26th International Conference
ENGINEERING MECHANICS 2020
Brno, Czech Republic, November 24–25, 2020

THREE-DIMENSIONAL NUMERICAL ANALYSIS OF CZECH VOWEL PRODUCTION

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Abstract: *Spatial air pressures generated in human vocal tract by vibrating vocal folds present sound sources of vowel production. This paper simulates phonation phenomena by using fluid-structure-acoustic scheme in a three-dimensional (3D) finite element model of a Czech vowel [o:]. The computational model was composed of four-layered M5-shaped vocal folds together with an idealized trachea and vocal tract. Spatial fluid flow in the trachea and in the vocal tract was obtained by unsteady viscous compressible Navier-Stokes equations. The oscillating vocal folds were modelled by a momentum equation. Large deformations were allowed. Transient analysis was performed based on separate structure and fluid solvers, which were exchanging loads acting on the vocal folds boundaries in each time iteration. The deformation of the fluid mesh during the vocal fold oscillation was realized by the arbitrary Lagrangian-Eulerian approach and by interpolation of fluid results on the deformed fluid mesh. Preliminary results show vibration characteristics of the vocal folds, which correspond to those obtained from human phonation at higher pitch. The vocal folds were self-oscillating at a reasonable frequency of 180 Hz. The vocal tract eigenfrequencies were in the ranges of the formant frequencies of Czech vowel [o:] measured on humans; during self-oscillations the formants shifted to lower frequencies.*

Keywords: Simulation of phonation, Fluid-structure-acoustic interaction, Compressible flow, Finite element method, Biomechanics of voice.

1. Introduction

When computational resources started to be affordable, three-dimensional (3D) computational modeling of human phonation gained on importance. The spatial character of air vortices in the vocal tract and the presence of a third dimension in the vocal fold geometry raised the level of the biomechanical models.

The first 3D model of self-oscillating vocal folds was created by de Oliveira Rosa et al. (2003). Interaction between fluid flow and vocal fold structure was solved using the finite element method. The results showed to be in line with the current myoelastic-aerodynamic theory of phonation (van den Berg, 1958; Titze, 2006). Acoustics was not included in the solution, however.

In most publications, the acoustic field has been solved indirectly, i.e. by using incompressible Navier-Stokes equations accompanied by some chosen acoustic analogy (see e.g. Link et al., 2009).

One of the first models, which combined self-oscillations of 3D vocal folds, 2D flow and 1D acoustics, was the computational model of Alipour and Scherer (2015). Vowel spectra, obtained by solving the wave equation, were in good agreement with the measured ones.

Using a full 3D model of phonation, Šidlof et al. (2013) demonstrated importance of the spatial geometry of the vocal tract. They showed that the spatial vortical structures generated by prescribed oscillations of

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doi: 10.21495/5896-3-182

the vocal folds are important sound sources in phonation. The fluid-acoustic interaction was described by incompressible Navier-Stokes equations together with the acoustic perturbation equations.

Direct numerical simulation (i.e. solution of the compressible Navier-Stokes equations) of phonatory events was utilized by Zhang et al. (2002). The results were in accordance with those obtained from the method of acoustic analogy. Instead of flow-induced oscillations, prescribed movements of the vocal folds were considered here, however.

Until recently, 3D compressible Navier-Stokes equations were not used for studying the flow-induced oscillation of the vocal folds. In a previous study of these authors (Švancara, 2011) the first 3D computational model of such a fluid-structure-acoustic interaction was created and applied for modelling phonation of vowel [a:]. This study employs a newly developed model for simulating of the Czech vowel [o:]. The new model is refined here by incorporating more vocal fold layers, refined finite-element mesh and air pressure as a driving parameter instead of airflow.

2. Methods

The finite-element model (Fig. 1) was created using the program system ANSYS® 15.0. The geometry of the vocal tract (upper part of the model in Fig. 1a) with the central length of 187 mm was extracted from magnetic resonance images (Vampola, 2008). The trachea (lower part of the model) was idealized to a rectangular duct of the length of 74 mm. The geometry of the vocal fold was adopted from the parametric M5 shape (Scherer, 2001) and set to have four layers (Fig. 1c). The overall size of the vocal folds, in $x \times y \times z$ directions, was 9 × 11 × 12 mm.

Fluid parts of the model were set to an isotropic viscous compressible air of 36 °C with the speed of sound 353 m·s^{-1}, density 1.205 kg·m^{-3} and fluid viscosity 1.81351×10^{-5} Pa·s. The vocal fold structures were built by homogenous isotropic linear elastic material with the density of 1040 kg·m^{-3}, Poisson's ratio 0.49 and different Young's moduli for each layer. These parameters were chosen based on Kakita et al. (1981) and Titze (2006): epithelium 25000 Pa, lamina propria 2000 Pa, ligament 8000 Pa and muscle 65000 Pa. All the layers were set to be proportionally damped with the coefficients α = 116.5279 s^{-1} and β = 0.0003 s.

