19th International Conference
ENGINEERING MECHANICS 2013
Svratka, Czech Republic, May 13 – 16, 2013

FINITE ELEMENT MODELLING OF SOUND PRESSURE AROUND THE HUMAN HEAD DURING PHONATION

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Abstract: *The study presents finite element (FE) model of sound propagation through the vocal tract and around the human head during speech production. Similar experimental studies are not easily realisable. The FE model of the acoustic spaces corresponding to the human vocal tract for Czech vowel [a:] and acoustic space around the human head was created from computer tomography (CT) images. Modal and transient analyses (excitation by a short pulse) are used for analysis of resonant characteristics of the FE model. The production of vowel is then simulated using transient analysis of the FE models excited by Liljencrants-Fant's (LF) glottal signal model. Formant frequencies detected from computed spectra are in good agreement with results of modal analysis and with literature. The results of numerical simulation enable evaluating of the transfer functions between a reference point and any point in the space around the head.*

Keywords: ***biomechanics of voice, finite element method, sound pressure level, human head model.***

1. Introduction

The sound pressure field around the human head during speech were experimentally studied in several papers (Dunn & Farnsworth, 1939; Halkosaari et al., 2005; Sugiyama, 1991). Knowledge of sound waves transformation during propagation around the head is important for calibration of microphones for speech and singing recordings, and for development of exact voice measurement methods. The aim of this study is to numerically simulate propagation of acoustic waves from vocal folds through the vocal tract and around the human head using the FE method. Advantage of numerical simulation is possibility of use various waveforms for excitation of vocal tract and stationary boundary conditions (not affected by experimental subject movement or voice loudness or pitch change during measurement). The FE models of the vocal tract for Czech vowel [a:] and the acoustic spaces around the head were developed from CT images taken during the subject phonation. For segmentation of images freeware software ITK-SNAP was used (Švarc, 2012). Fig. 1 shows an example of part of the head model created from the CT images. The geometry was exported to CAD programs CATIA and ATOS where the geometry was repaired and smoothed. The geometries of the vocal tract and the human head before and after smoothing are shown in Fig. 2. Because a top part of the head was missing in the CT images, it was necessary to complete this part manually using the software ATOS. Fig. 3 shows a complete geometry of the human head created from the CT images with manually modelled top of the head. After that a model of acoustic space between the head surface and a sphere of radius one meter around the head was created.

2. Finite element model

The FE meshing was performed by the program package ICEM CFD. The mesh was then exported to the software system ANSYS 14.0 where the acoustic modal and transient analyses were realized.

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The created FE mesh of the surface of human head and detail of cross-section through the designed FE model are shown in Fig. 4. The complete FE model consists of 674 480 acoustic elements. Created mesh fulfils the requirement of six elements per one wavelength up to the frequency 5000 Hz. For modelling the acoustic radiation into an infinite acoustic space a single layer of infinite elements was added onto the outer surface of the sphere. The infinite elements are based on an infinite geometry mapping and on special shape functions.

