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FINITE ELEMENT MODEL OF MALE VOCAL TRACT CONSIDERING CLEFTING AND INTERACTION BETWEEN HARD PALATE AND ACOUSTIC SPACES

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Summary : *Results of a voice numerical simulation using finite element (FE) model of acoustic spaces corresponding to the human vocal tract for English vowel / a / are presented. The approximate FE model was designed according to the data published in literature and amended by the model the nasal tract joint with the vocal tract by compliant bone of hard palate. The pronunciation of the vowel / a / is simulated using transient time analysis of the model. The acoustic pulse is realized by the time dependent displacement of a small circular plate moving in the plane of vocal folds. The time and frequency response functions are calculated in the points situated near the lips, the nostrils and at the vocal folds.*

1. Design of finite element model

Simplified FE model of male vocal tract corresponding to the English vowel / *a* / was designed in accordance with the MRI data published by Story et al. (1996). Afterwards the FE model was completed by the model of nasal tract (Dedouch et al., 2000, 2001) and compliant bone of hard palate. The flexibility of the bone enables to transfer the acoustic pressure pulses from the supraglottal acoustic spaces to the space of nasal cavity. The analyzed FE model of human vocal tract is presented in Fig. 1. The total length of vocal tract from the vocal fold (in Fig. 1 situated on the right) to the lips is 174,58 mm. The system ANSYS 5.7 was used for numerical solution. The acoustic 3D finite elements FLUID 30 were used in the acoustic spaces of the FE model and the bone of hard palate was modeled by the plate finite elements SHELL 63. The acoustic transient analysis was realized considering the speed of sound in supraglottal spaces c_0 = 353 ms^{-1} and the air density ρ_0 = 1,2 kgm^{-3}. Zero acoustic pressure (p=0) was assumed in the planes of lips and nostrils.

The boundary walls of the acoustic spaces were supposed acoustically absorptive. The acoustic damping associated with the fluid-structure interface of the air and tissues of the vocal tract was modeled by the boundary admittance coefficient μ. This dimensionless coefficient (between 0 and 1) is the ratio of real component of specific acoustic impedance, associated with the sound absorbing material, to the fluid characteristic impedance: $\mu = x/\rho_0 c_0$.

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The sound absorption characteristic is often expressed by the dimensionless absorption coefficient α (Nový, 1995) defined by the relation $\alpha = [0{,}5 + 0{,}25(\mu + 1/\mu]^{-1}$. The magnitudes of the boundary admittance coefficient μ used for the analyzed FE model of the vocal tract were $\mu = 0{,}006$ for supraglottal acoustic spaces and $\mu = 0.008$ for the nasal cavity.

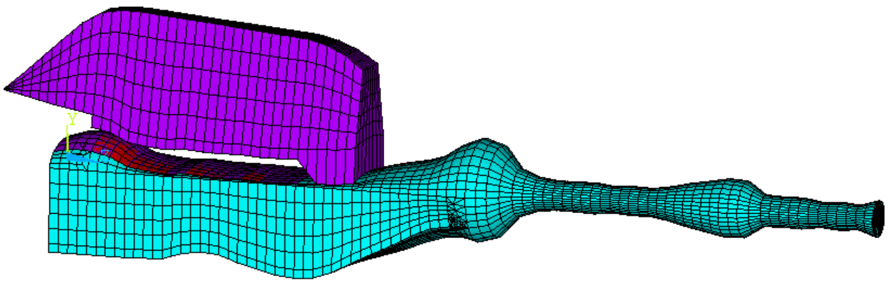

Fig. 1 Finite element model of male vocal tract including the nasal cavities.

