MODELLING OF INFLUENCE OF VELOPHARYNGEAL INSUFFICIENCY ON PHONATION OF VOWEL /A/

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Abstract: **The effects of velopharyngeal insufficiency (VFI) or clefting on acoustic frequency–modal characteristics of human supraglottal spaces are investigated. Finite element (FE) modelling is supported by experimental investigation using a physical model of the vocal and nasal tract fabricated by the rapid prototyping technique from the FE model. The FE model was developed from magnetic resonance images (MRI) of the subject during phonation. Finally the influence of the VFI on phonation of the vowel /a/ is numerically simulated in time domain and supported by clinical investigation.**

Keywords: **biomechanics of voice, acoustics, cleft**

I. FE MODEL AND MATHEMATICAL FORMULATION

The FE model of a male vocal tract for the Czech vowel /*a*/ was created by transferring the data directly from MRI images and adding afterward the nasal tract manually [1]. A connection of the nasal and oral cavities was considered in the back area of the soft palate modelling the velopharyngeal insufficiency. The FE model is presented in Fig. 1. A degree of the velopharyngeal insufficiency was modelled by varies sizes of the area joining the nasal and oral cavities.

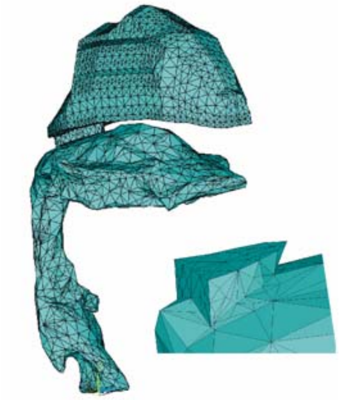

Fig. 1 FE model of the supraglottal spaces for vowel /*a*/ with the nasal cavity joint by cleft model.

The wave equation for the acoustic pressure can be written as:

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

where $c_0$is the speed of sound. Equations of motion for the acoustic system after discretization can be written as

$$\mathbf{M}\ddot{\mathbf{P}} + \mathbf{B}\dot{\mathbf{P}} + \mathbf{K}\mathbf{P} = \mathbf{F} \tag{2}$$

where **M**, **B**, **K** are the global mass, damping and stiffness matrices, **P** is the vector of nodal acoustic pressures and **F** is the effective "fluid load".
The acoustic modal and transient analysis were realised by the system ANSYS considering $c_0 = 343$ ms^{-1} and the air density $\rho_0 = 1.2$ kgm^{-3}. Zero acoustic pressure (p=0) was assumed at the lips and nostrils. Other boundary walls of the acoustic spaces were considered acoustically absorptive. The acoustic damping was modelled by the boundary admittance coefficient ($\mu = 0.005$).

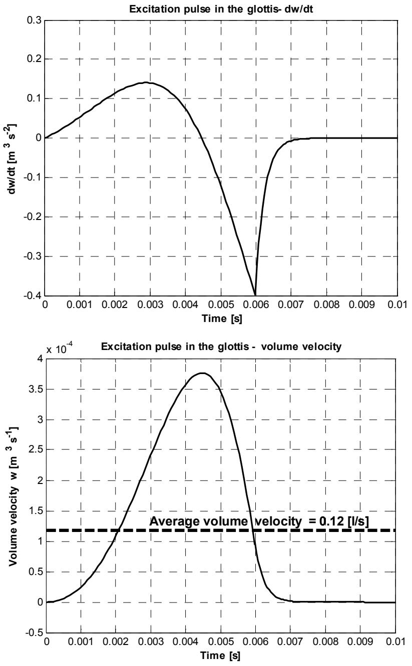

Fig. 2 Excitation L-F pulse used in transient analysis for modeling the phonation in time domain and its integral.

The supraglottal spaces were excited at the position of the vocal folds by pulses given by the derivative of the airflow volume velocity in accordance with the Liljencrants-Fant model [2]:

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$$\frac{d}{dt}\big(w(t)\big) = E_0 e^{\alpha t}\sin\big(\omega t\big),\ 0 < t < t_e\,,$$

$$\frac{d}{dt}\big(w(t)\big) = -\frac{E_e}{\varepsilon t_a}\Big(e^{-\varepsilon(t-t_e}\Big) - \Big(e^{-\varepsilon(t_c-t_e}\Big),\ t_e \le t \le t_c \qquad (3)$$

The parameters of the excitation pulses were adjusted according to the prescribed mean volume flow rate in the glottis (0.12 *l*/s) and the fundamental (pitch) frequency (*F0*=100 Hz) - see Fig. 2.