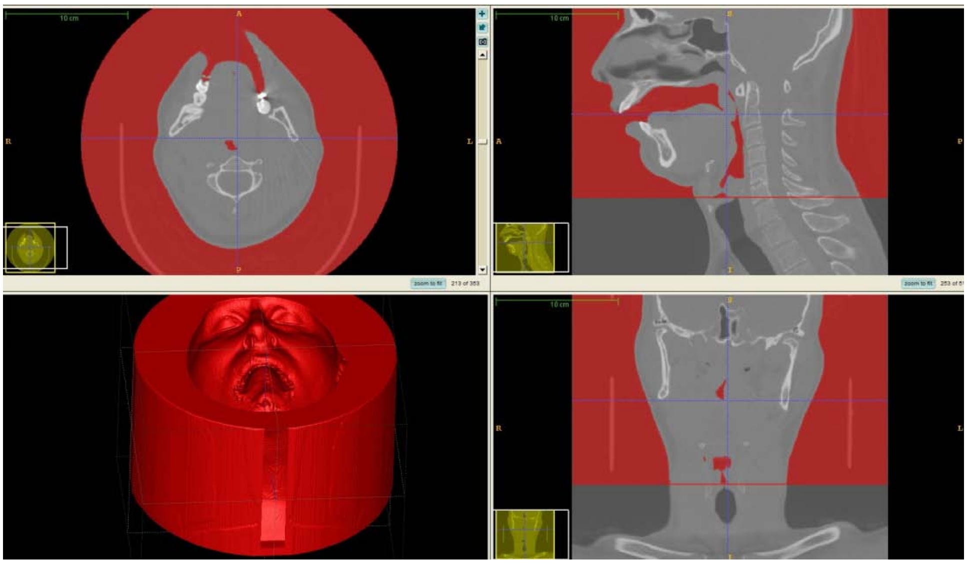


Fig. 1: Part of the human head model created from the CT images using the software ITK-SNAP.

For the air material properties: speed of sound c_0 = 353 ms^{-1} and the density ρ_0 = 1.2 kgm^{-3} was assumed. Boundary walls of the vocal tract, skin of the face and hairs were considered acoustically absorptive. The frequency constant normal impedance Z = 83 666 kgm^{-2}s^{-1} was assumed for the vocal tract (Švancara & Horáček, 2006) and the sound absorption coefficient α=0.03 for skin of the human face and α=0.4 for hair (Katz, 2000).

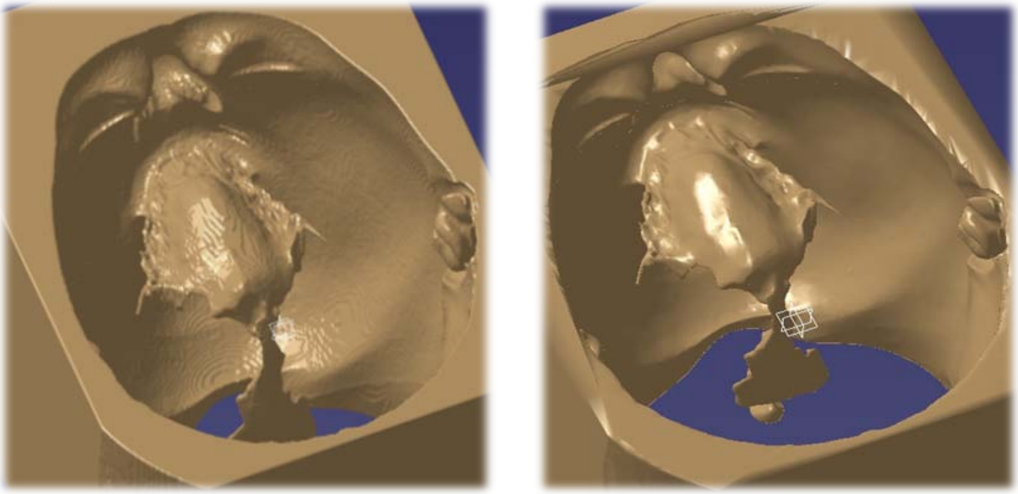


Fig. 2: Geometry of the human vocal tract and head before (left) and after the smoothing procedure using the software CATIA *(right).*

3. Mathematical formulation

Wave equation for the acoustic pressure *p* can be written as

$$\frac{\partial^2 p}{\partial t^2} = c_0^2.\nabla^2 p = c_0^2.div\ \vec{grad}\ p = c_0^2.\left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2}\right), \tag{2}$$

where c_0 is the speed of sound, t is the time and ∇^2 is Laplace operator, and after discretization using the finite element method as

$$\mathbf{M}\,\ddot{\mathbf{p}}+\mathbf{C}\,\dot{\mathbf{p}}+\mathbf{K}\,\mathbf{p}=\mathbf{f}\left(t\right), \tag{2}$$

where **M** is the acoustic mass matrix, **C** is the acoustic damping matrix, **K** is the acoustic stiffness matrix, **p** is the vector of nodal acoustic pressures and **f** is the vector of nodal acoustic forces. The Newmark integration scheme was used for solution of Eq. (1) in time domain.

