NUMERICAL MODELLING OF EFFECT OF TONSILLECTOMY ON PRODUCTION OF CZECH VOWELS /A/ AND /I/

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Abstract: **Aim of this study is to numerically examine the effect of tonsillectomy on production of Czech vowels /a/ and /i/. Similar experimental studies are not easily realisable on living subjects. The finite element (FE) models of the acoustic spaces corresponding to the human vocal tract for the Czech vowels /a/ and /i/ and acoustic space around the human head are used in numerical simulations of phonation. The acoustic resonant characteristics of the FE models are studied using modal and transient analyses (excitation by a short pulse). The production of vowels is simulated in time domain using transient analysis of FE model excited by Liljencrants-Fant's (LF) glottal signal model. Calculated results show that tonsillectomy causes significant frequency shifts down to lower frequencies for 2nd (down by ~40Hz) and 4th (down by ~120Hz) formants for the vowel /a/, and similar shifts for 2nd (down by ~100Hz) and 4th (down by ~50Hz) formants for the vowel /i/. The frequency shifts of formants after tonsillectomy significantly depends on position and size of the tonsils.**

I. INTRODUCTION

The effects of tonsillectomy on the voice production were experimentally studied in several papers [1, 2]. Their main drawback is that the patients are not able to repeat the same manner of voice production during experiment before and after tonsillectomy. The results can be evaluated statistically only. Numerical modelling of this problem is not limited by these difficulties.

In the previous papers of the authors [3-5] acoustic characteristics of the human vocal tract of a healthy man and a man with velofaryngeal insufficiency were studied by FE modelling. Here, the FE models are used to examine the effect of tonsillectomy on production of Czech vowels /a/ and /i/. The FE models of the acoustic spaces of the vocal tract were created using magnetic resonance imaging technique. The FE mesh of a hollow sphere, representing an acoustic space around the human head, was added manually to the FE model of the vocal tract. The designed FE model is shown in Fig. 1. A single layer of infinite elements was matched onto the FE mesh of the outer surface of the sphere, for modelling the acoustic radiation into the infinite acoustic space. The infinite elements are based on an infinite geometry mapping, extending the elements to infinity, and on special shape functions.

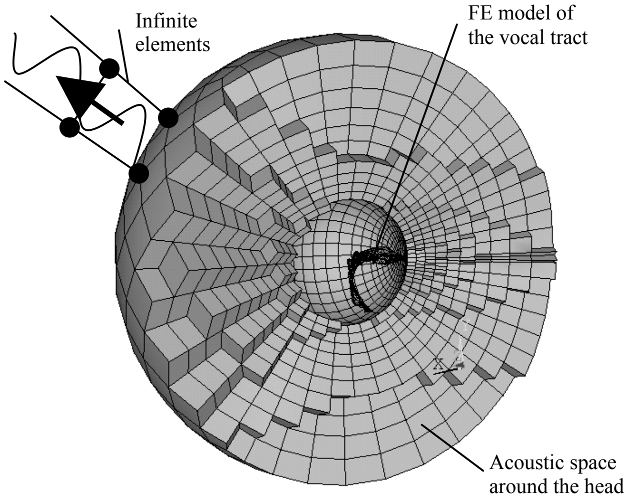

Fig. 1: FE model of the vocal tract for the vowel /a/ including an acoustic space around the human head.

The FE models were modified by adding acoustic spaces that arise in the vocal tract after tonsillectomy, see Fig. 2. Three basic FE models were created for each vowel, one for the vocal tract with tonsils, and two FE models for the vocal tract after tonsillectomy with added acoustic space 1.5 cm^3 per one tonsil and with a reduced volume 0.7 cm^3 per one tonsil considering a constriction of living tissue after operation.