II. PHYSICAL MODEL AND MEASUREMENT SET-UP

The model for experimental analyses was created from the FE model by the CAD program Unigraphics utilizing the triangular mesh that describes the inner surface of the supraglottal spaces. After adding some constructional elements the 3D computer model was the input for the Rapid Prototyping technology. The model made of thermoplast ABS was fabricated by the Fused Deposition Modelling technology on the machine FDM 1650-STRATASYS with the accuracy ± 0.1 mm.

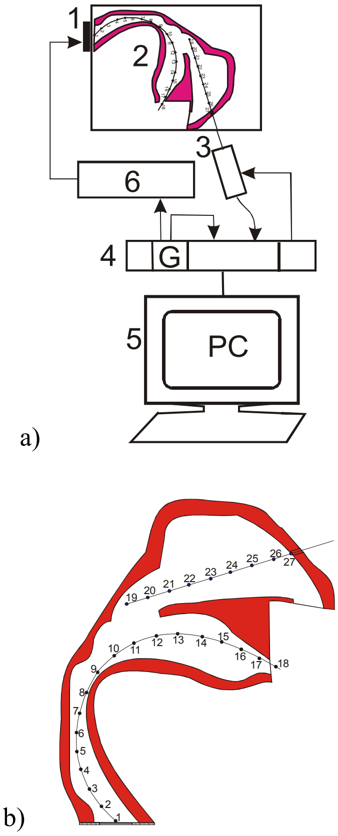

Fig. 3 - a) measurement set up: 1- miniature loudspeaker, 2 – the model, 3 – B&K microphone probe 4182, 4 and 5 - B&K front-end and PC with SW B&K PULSE, 6 – power amplifier LDS PA25E; b) schema of the physical model with 27 measurement points inside the supraglottal spaces.

The model construction enabled to change the magnitudes of the area *A* (cleft size) connecting the nasal cavities with the vocal tract (*A*=0, 42, 132 and 252 mm^2). The model and the measurement set-up are schematically shown in Fig. 3. Random excitation was used in experimental modal analysis.

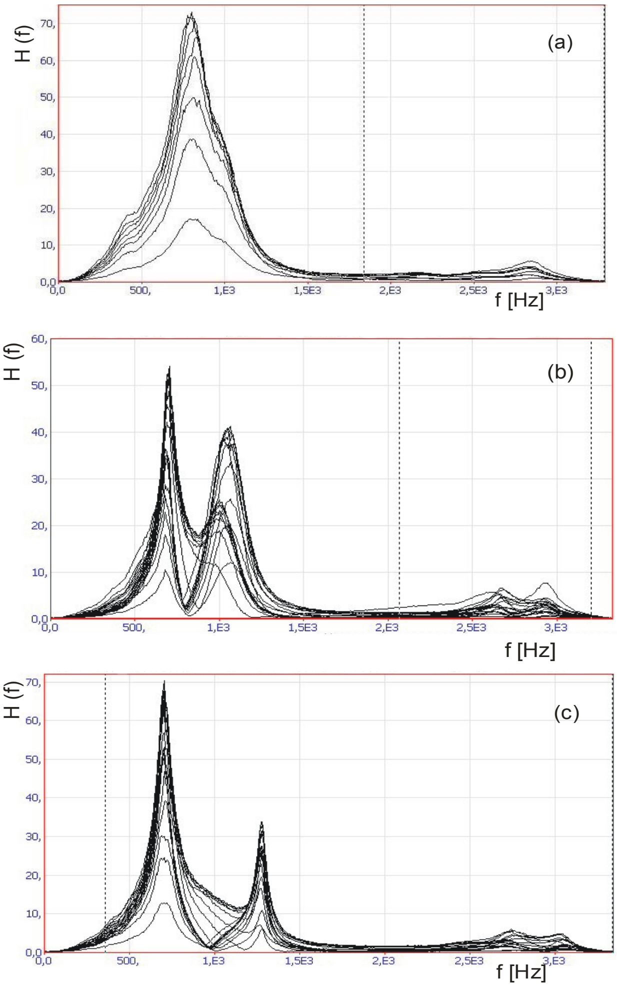

Fig. 4 Measured reasonance curves for cleft areas: a) A=0, b) A=42, c) A=132mm^2.

III. RESULTS OF THE ACOUSTIC MODAL ANALYSIS

The resonance curves measured inside the model (in the points marked in Fig. 3b) are shown in Fig. 4. The results of the computational and experimental modal analysis are summarized in Fig. 5, where the calculated and measured natural frequencies are compared for fourth magnitudes of the area *A*. In the case of velopharyngeal insufficiency (*A*>0) new nasopharyngeal (oro-nasal) natural frequencies appeared between the formants F2 and F3. Measured modes of vibration for the formants F1-F3 and the nasopharyngeal frequency $f_{naso.}$ are shown in Fig. 6 for A=132mm^2 and the corresponding calculated mode shapes are presented in Figs. 7 and 8. The first calculated oro-nasal acoustic mode shape with the predominant vibrations in the horizontal direction (see Fig. 8a) was not excited in the experiments.