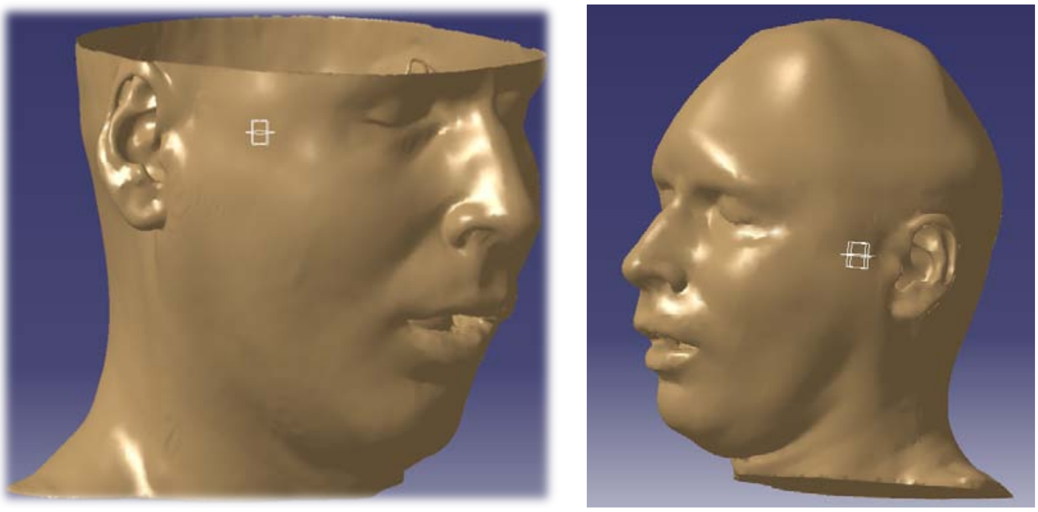


Fig. 3: Geometry of the human head created from CT images (left) and with manually modelled top of the head (right).

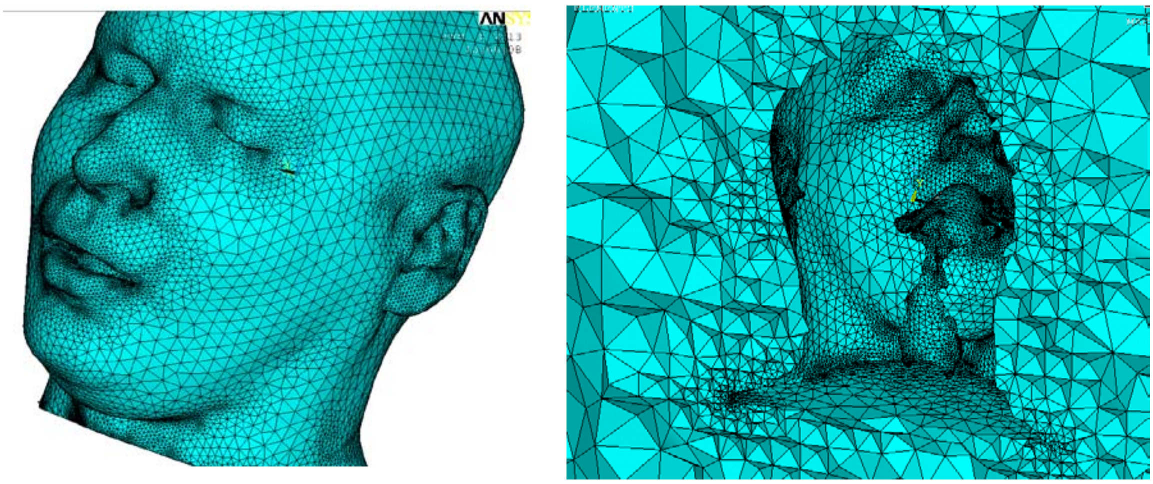


Fig. 4: Details of the FE mesh of surface of the human head (left) and detail of cross-section through the designed FE model (right).

4. Resonant frequencies analysis

Two methods for analysis of acoustic resonant frequencies (formants) were used. At first, the resonance frequencies of the FE model of the vocal tract without the acoustic space around the head were computed by the modal analysis, with zero acoustic pressure prescribed on the open area at the lips and no absorption on the walls. The computed acoustic mode shapes for first three resonant frequencies are shown in Fig. 5. The formants are in good agreement with the experimental data known from literature for phonation on vowel [a:] (Palková, 1994).