The boundary conditions are shown in Fig. 1a. Open lips were modeled using a zero pressure condition. The trachea was excited by a lung pressure p_L of 165 Pa. Walls of the fluid model were made totally acoustically reflective and zero flow velocity was prescribed here. Both the vocal folds were clamped at the lateral, anterior and posterior sides (Fig. 1c).

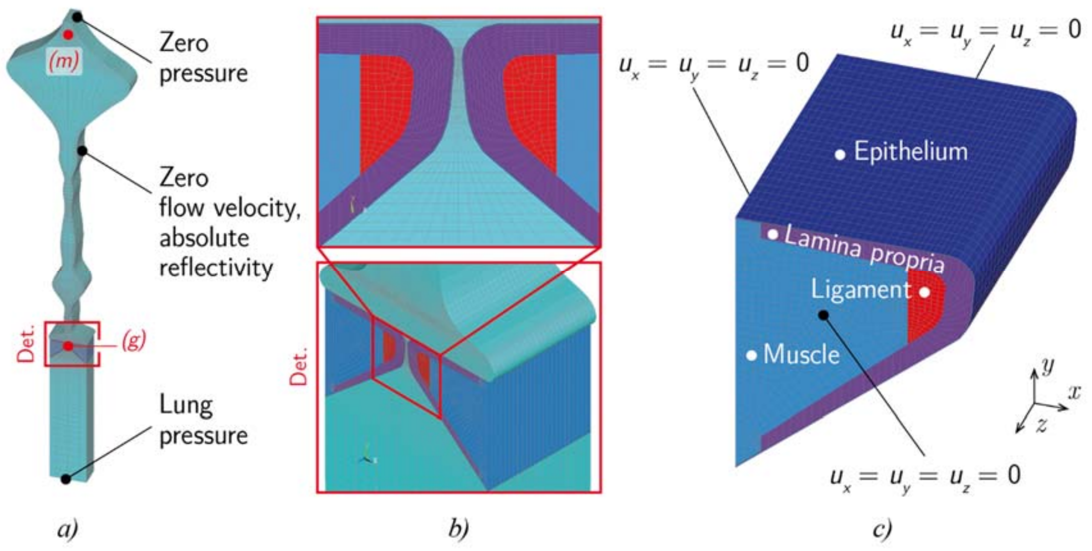

Fig. 1: a) The finite-element model of the Czech vowel [o:] with the boundary conditions (black) and evaluating points (red); b) the detail of the mesh in the glottal region, c) four-layered vocal fold structure with the boundary conditions.

The algorithm of the fluid-structure-acoustic interaction was identical with the earlier 3D and 2D models published in Švancara (2011), resp. Hájek (2016). It was designed as a transient analysis with a time step 1.5×10^{-4} s. This led to 0.1425 s of the phonation after 950 steps. The algorithm consisted of three main parts: (1) the vocal folds were adducted to a contact, (2) air pressure was incrementally increased in the trachea and (3) fluid-structure-acoustic interaction started, forcing the vocal folds to oscillate. The vocal folds were coming periodically into contact during the oscillation. This was realized by an augmented Lagrangian method implemented in ANSYS® 15.0. The fluid flow was separated during the closed (contact) phase of each oscillatory cycle.

The complete finite-element model was composed of 305664 linear fluid, structural and contact elements with 324650 nodes (see the detail of the mesh in Fig. 1b). The total time necessary to compute all steps was in the range from 15 to 40 days depending on a chosen hardware.

3. Results and Discussion

Vibration characteristics of the vocal folds were computed from the vocal fold edge waveforms (see Fig. 2a). They show stabilized periods of the vocal fold oscillation. Maximal width of the glottis W_g^{max} reached 0.31 mm, open quotient $OQ = 0.49$ and the fundamental frequency of the vocal fold oscillation was $f_o = 180$ Hz. Such small W_g^{max} and high f_o are related to the low value of the lung pressure p_L (Titze, 2006). Nevertheless, the OQ falls within an interval measured on healthy subjects (Lohscheller, 2013). Glottal airflow rate U_g (Fig. 2b) reaches the maxima around 0.45×10^{-5} $m^3 \cdot s^{-1}$. This value is approx. 8× lower compared to Alipour and Scherer (2015) and can be related to the 8× lower lung pressure used here.