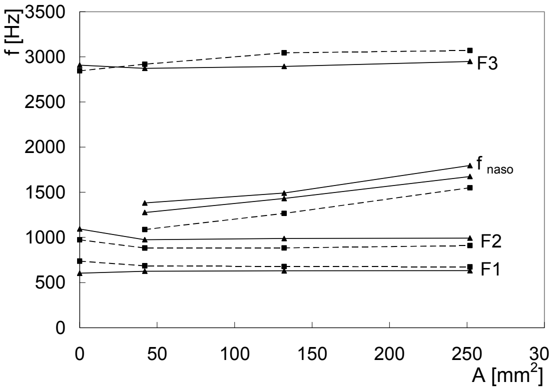

Fig. 5 Calculated (———) and measured (------) formant (F1-F3) and nasopharyngeal frequencies for the vowel /a/ for increasing area A of the cleft.

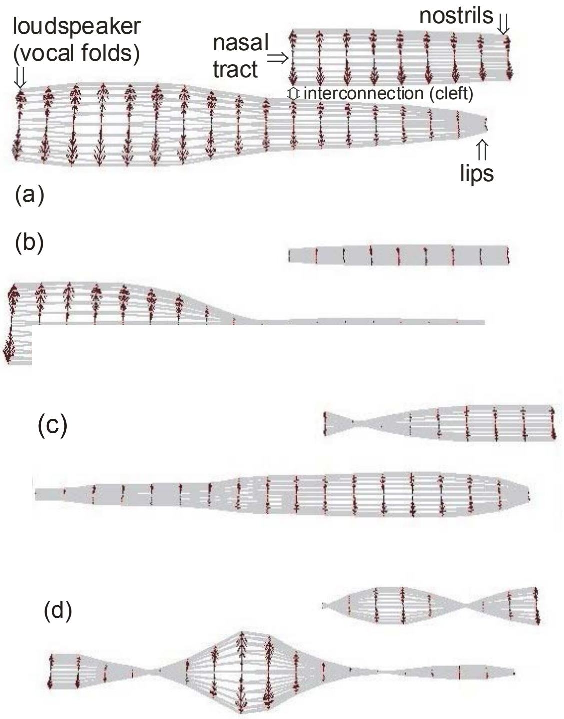

Fig. 6 Measured acoustic mode shapes of vibration for the cleft size A=132 mm^2. The double amplitudes of the pressure are shown in 27 measurement points along the vocal and nasal tracts - a) F_1= 679 Hz, b) F_2= 884 Hz, c) f_{naso}= 1266 Hz, d) F_3= 3042 Hz.

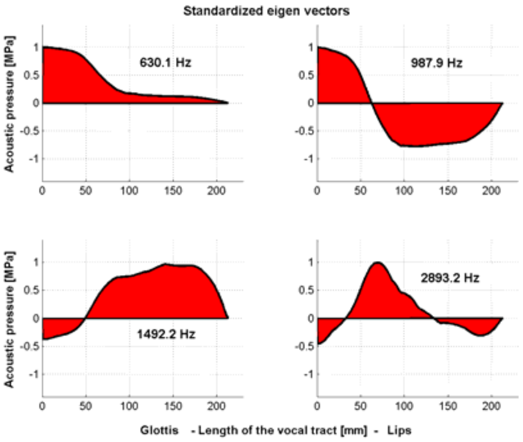

Fig. 7 Computed acoustic mode shapes of vibration for the cleft size A=132mm^2.

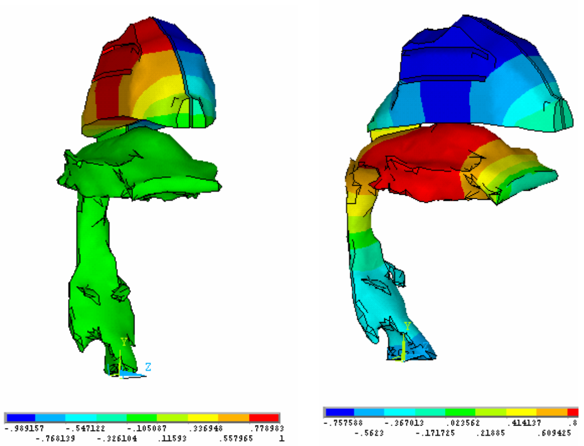

Fig. 8 Computed acoustic oro-nasal modes of vibration for the cleft size A=132mm^2 (f_{naso}= 1432 Hz and 1492 Hz).

IV. NUMERICAL SIMULATION OF PHONATION

The behavior of the FE model was tested by a broadband frequency pulse. The power spectral density of this pulse is presented in the Fig. 9.