Then the resonant frequencies of the complete FE model (with acoustic space around the head, infinite elements and absorption on walls) were computed by transient analysis in time domain. The FE model was excited by a very short triangular pulse of differential glottal flow (see Fig. 6) defined at the faces of FE elements in position of the vocal folds. The spectrum of this pulse (also shown in Fig. 6) is sufficiently flat in analyzed the frequency range 0 - 5000 Hz, at least for the purpose of this pilot study.

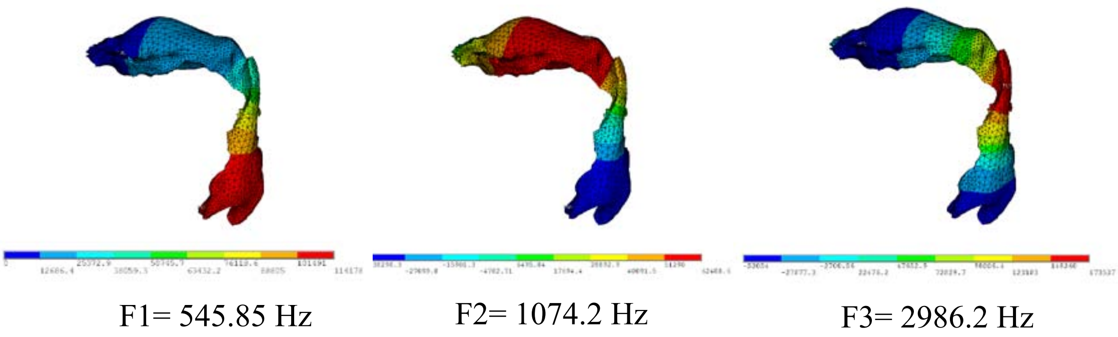


Fig. 5: Computed acoustic mode shapes for first three resonant frequencies of the vocal tract.

The time response computed for the complete FE model at a point near the lips is shown in Fig. 7 together with the corresponding spectrum. The formant frequencies clearly detectable in the spectrum are close to the eigenfrequencies computed by the modal analysis of the vocal tract (recall Fig. 5).

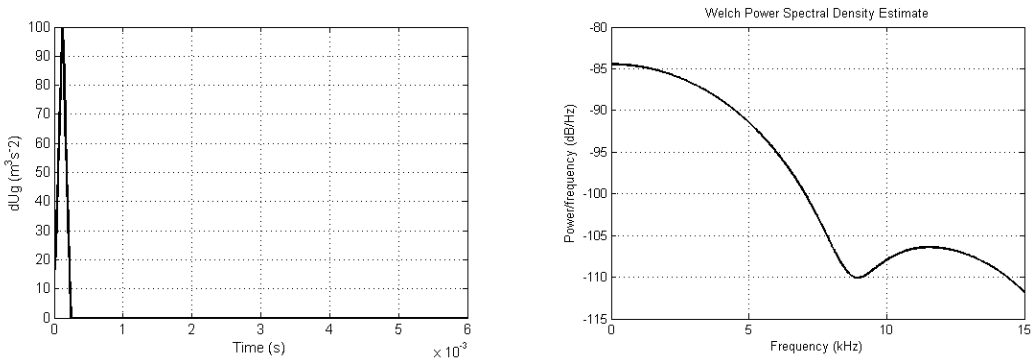


Fig. 6: Triangle pulse of differential glottal flow used for excitation of the model (left) and corresponding spectrum (right).