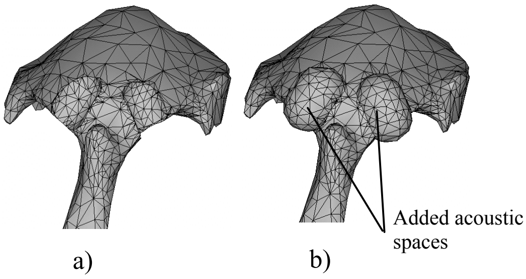

Fig 2: Detail of FE model of the vocal tract for the vowel /a/ a) vocal tract with tonsils b) vocal tract after tonsillectomy.

II. MATHEMATICAL FORMULATION

Wave equation for the acoustic pressure can be written as

$$\nabla^2 p = \frac{\partial^2 p}{c_0^2 \partial t^2}, \tag{1}$$

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where c_0 is the speed of sound, with boundary conditions as follows

- on acoustically hard area $\partial p / \partial \mathbf{n} = 0$,
- on acoustically absorptive area a normal impedance $Z = p / v_n$ can be prescribed,

where **n** is the normal to the boundary area and v_n is normal velocity.

Equations of motion after discretization can be written as

$$\mathbf{M}\,\mathbf{p}(t)+\mathbf{C}\,\mathbf{p}(t)+\mathbf{K}\,\mathbf{p}(t)=\mathbf{f}(t), \qquad (2)$$

where **M**, **C**, **K** are mass, damping and stiffness matrices, **p** is the vector of nodal acoustic pressures and **f** is the vector of nodal acoustic forces. Newmark integration method was used for solution in time domain.

The acoustic transient and modal analysis were realized by the software code SYSNOISE 5.5 considering the speed of sound c_0 = 353 ms^{-1} and the air density ρ_0 = 1.2 kgm^{-3}. Boundary walls of the vocal tract were considered acoustically absorptive with normal impedance Z = 83 666 $\mathrm{kgm}^{-2}\mathrm{s}^{-1}$ assuming for the soft tissue the Young modulus E = 5 MPa and density _ = 1400 kgm^{-3} [6].

III. FREQUENCY MODAL AND RESONANT CHARACTERISTICS

Firstly the eigenfrequencies of the FE models of the vocal tract without the acoustic space around the head were studied using modal analysis, assuming zero acoustic pressure at the nodes belonging to the area of the lips and acoustically hard boundary walls. Calculated formant frequencies for both vowels and all three FE models are summarized in Table 1.

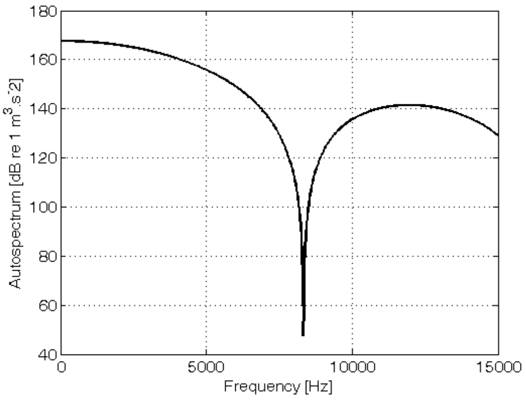

Fig. 3: Spectrum of the excitation pulse.

Then the resonant characteristics of the FE models with acoustic space around the head, infinite elements and absorption on the vocal tract walls were computed by transient analysis in time domain. The FE models were excited by a very short pulse of differential glottal flow (duration 0.25 ms) at the faces of FE elements in position of the vocal folds. The spectra of the excitation pulse and the sound pressure calculated near the lips are shown in Figs. 3 and 4, respectively. The evaluated acoustic resonant frequencies were close to the formant frequencies obtained by the modal analysis.

Table 1: Calculated resonant frequencies.