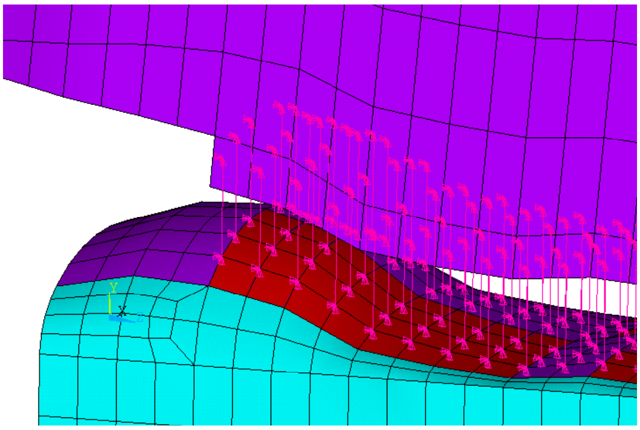

Fig. 2 Detail of connection of plates corresponding to bones of hard palate.

The material properties of the bone of hard palate were assumed as follows: Young modulus $E_1 = 6{,}50\ .10^9$ Pa, Poisson ratio $\mu_1 = 0{,}21$, density $\rho_1 = 1.41\ 10^3$ kg/m^3 and wall thickness h = 0.6 mm. The bone of hard palate was modeled using two separated parts. The first part of the finite elements SHELL 63 was directly joined with the acoustic finite elements of supraglotall acoustic spaces using the material properties E_1, μ_1 and ρ_1. The second part of the finite elements SHELL 63 was joined with the acoustic finite elements of the nasal tract on its lower boundary area. The material properties corresponding to the second part of the FE model of the bone were identical with the first part of the bone model except the Young modulus $E_2 = 0{,}01\ E_1$ respecting a much more compliant material. Each node of the lower part of FE model of the bone was connected with the corresponding node on the upper part of FE model of the bone of hard palate. This connection of corresponding nodes guarantees identical motion of the nodes on both parts of FE models. A detail of connection of upper and lower plate finite elements corresponding to bones of hard palate is presented in Fig. 2.

A small cleft was considered in the calculations in the back area of the soft palate. The size of clefting was about N=20 finite elements creating the junction of the vocal and nasal tracts (Horáček et al., 2002).

2. Mathematical formulation

The wave equation describes the distribution of acoustic pressure inside a closed acoustic space

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

where c_0 is the speed of sound. The boundary condition corresponding to the acoustically hard area is

$$\frac{\partial p}{\partial \mathbf{n}} = 0 \quad , \tag{2}$$

where n is the direction of the normal to the boundary area. At the open end the boundary condition is

$$p = 0 \, . \tag{3}$$

The boundary condition on the interface between the flexible structure and the fluid elements on the acoustic boundary area is

$$\frac{\partial p}{\partial \mathbf{n}} = -\rho_0 \frac{\partial^2 \mathbf{w}_{\mathrm{n}}}{\partial \mathrm{t}^2} \quad , \tag{4}$$

where on the right hand side is the acceleration of the moving structural boundary.
Equation of motion for the elastoacoustic system after discretization can be written as

$$\begin{bmatrix} \mathbf{M}_s & \mathbf{0} \\ \rho_0 \mathbf{R}^T & \mathbf{M}_f \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{u}} \\ \ddot{\mathbf{P}} \end{bmatrix} + \begin{bmatrix} \mathbf{B}_s & \mathbf{0} \\ \mathbf{0} & \mathbf{B}_f \end{bmatrix} \begin{bmatrix} \dot{\mathbf{u}} \\ \dot{\mathbf{P}} \end{bmatrix} + \begin{bmatrix} \mathbf{K}_s & -\mathbf{R} \\ 0 & \mathbf{K}_f \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ \mathbf{P} \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \end{bmatrix} \tag{5}$$

where **M**, **B**, **K** are mass, acoustic boundary damping and stiffness matrices, respectively, and **P** is the vector of nodal acoustic pressures and **u** is the structural displacement.
In the case of a kinematic excitation by the moving surface of the structure the equations of motion can be rewritten in the form

$$\begin{aligned} \mathbf{RP} &= \mathbf{M}_s \ddot{\mathbf{u}} + \mathbf{K}_s \mathbf{u} \\ \mathbf{M}_f \ddot{\mathbf{P}} + \mathbf{B}_f \dot{\mathbf{P}} + \mathbf{K}_f \mathbf{P} &= \rho_0 \mathbf{R}^T \ddot{\mathbf{u}} \end{aligned} \tag{6}$$

where the structural motion **u**(t) is prescribed.