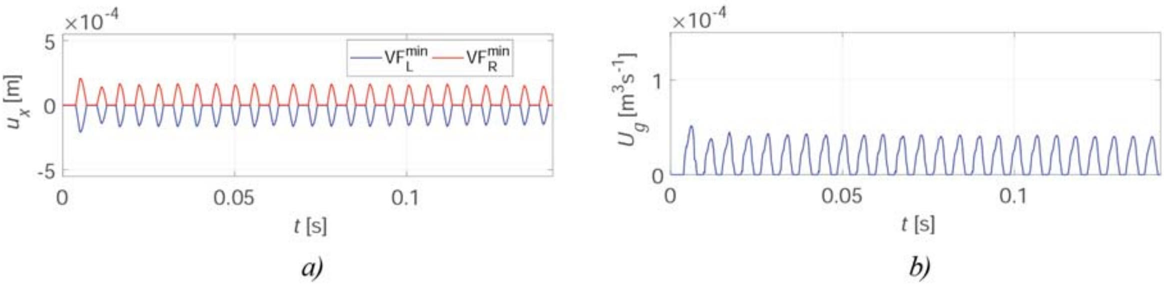

Fig. 2: Vocal fold edge waveforms u_x from the most medial point in frontal plane and b) glottal airflow rate U_g evaluated in the cross-section at the point (g) shown in Fig. 1.

The acoustic results are depicted in Fig. 3. The first two eigenmodes of the acoustic pressure are shown in Fig. 3a and 3b. Natural frequencies corresponding to these modes were within the range of formant frequencies for the Czech vowel [o:] measured by Skarnitzl and Volín (2012). For the flow-induced phonations, the frequencies of the dominant harmonic peaks, which should be in the neighborhood of formants F_1 and F_2 (circled in Fig. 3c), were lower compared to the measured eigenfrequencies, probably because of the vocal fold-vocal tract interactions (Titze, 2008).

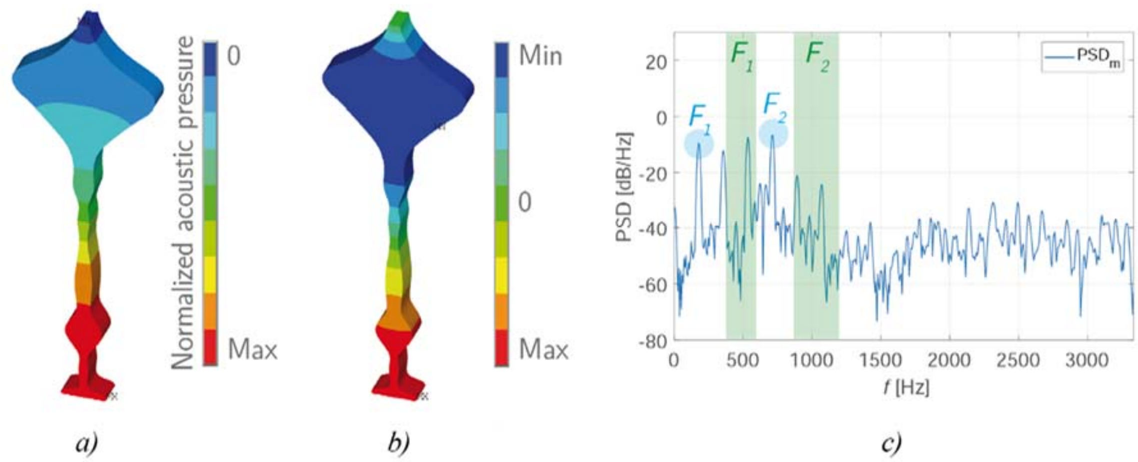

Fig. 3: a) The first eigenmode of the acoustic pressure in the vocal tract cavity with the eigenfrequency of 518 Hz; b) the second eigenmode with the eigenfrequency of 929 Hz; c) power spectral density of the pressures evaluated in point (m) (recall Fig. 1). The dominant harmonics which should be in neighborhoods of the formants F_1 and F_2 are encircled in blue. The formant frequencies measured by Skarnitzl and Volín (2012) in Czech speakers are indicated in green.

4. Conclusions

The fundamental frequency of the vocal fold oscillation f_o = 180 Hz corresponds to a slightly raised male or female comfortable voice (Titze, 2006). The computational model of the vowel [o:] production shows similarities with normal human phonation also in the open quotient OQ or natural frequencies of the vocal tract. Some results were affected by the lung pressure p_L, which was rather low than the pressures reported during normal phonation (Titze, 2006) in order to avoid an undue fluid mesh distortion in the glottal region. The low p_L value resulted in a low glottal flow U_g and low glottal width W_g^{max}. The first two eigenfrequencies of the vocal tract corresponded to the expected formant frequencies F_1 and F_2 for vowel [o:] (Skarnitzl and Volín, 2012). During self-oscillation these formants shifted to lower frequencies, which is likely due to nonlinear interaction effects. The presented 3D model of phonation reveals phenomena related to the both-way fluid-structure-acoustic interaction, which can be captured only by using the compressible Navier-Stokes equations.

Acknowledgement

This work was supported by Czech Science Foundation project No. 19-04477S and by project of Faculty of Mechanical Engineering, Brno University of Technology FSI-S-20-6175. Access to computing and storage facilities owned by parties and projects contributing to the National Grid Infrastructure MetaCentrum provided under the programme CESNET LM2015042, is greatly appreciated.

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