<table>
<tr><th colspan="6">Vowel /a/</th></tr>
<tr><th>formant</th><th>With tonsil. [Hz]</th><th>After tonsill. [Hz]</th><th>Diff. [Hz]</th><th>After tonsill. reduced vol. [Hz]</th><th>Diff. [Hz]</th></tr>
<tr><td>F1</td><td>678</td><td>683</td><td>5</td><td>686</td><td>8</td></tr>
<tr><td>F2</td><td>1177</td><td>1137</td><td>-40</td><td>1150</td><td>-27</td></tr>
<tr><td>F3</td><td>2869</td><td>2875</td><td>6</td><td>2904</td><td>35</td></tr>
<tr><td>F4</td><td>4113</td><td>3992</td><td>-121</td><td>4038</td><td>-75</td></tr>
<tr><td>F5</td><td>4286</td><td>4308</td><td>22</td><td>4312</td><td>26</td></tr>
<tr><td>F6</td><td>4442</td><td>4494</td><td>52</td><td>4492</td><td>50</td></tr>
<tr><th colspan="6">Vowel /i/</th></tr>
<tr><th>formant</th><th>With tonsil. [Hz]</th><th>After tonsill. [Hz]</th><th>Diff. [Hz]</th><th>After tonsill. reduced vol. [Hz]</th><th>Diff. [Hz]</th></tr>
<tr><td>F1</td><td>258</td><td>248</td><td>-10</td><td>251</td><td>-7</td></tr>
<tr><td>F2</td><td>2374</td><td>2267</td><td>-107</td><td>2307</td><td>-67</td></tr>
<tr><td>F3</td><td>3188</td><td>3213</td><td>25</td><td>3198</td><td>10</td></tr>
<tr><td>F4</td><td>3809</td><td>3763</td><td>-46</td><td>3794</td><td>-15</td></tr>
<tr><td>F5</td><td>4778</td><td>4722</td><td>-56</td><td>4741</td><td>-37</td></tr>
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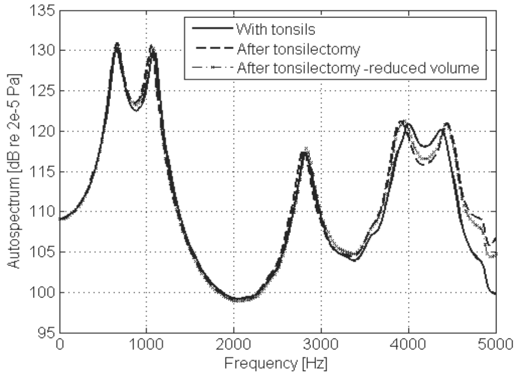

Fig. 4: Spectrum of the pressure response near the lips for the vowel /a/.

Results calculated by both methods for FE models with the tonsils are in good agreement with experimental data known for formants of the Czech vowels /a/ and /i/ [7, 8]. Tonsillectomy for the vowel /a/ caused the biggest decrease of formants F2 and F4 of about 40 Hz and 120 Hz, respectively. And for vowel /i/, the tonsillectomy caused the biggest frequency shift down of about 100 Hz for the formant F2, and about 50 Hz for the formants F4 and F5. For the model with consideration of constriction of tissue after operation the frequency shifts of the formants are approximately two times smaller. We should note that the eigenfrequency F5 for the vowel /a/ is associated with a lateral acoustic mode shape of vibration in the horizontal direction.

As a next step a sensitivity of formants frequency shift on the position and size of tonsils were examined. Firstly, a penetration of the volumes of the tonsils and the vocal tract was changed, i.e., the portion of tonsil volume interference with the acoustic space of the vocal tract. Three cases of tonsil-vocal tract volume interference were considered: 1/2 (this case was used in previous calculations), 3/4 and 1/4. The results are summarized in Fig. 5.

