FINITE ELEMENT MODELLING OF MALE VOCAL TRACT WITH CONSIDERATION OF CLEFT PALATE

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ABSTRACT

Two finite element models of male vocal tract designed for vowel / *a* / are analysed considering the cleft palate. The first of them is designed on the base of the data published by Story the second finite element (FE) model corresponds to the real male vocal tract designed by applying of magnetic resonance imaging (MRI) data. Performed acoustic modal analysis is focused on investigation of the influence of the area of cleft palate on the formant frequencies F1, F2 and F3. The results for the vowel / *a* / indicate, that after a small jump of the acoustic natural frequencies for a very small cleft area the formant frequencies F1 and F2 are influenced by the increasing size of the cleft palate only very slightly.

DESIGN OF FE MODELS OF MALE VOCAL TRACT

First an original simplified FE model of male vocal tract [1] corresponding to the English vowel / *a* / was designed in accordance with the data published by Story *et al.* [2]. Magnitude of the acoustic space of nasal cavity and nasopharynx and position and size of cleft palate in this simplified FE models [3] were approximated according to the anatomy data published in literature [4].

Recently, the second FE model [5] that corresponds to the real male vocal tract for the Czech vowel / *a* / was designed by using the method based on a direct transformation of the MRI data files to the FE model. The method developed by Krsek [6] enables to create an optimal finite element mesh of the FE model. Afterwards this FE model was manually complemented by the acoustic space of nasal cavity and nasopharynx. Supraglottal and nasopharynx acoustic spaces were connected by an acoustic space modelling a cleft palate.

Both FE models are composed of only acoustic finite elements. Boundary areas of acoustic spaces are considered as acoustically hard. No interaction of flexible structure with the acoustic medium was taken into account for the both models analysed, because the influence of a flexibility of some parts of the vocal tract (e.g., hard palate or thyroid cartilage) on the formant frequencies F1, F2 was found to be negligible in the previous studies [7].

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

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

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

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

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

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

After discretization of the wave equation we obtain the equation of motion for acoustic nodal pressures in the matrix form

$$\mathbf{M}\,\ddot{\mathbf{P}} + \mathbf{B}\,\dot{\mathbf{P}} + \mathbf{K}\,\mathbf{P} = \mathbf{0} \, , \tag{4}$$

where **M**, **B**, **K** are mass, acoustic boundary damping and stiffness matrices, respectively, and **P** is the vector of nodal acoustic pressures.

The modal analysis was applied on both developed FE models and natural frequencies and acoustic mode shapes of vibration were calculated. The FE code ANSYS 5.7 was used for the modal analysis. The acoustic space was modelled by the acoustic 3D finite elements FLUID30 with the following material properties: air density ρ_0 = 1.2 kgm^{-3}, speed of sound c_0 = 353.2 m/s. The acoustic boundary damping matrix **B** was zero (**B** = **0**) for both models analysed here, because, no absorptive boundary areas of the acoustic spaces were considered in the numerical calculations.

The first, original and simplified FE model for the vowel / a / considering cleft palate is presented in Fig. 1.

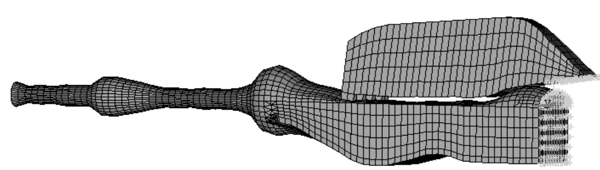


Fig.1 Original FE model for the English vowel / *a* / considering cleft palate.

The second FE model of the real male vocal tract designed by using the method of direct transformation of the MRI data files to the finite element mesh is presented in Fig. 2. The nasal tract had to be added to the model artificially, because the nasal cavity is divided by *septum* and *turbinates* (especially c*oncha nasalis media* and c*oncha nasalis inferior*) into very small and geometrically very complicated acoustic spaces (see also Fig.7e). Consequently the images of very thin bones, areas and small acoustic volumes in the nasal cavity could not be successfully created by using the MRI technique due to a limited resolution of individual MRI slices. Therefore, the acoustic space of nasal cavity and nasopharynx along with the space, which connects nasal tract with supraglottal acoustic space, were designed according to the anatomical data published by Grim [8]. The Fig.3 presents in detail two examples of the FE modelling of the cleft palate, i.e., the two different models of the acoustic space connection between the nasal and the supraglottal tracts.

