Influence of Clefting on Phonation of Czech Vowels by FE Modeling of Real Male Vocal Tract

Karel Dedouch[1)], Jaromír Horáček[2)], Tomáš Vampola[1)], Jan Vokřál[3)] & Jan G. Švec[4)]

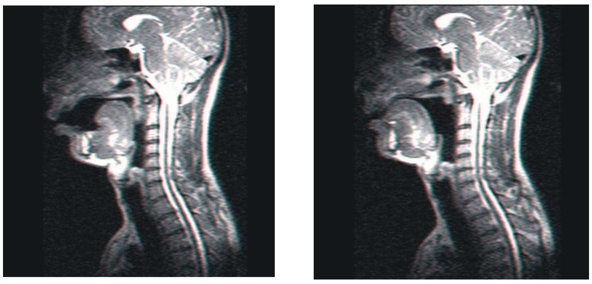
[1)]Dept. of Mechanics, Faculty of Mechanical Engineering, Czech Technical University in Prague
[2)]Institute of Thermomechanics, Academy of Sciences, Prague, Czech Republic
[3)] Phoniatric Laboratory, 1st Faculty of Medicine, Charles University, Prague, Czech Republic
[4)]Medical Healthcom, Ltd., Centre for Communication Disorders, Prague, Czech Republic

Abstract

Finite element (FE) models of the vocal tracts corresponding to the vowels /i/ and /u/ joint with a FE model of the nasal tract are analyzed. Acoustic modal and transient analyses of the FE models are performed in frequency and time domains. The frequency response functions and time responses are calculated in the nodes near the lips and nostrils. Both FE models involve the effect of cleft palate. The numerical results are compared with acoustic measurements.

1. Finite element models of the vocal tract

The FE models were created from MRI images using a direct transformation of MRI data into FE models. The FE model relevant to the nasal cavities was added to the models of vocal tract manually according to the anatomical literature. Both models involve effect of clefting of the soft palate for various the cleft sizes.



/ú/ /i/

Figure 1: Midsagittal MR images for the vowels /u/ and /i/

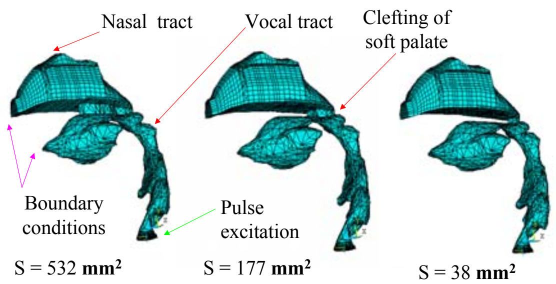


Figure 2: FE models for the vowel /u/ and various cleft areas S.

Material properties: speed of sound c_0=353 m/s, air density ρ_0=1.2 kg/m^3. ***Boundary conditions:*** zero acoustic pressure at the lips and nostrils, boundary areas of acoustic spaces acoustically hard and the absorption was modelled by the coefficient $\beta = r/\rho_0 c$.

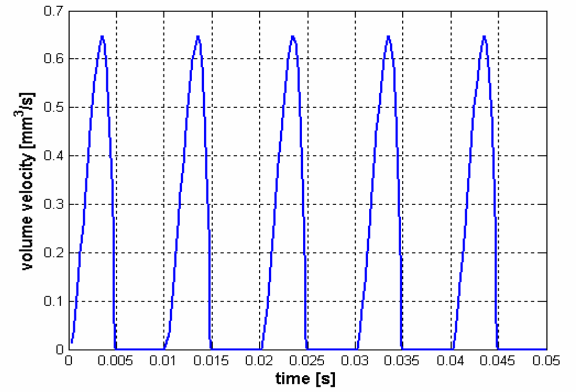


Figure 3: Excitation pulses according to Titze *et al* [1].

A connection of the nasal and oral cavities was considered in the back area of the soft palate modelling the velofaryngeal insufficiency. Excitation pulses corresponding to the acoustic velocity of the airflow throw the glottis were used for the transient analysis of the FE models in time domain.

2. Mathematical formulation

Wave equation for the acoustic pressure: $\nabla^2 p = \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2}$.

Boundary conditions on acoustically hard area and on the open end: $\frac{\partial p}{\partial n} = 0,\; p = 0$. Boundary conditions between the flexible structure and the fluid elements: $\frac{\partial p}{\partial n} = -\rho_0 \frac{\partial^2 u}{\partial t^2}$.

Equation of motion for the elasto-acoustic system after discretization :

$$\begin{bmatrix} M_s & 0 \\ \rho_0 R^T & M_f \end{bmatrix}\begin{bmatrix} \ddot{u} \\ \ddot{P} \end{bmatrix} + \begin{bmatrix} B_s & 0 \\ 0 & B_f \end{bmatrix}\begin{bmatrix} \dot{u} \\ \dot{P} \end{bmatrix} + \begin{bmatrix} K_s & -R \\ 0 & K_f \end{bmatrix}\begin{bmatrix} u \\ P \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix},$$

where n is normal to the boundary area, u is displacement vector of the structure in the normal direction to the vibrating surface, M, B, K are the global mass, damping and stiffness matrices, P is the vector of nodal acoustic pressures, subscripts s or f denote the structure or fluid and R is the coupling matrix.