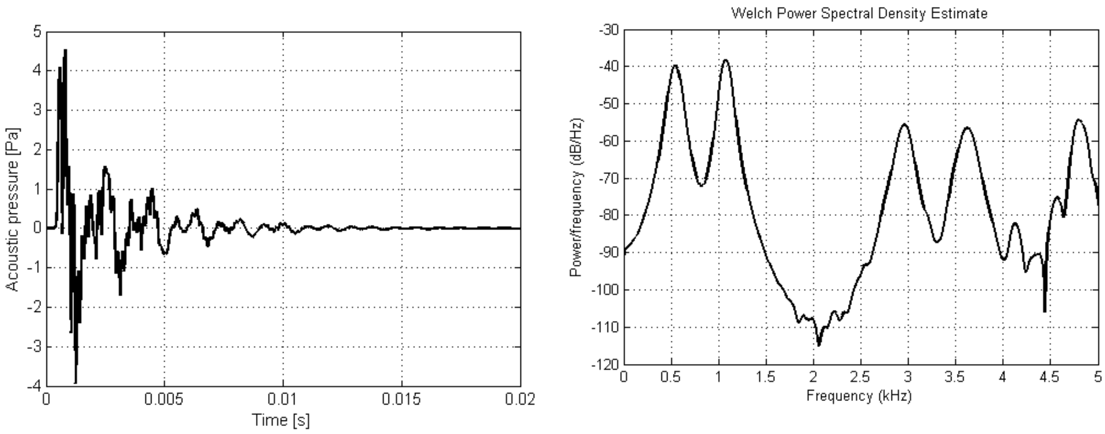


Fig. 7: Computed sound pressure at a point very near the lips (left) and corresponding spectrum (right).

Computed sound pressure at a point 10 cm in front of the lips and corresponding spectrum are shown in Fig. 8. The sound pressure level is substantially lower than in previous case and the numerically simulated signal is noisier in the frequency range above 1.5 kHz.

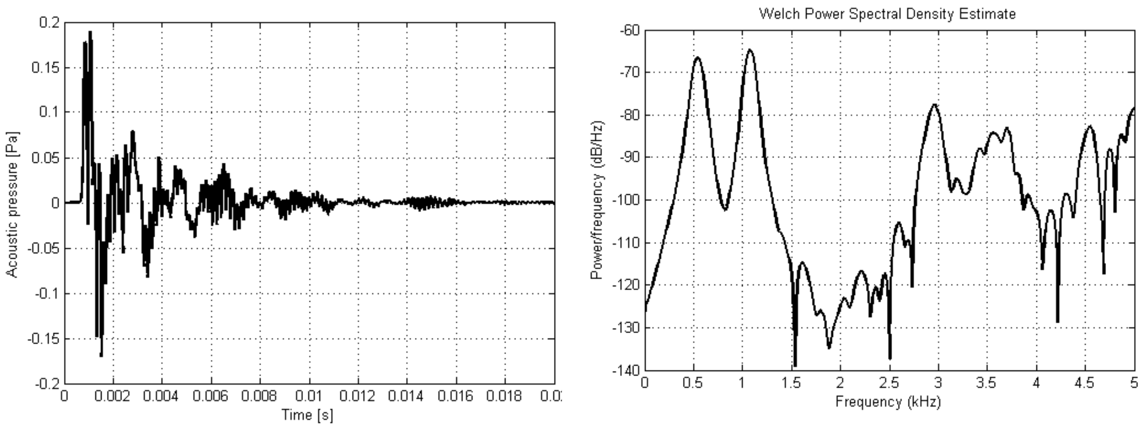


Fig. 8: Computed sound pressure at a point 10 cm in the front of the lips (left) and corresponding spectrum (right).

The transfer function between a reference point near lips (numerically simulated signal *x*) and any individual point in the space around the head (signal *y*) could be evaluated from the computed signals as

$$T_{xy} = \frac{G_{xy}(f)}{G_{xx}(f)} = \frac{G_{yy}(f)}{G_{yx}(f)} \tag{3}$$

where $G_{xy}(f)$ is the estimated cross-spectrum of signals and $G_{xx}(f)$ is the estimated autospectrum calculated for the signal itself. Example of transfer functions computed between the sound pressure at a point near the lips and the points 2.5 cm and 10 cm in front of the lips are shown in Fig. 9.