The original as well as the new FE models had identical position of front part of the cleft palate. The magnitude of the clefts was determined by the number N_r of finite elements creating the area, which connects both above-mentioned acoustic spaces.

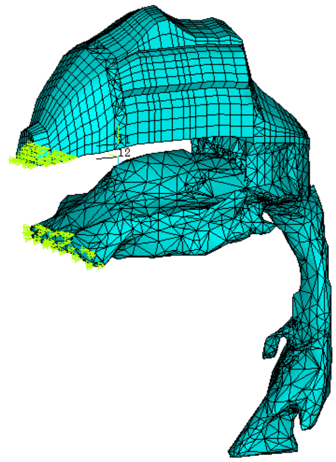
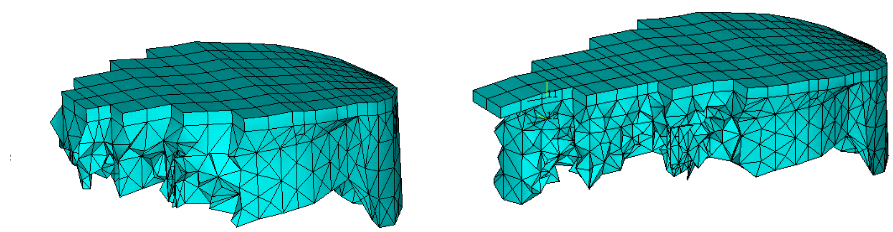


Fig. 2 FE model of real male vocal tract for the Czech vowel / *a* / obtained from MRI data file with the added nasal cavity.



a) b)

Fig. 3 Magnitudes of connecting acoustic spaces corresponding to analysed variants: a) N_r = 40 (4th variant), b) N_r = 70 (5th variant).

RESULTS OF NUMERICAL SOLUTION

The calculated formant frequencies F1, F2 and F3 and the acoustic natural frequency of nasal tract $f_{nasopharynx}$ as functions of the magnitude of the cleft palate are presented in Figs. 4 and 5. The results shown in Fig. 4 belong to the original FE models (see Fig. 1), and the calculated natural frequencies for the newly developed FE models (see Fig. 2) are presented in Fig. 5.

Normalised acoustic mode shapes of vibration for the vowel /*a* / belonging to the original FE model are presented in Fig. 6 and for the newly designed FE model in Fig. 7, respectively. The acoustic mode shapes presented in Fig. 7 correspond to the 2nd variant of the solution, i. e, for N_r = 8 finite elements.

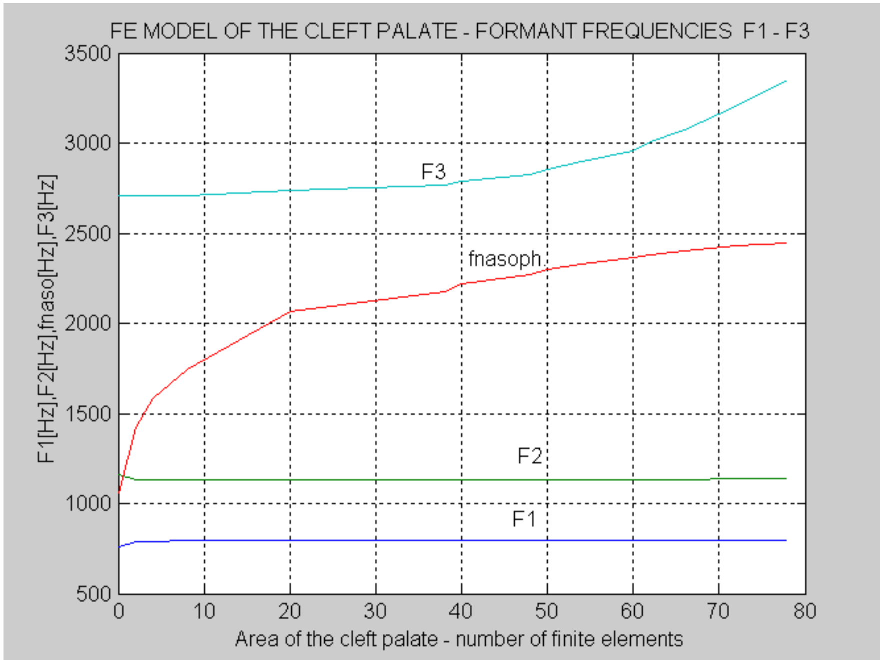


Fig. 4 Acoustic natural frequencies corresponding to the original FE models for the English vowel / *a* / *versus* the cleft palate magnitude.