3. Results of numerical solution

Time responses of the acoustic pressure investigated in several selected points of the vocal tract are the results of transient dynamic analysis of the FE models. The first point was situated near the plane of vocal folds, the second point on the axis *z* of symmetry of the supraglottal space near the lips and the third point in the plane of symmetry of the nasal tract near the nostrils. The results of transient dynamic analysis were obtained in the form of very large data files and the computational time was approximately 19 hours on the workstation DEC. Therefore it is very important to choose an optimal time step and the time interval of computation in the transient analysis. The FFT images of exciting acoustic pressure input pulses as well as the pressure time responses in the selected points of the vocal tract were calculated by using system MATLAB.

The input velocity of the air flowing through the vocal folds is presented in Fig. 3 in the time and frequency domains. The second graph in this figure shows the autospectrum of the pulse used for exciting the FE models.

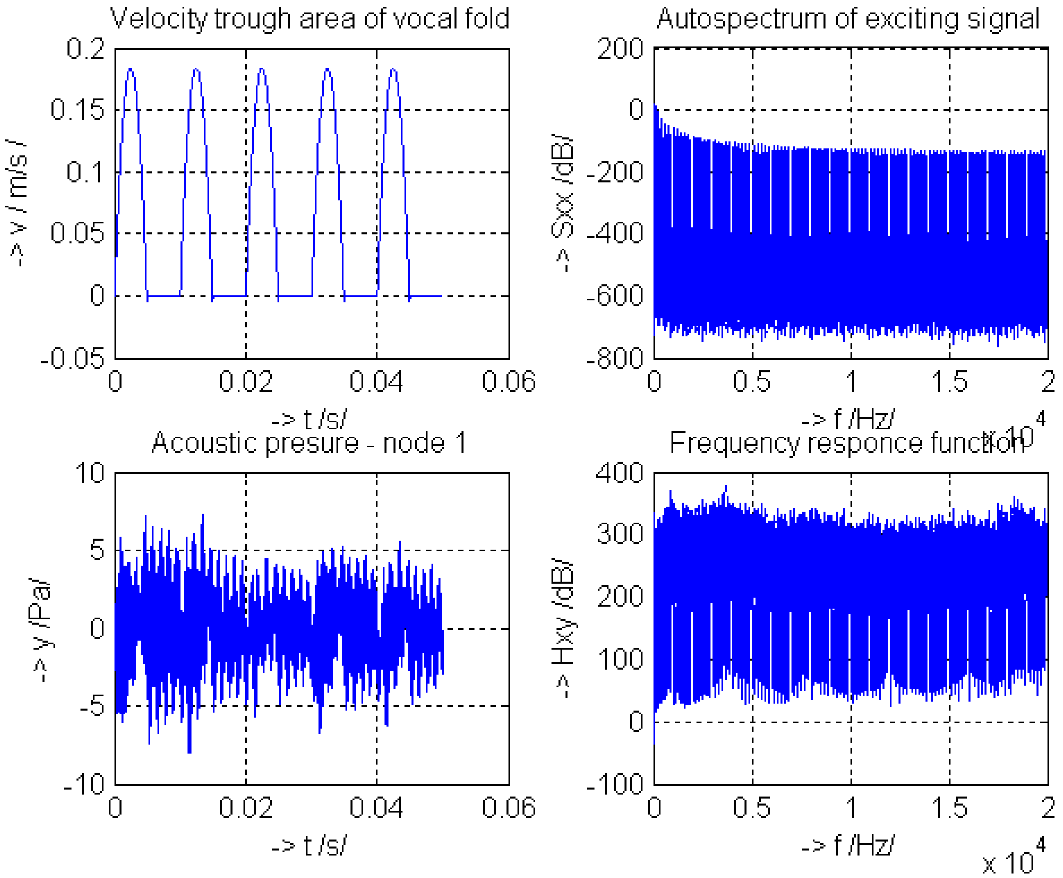

Fig. 3 Characteristics of the pulse excitation: airflow velocity in the glottis, autospectrum of exciting signal, acoustic pressure in the node near the vocal folds and the frequency response function calculated in the same point.

