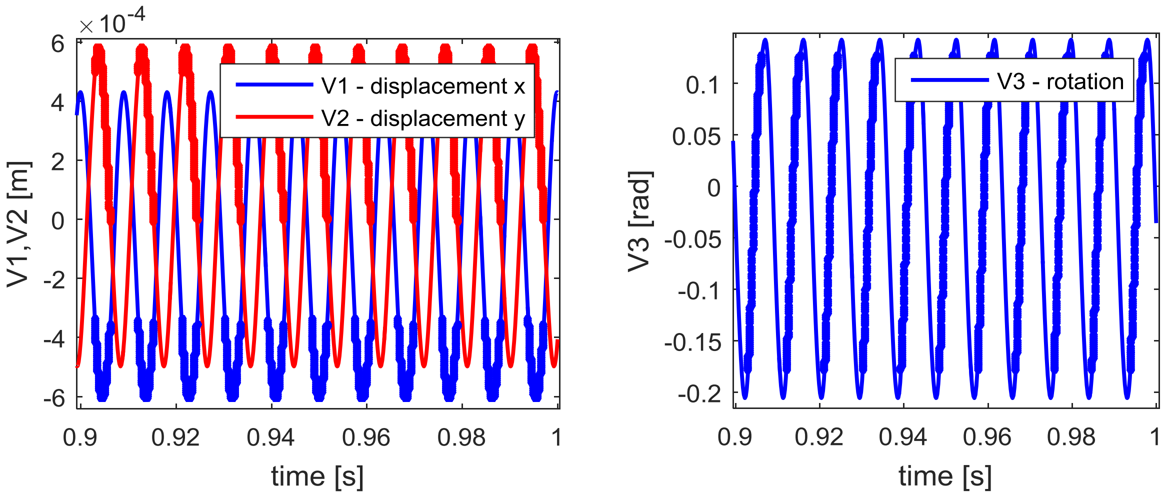

Fig. 2: Displacement and rotation vocal fold after stabilization vibration.

3. Conclusion

Single body parametric simulation model of self-exited vibration of the VF with 3 DOF was created by generalization of model (Horáček et al., 2005). VF is attached to be able to move in the longitudinal direction. Excitation consist of aerodynamics forces and hertz forces during the collision. The model shows a similar behavior as model (Horáček et al., 2005) which has good agreement with the generally acknowledged behavior of the VF. The model is not numerically consuming. Simulation takes about two times of simulation time interval on the standard office PC. The model was used for generating pressure fields for excitation more sophisticated FEM model of VF.

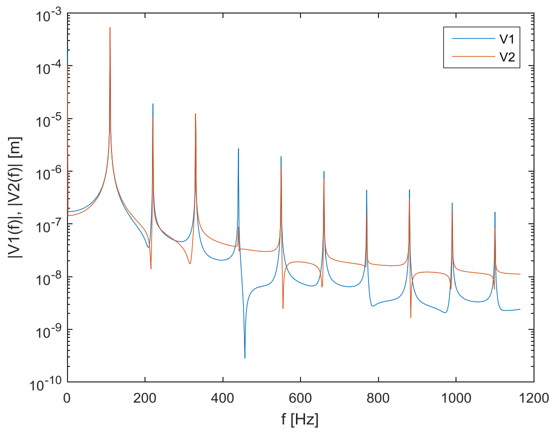

Fig. 3: Amplitude spectrum of V1 and V2.

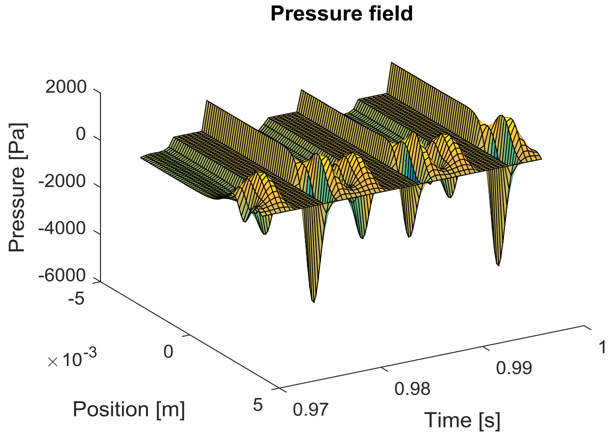

Fig. 4: Pressure field in the last three periods of vibration.

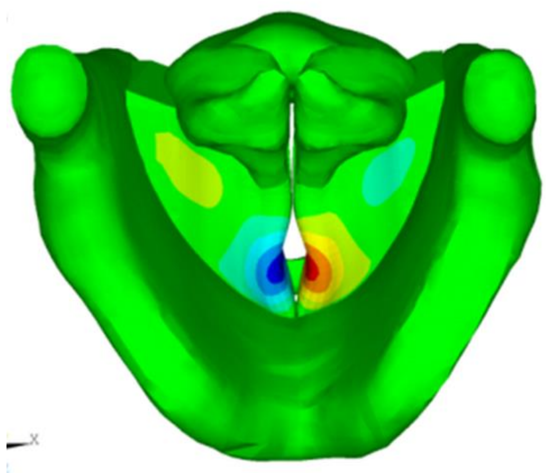

Fig. 5: Displacement field of FEM simulation.

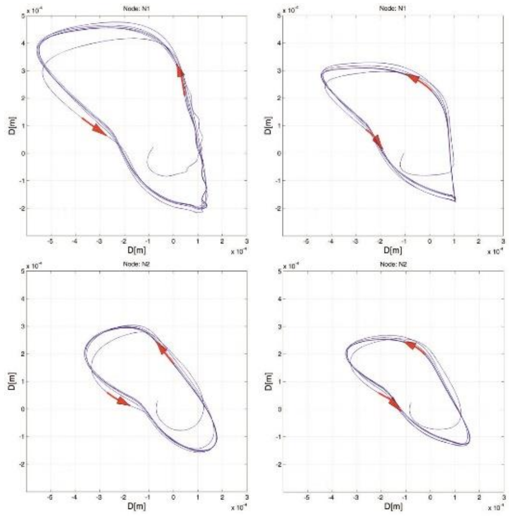

Fig. 6: Trajectories of four point from the FEM simulation.

Acknowledgement

The research is supported by the Grant Agency of the Czech Republic by project No 16-01246S “Computational and experimental modelling of self-induced vibrations of vocal folds and influence of their impairments on human voice “.

References

Fant, G. (1970) Acoustic Theory of Speech Production. 2nd edition, The Hague, Netherlands: Mounton.

Horáček, J. and Švec, J.G. (2002) Aeroelastic model of vocal-fold-shaped vibrating element for studying the phonation threshold. Journal of Fluid and Structures, Vol. 16, pp. 931-955.

Horáček, J., Šidlof, P. and Švec, J.G. (2005) Numerical simulation of self-oscillations of human vocal folds with Hertz model of impact forces. Journal of Fluids and Structures, Vol. 20, pp. 853-869.

Vampola, T., Horáček, J. and Klepáček, I. (2016) Computer simulation of muscoal waves on vibrating human vocal foolds. Biocybernetic and Biomedical Engineering, Vol. 36, Iss. 3, pp. 451-465.