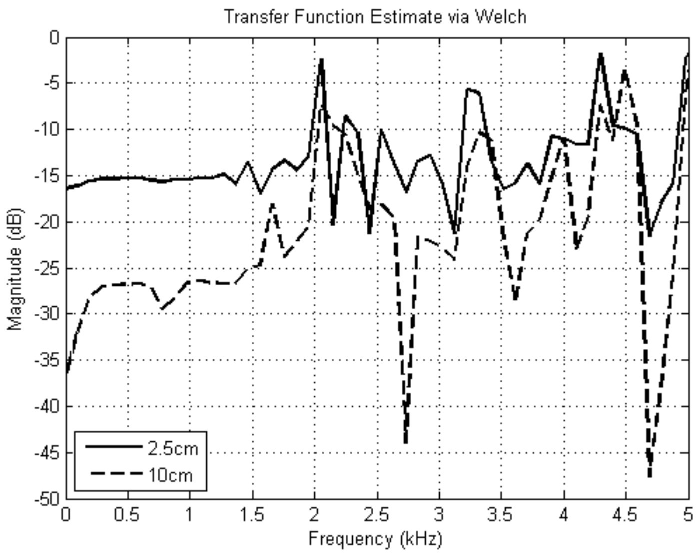


Fig. 9: Transfer functions between the sound pressure at a point near the lips and the points at 2.5 cm (solid line) and 10 cm (dashed line) distances in front of the lips.

5. Simulation of vowel phonation

For simulation of vowel production the FE model was excited at the faces of FE elements in a position of vocal folds by Liljencrants-Fant's (LF) glottal signal model (Fant et al., 1985). The solution was realised in time domain by the transient analysis within the software ANSYS 14.0 with the time step $\Delta t = 5.10^{-5}$ s. Ten subsequent pulses of differential glottal flow were used with the fundamental frequency *F0* = 100 Hz. The first three periods of time derivative of the glottal flow waveform used for excitation are shown in Fig.10 together with the corresponding spectrum.

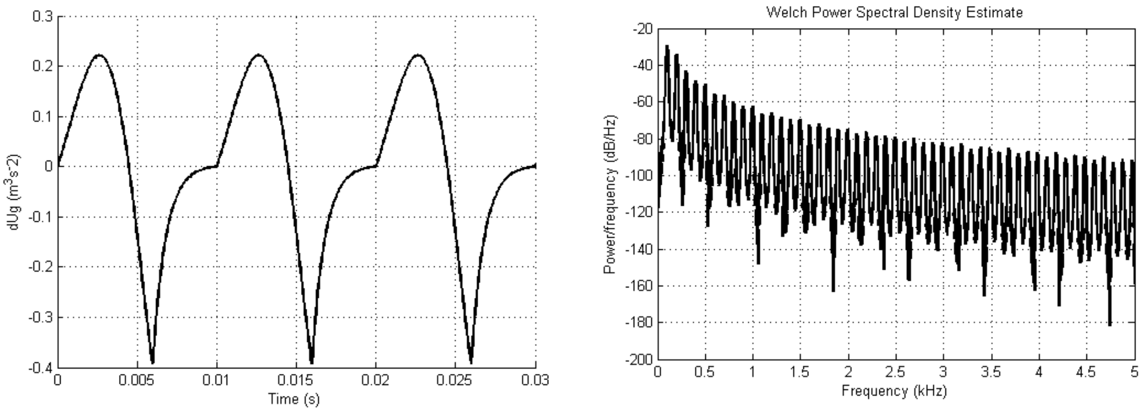


Fig. 10: First three periods of glottal flow derivative used for the vocal tract excitation (left) and corresponding spectrum (right).

The numerically simulated sound pressure at the distance 10 cm and 30 cm in front of the lips and its spectrum are shown in Fig. 11. The formant frequencies detectable from the calculated spectra of the sound pressure in front of the lips are close to the resonant frequencies computed by the modal analyses.