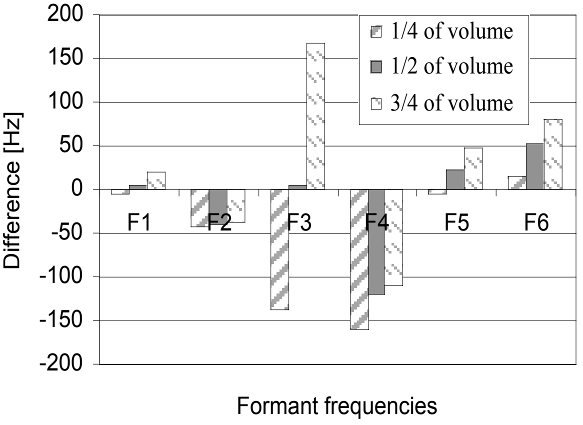

Fig. 5: Difference of formant frequencies before and after tonsillectomy for different positions of tonsils for the vowel /a/.

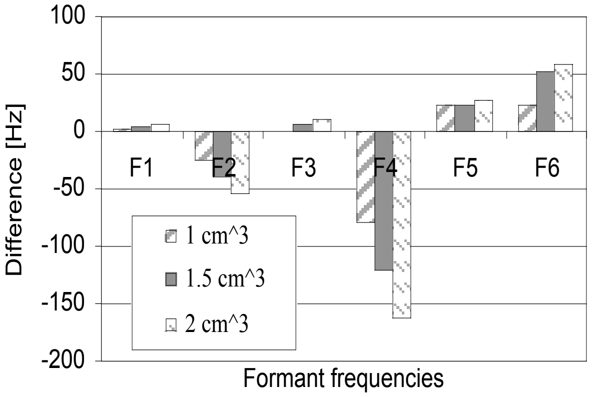

Fig. 6: Difference of formant frequencies before and after tonsillectomy for different size of tonsils for the vowel /a/.

Then for case of 1/2 of the tonsil-vocal tract volume interference, the volume of the tonsils was varied, and again three cases were analyzed for the tonsil volumes 1.5 cm^3 (as in the previous calculations), 2 cm^3 and 1 cm^3 per one tonsil. The obtained differences in formant frequencies are shown in Fig. 6.

The results show that some formant frequencies are very sensitive to the change of position and size of the tonsils. For example, the difference in formant frequency F3 for the vowel /a/ changed from -137 Hz to +168 Hz with changing the portion of the tonsil volume interference with the acoustic space of the vocal tract. The frequency changes of the most formants are more or less proportional to the size of the tonsils.

IV. NUMERICAL SIMULATION OF PRODUCTION OF VOWELS

The production of the vowels was simulated using transient analysis of FE model in time domain with excitation by Liljencrants-Fant's (LF) glottal signal model [9]. The LF model describes differentiated airflow in time domain. Each fundamental period of the glottal signal can be expressed as

$$\frac{dU_g(t)}{dt} = \begin{cases} E_0 e^{\alpha t} \sin\omega_g t & , \; 0 \le t < t_e \\ -\dfrac{E_e}{\varepsilon t_a}\left(e^{-\varepsilon(t-t_e)} - e^{-\varepsilon(t_c-t_e)}\right) & , \; t_e \le t < t_c \end{cases} , \qquad (3)$$

where t is in the range $[0,t_c]$, t_c is equal to the fundamental period T_0. The so-called waveshape parameters t_p, t_e, t_a, and E_e together with T_0 completely determine the shape of differential flow $dU_g(t)$. Figure 7 illustrates these waveshape parameters. Here, the following normalized parameters derived from the waveshape parameters were used:

- R_a the ratio of t_a to t_c-t_e ,
- R_k the ratio of t_e-t_p to t_p ,
- R_g the ratio of half fundamental period $T_0/2$ to t_p.

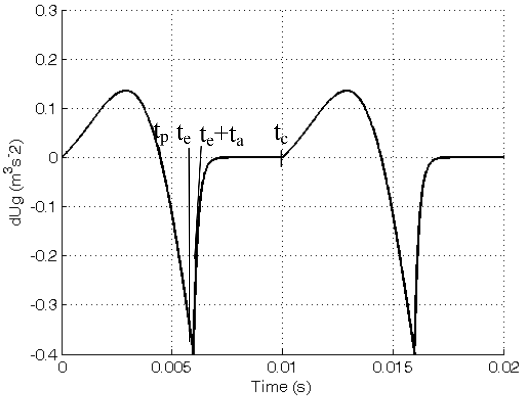

Fig. 7: Derivative glottal flow wave shape used for acoustic excitation of the vocal tract.