3. Numerical results

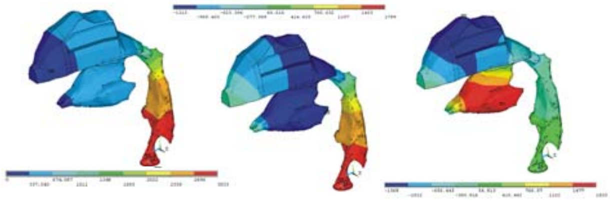


Figure 3: Acoustic mode shapes for the eigenfrequencies F1 – F3 for the model of vowel /u/ for cleft area S=532 mm^2

vowel / *u* /	F1 [Hz]	F2 [Hz]	F3 [Hz]
β=0, S=0mm^2	375	798	2069
β=0.005	-51 ± j 372	-31 ±j 797	-57 ± j 2069
β=0.01	-104 ±j 361	-63 ±j 795	-120±j 2066
β=0,S=38mm^2	533	797	989
β=0.005	−59 ± j 530	−32 ± j 797	−59 ± j 987
β=0.01	−119 ± j520	−65 ± j 795	−119 ± j 982
vowel / *i* /	F1 [Hz]	F2 [Hz]	F3 [Hz]
without cleft	254	2 358	3 194
with cleft	567	1 264 =f_{naso}	2 343

Table 1: Formants evaluated for the vowels /u/ and /i/ for different absorption coefficient β and cleft size S.

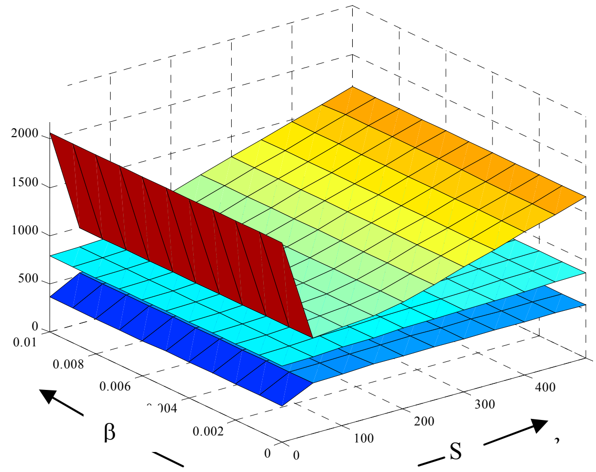


Figure 4: Formants F1-F3 *versus* cleft size S for different absorption cofficients β.

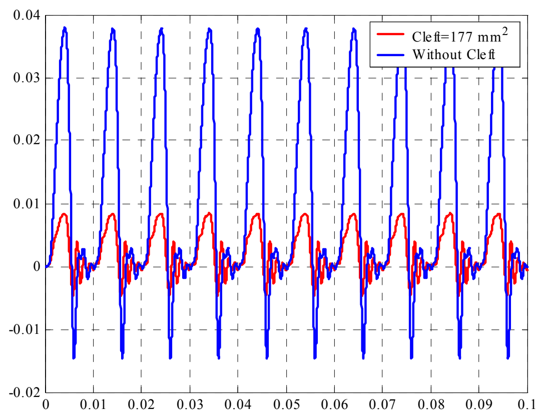


Figure 5: Acoustic pressure simulated for the vowel /u/ near the lips without and with the cleft palate for the absorption coefficient $\beta = 0.001$.

4. Experimental verification

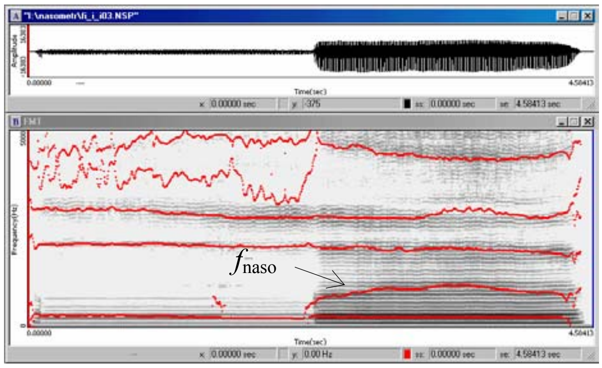


Figure 6: Evaluated formants during a sudden opening of the soft palate by a male subject for phonation of the vowel /i/; new oro-nasal formant frequency f_{naso} appeared between the ordinary formants F1 and F2 after opening the soft palate.

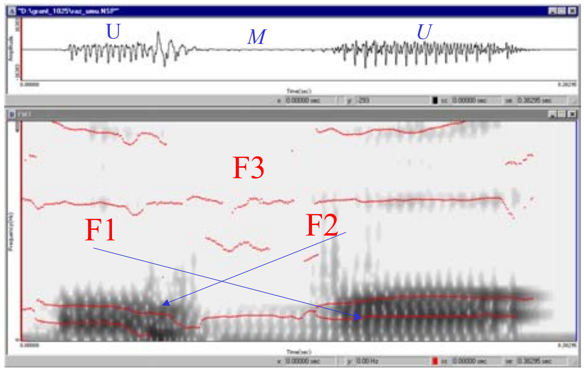


Figure 7: Evaluated formants during the subject pronunciation of the interconnection /*umu*/, where the second vowel is nasalized.

5. Conclusions

The results shows that the formant frequencies F1–F3 for vowels /i/ and /u/ are considerably influenced by the cleft connecting the acoustic spaces of the vocal and nasal tracts of the FE models. This is in good qualitative agreement with the clinical acoustic data on velofaryngeal insufficiency, from that it is known that the cleft influences the pronunciation of vowels /i/ and /u/ in the most significant way [2]. The existence of the calculated oro-nasal formants was verified by *in vivo* measurements when the velofaryngeal insufficiency was simulated by the normal subjects.

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References

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