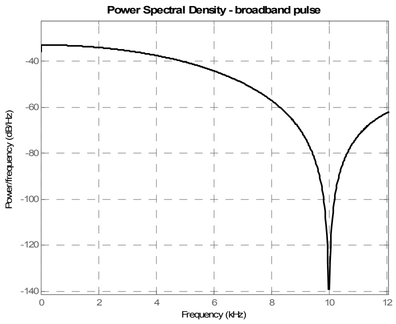

Fig. 9 Power spectral density of the broadband frequency pulse for testing the FE model by the transient analysis.

The results of transient analysis in the frequency domain are presented in Fig. 10 for the broadband frequency pulse and in the Fig. 11 for L-F pulse model.

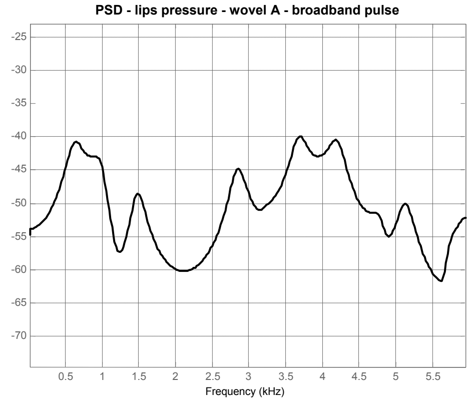

Fig. 10 Power spectral density of the pressure near the lips for Czech vowel /*a*/ for broadband frequency pulse and the cleft size A=132mm^2.

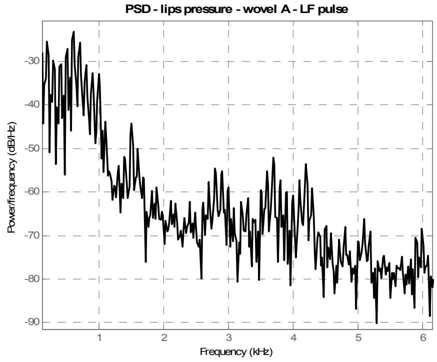

Fig. 11 Power spectral density of the pressure near the lips for vowel /*a*/ for L-F pulse (A=132mm^2).

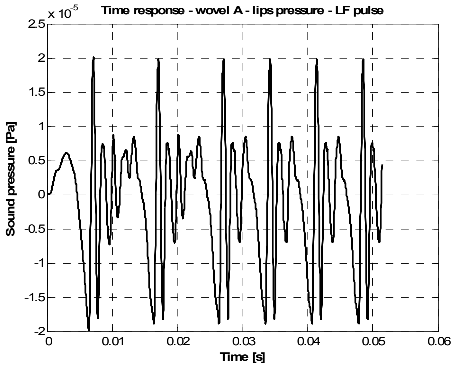

Fig. 12 Acoustic pressure near the lips for LF pulse.

The formant frequencies F1≈630 Hz, F2≈987 Hz and F3≈2893 Hz can be found in the frequency response functions in Fig. 11. The formant frequencies are in good agreement with the data known for Czech vowels. Another resonant frequencies f_{naso} ≈1432, 1492 Hz appears in Fig. 5 and 11 due to the velopharyngeal insufficiency.

V. CLINICAL INVESTIGATION

The theoretical results were compared with the results of the acoustic voice analysis. Eight adults with mild velopharyngeal insufficiency phonated vowel /a/ and pronounced the interconnection /ama/. The nasal and oral signals were picked up by microphones of the head part of Nasometer 6200-3 (Kay Elemetrics Corp.) and analysed by Multi-Speech (Kay El. Corp.) programme. The new resonant region (formant) was found between formants F2 and F3. Its position was located between 1800 Hz to 2050 Hz, the relative intensity of harmonics in this region was between –7 dB to +3 dB with regard the formant F3. The example of the acoustic analysis is shown in Fig. 13.

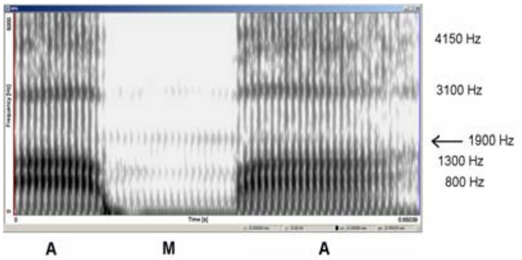

Fig. 13 Acoustic analysis of the pronounced interconnection /ama/.

VI. CONCLUSIONS

The time response functions for the pressure near the lips were obtained by the transient analysis of the FE models of the vocal tract for the model excited by a broadband frequency pulse and L-F pulse. The formant frequencies F1 – F3 evaluated from the resonances of the calculated frequency response functions are in good agreement with the experimental data. The existence of calculated oro-nasal formant was verified by the measurements on physical model as well as on subjects suffered by the velopharyngeal insufficiency.

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