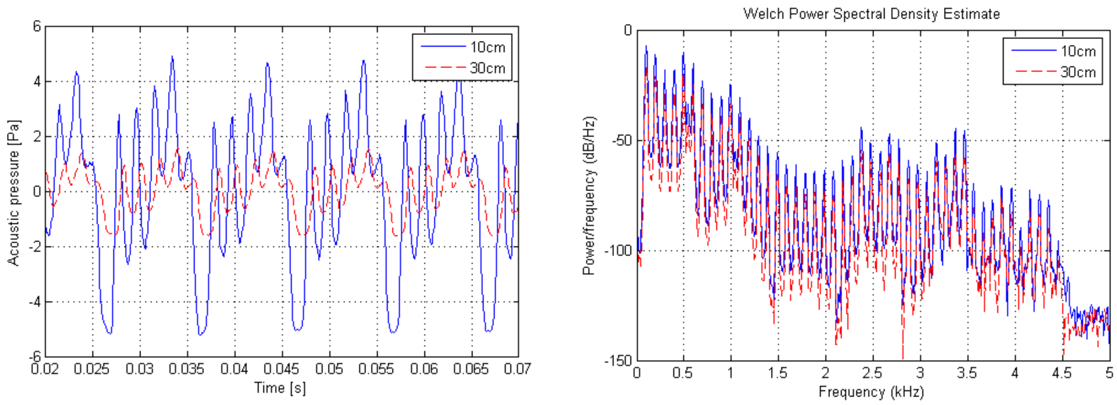
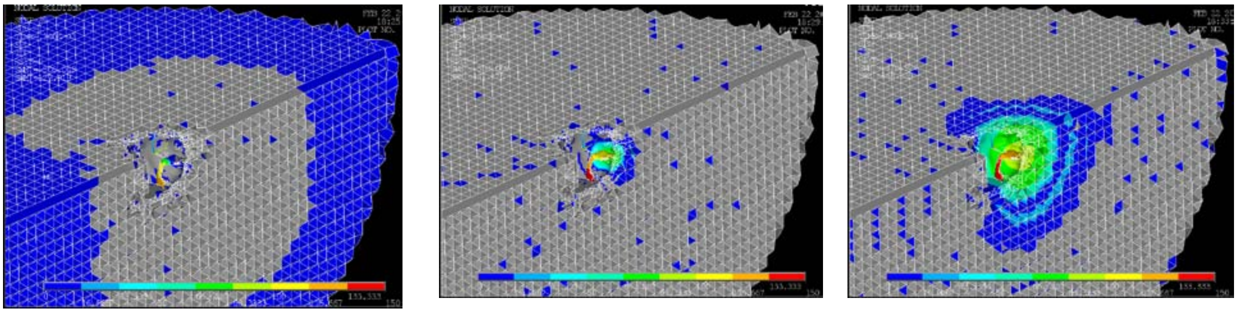


Fig. 11: Sound pressure computed 10 cm and 30 cm in the front of the lips (left) and corresponding spectrum (right).

The results could be used for evaluation of the transfer functions between a reference point and points around the head, where the microphones are usually placed (in front of the lips, cheek bone, forehead etc.). The time domain solution allows creating audio files for a checking of the quality of sound at different points by listening. The results could also enable to create directivity diagrams for different distances from the lips. The computing time per oscillation period for this model with 674 480 elements is approximately 4 hours on two Intel Xeon E5520 (8 cores/16 threads) and model creates rather big database (1.7 TB). Because the created FE model contains detailed geometry of the pinna the numerical simulations could be eventually used for evaluation of head related transfer functions -HRTFs (see Katz, 2000) between point sources around the head and left or right ear. Fig. 12

shows the computed sound pressure at three time instants during triangle pulse excitation in a cross-section through the designed FE model.



t=0.0003s t=0.0006s t=0.0009s

Fig. 12: Computed sound pressure at three time steps during triangle pulse excitation (0.0003-0.0009s).

6. Conclusions

The finite element model of the acoustic cavities corresponding to the human supraglottal spaces for vowel [a:] and incorporating the acoustic spaces around the human head was created from computer tomography (CT) images. The formant frequencies of the FE model were evaluated by modal analysis of vocal tract and by excitation of the complete FE model by a short pulse of glottal airflow. Results of both methods are similar and are in good agreement with data in literature. Phonation on vowel [a:] was numerically simulated using the Liljencrants-Fant's (LF) glottal source signal model applied at the position of vocal folds and using the transient analysis in time domain.

The transfer functions between a reference point at the lips and any point in the space around the head could be evaluated from the results of numerical simulations, for example in the points where the measurement microphones are usually placed. The time domain solution allows creating sound files for verification of the quality of numerically produced sound at different points around the head by listening. This pilot study should also enable to simulate sound waves propagation around the human head during phonation with applications in modelling the hearing of own voice by the air conduction.

Acknowledgement

This research is supported by the Grant Agency of the Czech Republic by the project No P101/12/1306 and by the European Social Fund Projects OP VK CZ.1.07/2.4.00/17.0009.

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