Figs. 4, 5 and 6 present the time and frequency response functions for the acoustic pressure calculated in the nodes situated near the vocal folds, near the plane of lips and in the nasal tract near the nostrils, respectively. The maximum value of the pressure amplitude near the vocal fold is approximately 6 Pa. This value of the acoustic pressure is much higher than the pressure near the lips as well as near the nostrils, where the maximal amplitudes of the acoustic pressure is approximately 0,3 Pa.

The formant frequencies F1 ≅ 760 Hz and F2 ≅ 1150 Hz are visible in the frequency response functions presented in Figs 4–6. There is also visible another considerable frequency f ≅ 4000 Hz. This frequency is not probably the resonant frequency of the acoustic spaces that corresponds neither to the third formant frequency F3 nor to a natural frequency of the nasal tract, because it has not occurred in the frequency response functions for the acoustic pressure calculated in the previous papers of the authors (Krampera et al. 2002, Horáček et al., 2002). For this reason it will be necessary to perform the modal analysis of this FE model and to investigate properly the eigenfrequencies of the bone of hard palate.

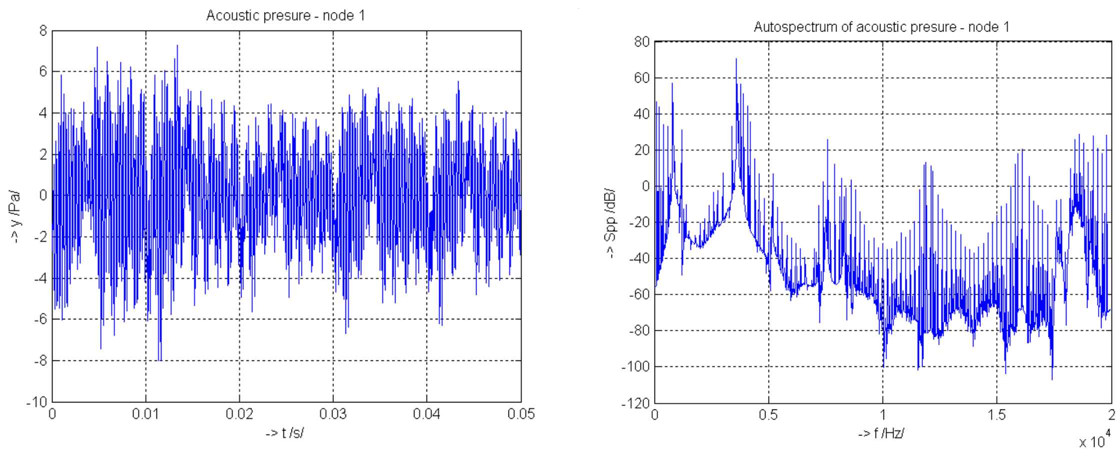

Fig.4 Time and frequency response functions for the acoustic pressure near the vocal folds.