The parameters corresponding to a normal phonation were used (R_a = 0.05 ms, R_k = 0.34, R_g = 1.12, E_e = 0.4 m^{3}s^{-2}). The FE models were excited at the faces of FE elements in position of vocal folds by fifteen subsequent pulses of differential glottal flow with the period corresponding to the fundamental (pitch) frequency $F0$ = 100 Hz. The numerical solution was realised by the transient analysis within the software SYSNOISE with the time step $\cap t = 1.10^{-5}$ s. The time responses – sound pressures and their spectra were calculated at distance 0.2 m in front of the lips (see the example in Fig. 8).

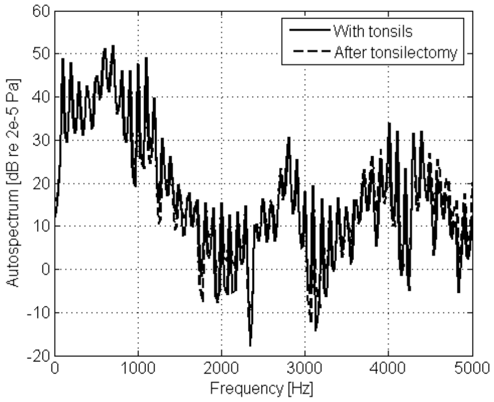

Fig. 8: Spectra of the calculated sound pressure at the distance 0.20 m in front of the lips for the vowel /a/ before and after tonsillectomy.

IV. DISCUSSION

Formant frequencies after tonsillectomy determined from the calculated spectra of the sound pressure near the lips show the same frequency shifts as results of the modal analysis. Solution in the time domain allows creating sound (audio) files for an acoustic checking of the quality of numerically produced vowels by listening. To achieve longer time duration of the sound files, the computed time sequences of sound pressure are repeated many times. Comparison of these sound files for the models with and without the tonsils shows a different colour of the phonated vowels. For the models with consideration of constriction of tissue after operation (reduced tonsil volume) the differences between the sounds before and after the tonsillectomy are not nearly audible.

V. CONCLUSION

Finite element (FE) models of the acoustic spaces corresponding to the human vocal tract for the Czech vowels /a/ and /i/ incorporating the acoustic spaces around the human head was created and the production of these vowels was simulated using the transient analysis in time domain with Liljencrants-Fant's (LF) glottal signal model. Designed FE models allow observing radiation of acoustic waves from the lips to the outer acoustic space. The time domain solution allows creating sound files for verification of the quality of numerically produced vowels by listening. This methodology can be used for an on-line subjective evaluation of the effects of tonsillectomy on the human voice production.

The formant frequencies evaluated from the calculated spectra of the acoustic pressure near the lips correspond well with the results of the performed acoustic modal analysis. The formants F2, F4 for the vowel /a/, and formants F2, F4 and F5 for the vowel /i/ are significantly lowered by the tonsillectomy. For the vowel /a/, the formant F2 was shifted down to the lower frequencies by 40 Hz and the formant F4 by 121 Hz. For the vowel /i/, the formant F2 was decreased by 107 Hz and formants F4 and F5 were shifted down of about 50 Hz. However, the frequency changes of formants after the tonsillectomy significantly depend on position and size of the tonsils. For example, for the vowel /a/ the formant F3 was changed from -137 Hz to +168 Hz by changing a portion of the tonsil volume interference with the acoustic space of the vocal tract.

Consequently, it can be concluded that the effects of tonsillectomy on the voice production are very individual for each subject depending on a concrete anatomy of his vocal tract and position and size of the tonsils inside.

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