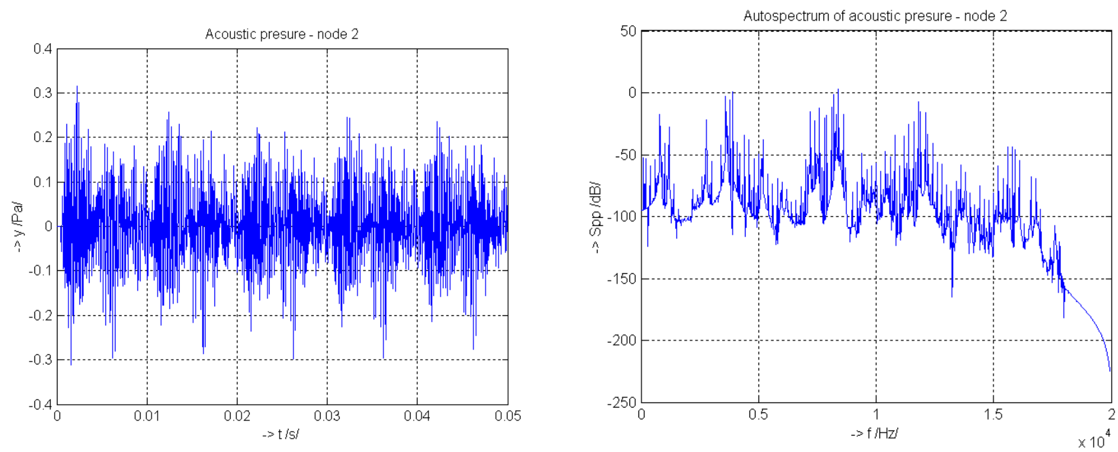

Fig.5 Time and frequency response functions for the acoustic pressure near the lips.

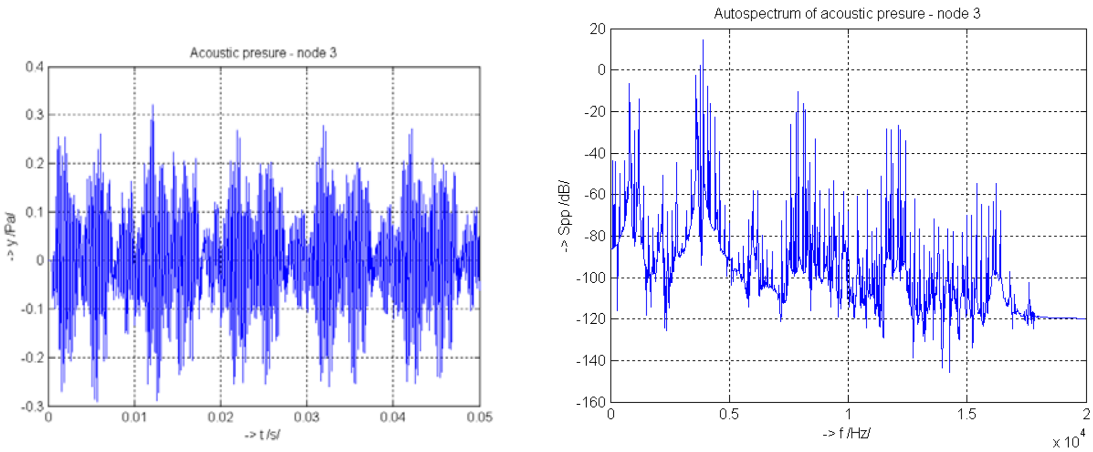

Fig.6 Time and frequency response functions for the acoustic pressure in the nasal cavity near the nostrils.

4. Conclusions

The FE models of male vocal tract corresponding to English vowel / *a* / completed by the FE model of the nasal tract and the bone of hard palate were analyzed by finite element system ANSYS 5.7. The FE models were excited kinematically by time depended translation motion of a small rigid plate situated in the area of vocal folds. Excitation function in time domain was obtained after integration of volume velocity of air flowing through the vocal folds. The main conclusions resulting from the numerical simulations are as follows:

- The frequency bandwidth corresponding to the pressure exciting pulses used was sufficient for excitation of the acoustic response of the system in the whole hearing frequency range.
- The values of formant frequencies F1 – F2 obtained from the resonance peaks of the calculated frequency response functions for the pressure are in good agreement with the data known from the literature (Hála, 1962; Palková, 1994).
- Influence of the absorptive boundary areas on the time responses was found to be negligible.
- Investigation of the influence of stiffness of the hard palate on the frequency response in higher frequency region requires performing the modal analysis of the FE model.

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