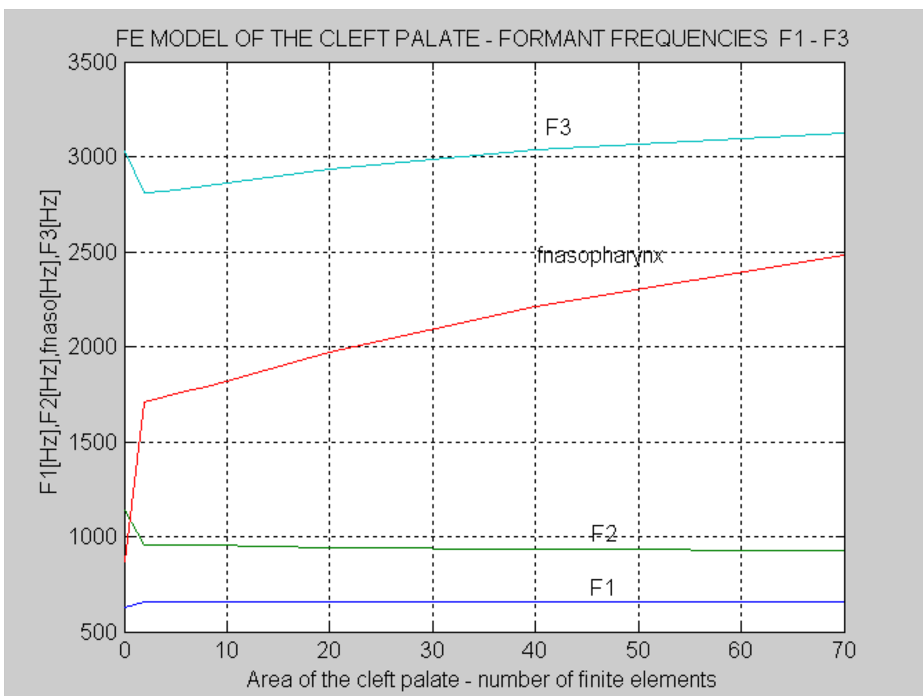


Fig. 5 Acoustic natural frequencies corresponding to the newly designed FE models for the Czech vowel / *a* / *versus* the cleft palate magnitude.

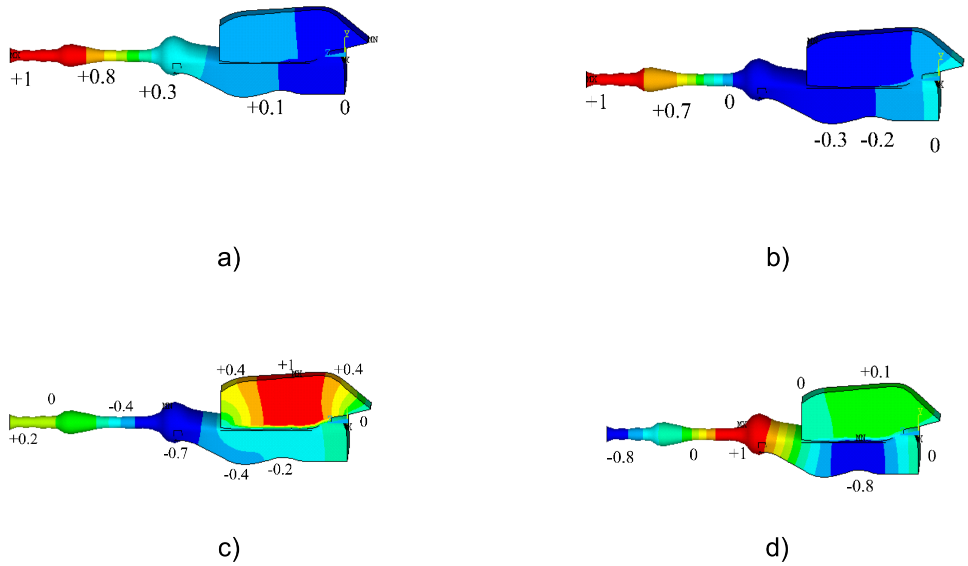


Fig. 6 Normalised acoustic mode shapes – FE model for English vowel / *a* /:
a) F1 = 795.5 Hz; b) F2 = 1 133.3 Hz; c) $f_{nasopgarynx}$ = 2 065.2 Hz; d) F3 = 2 736.2 Hz.

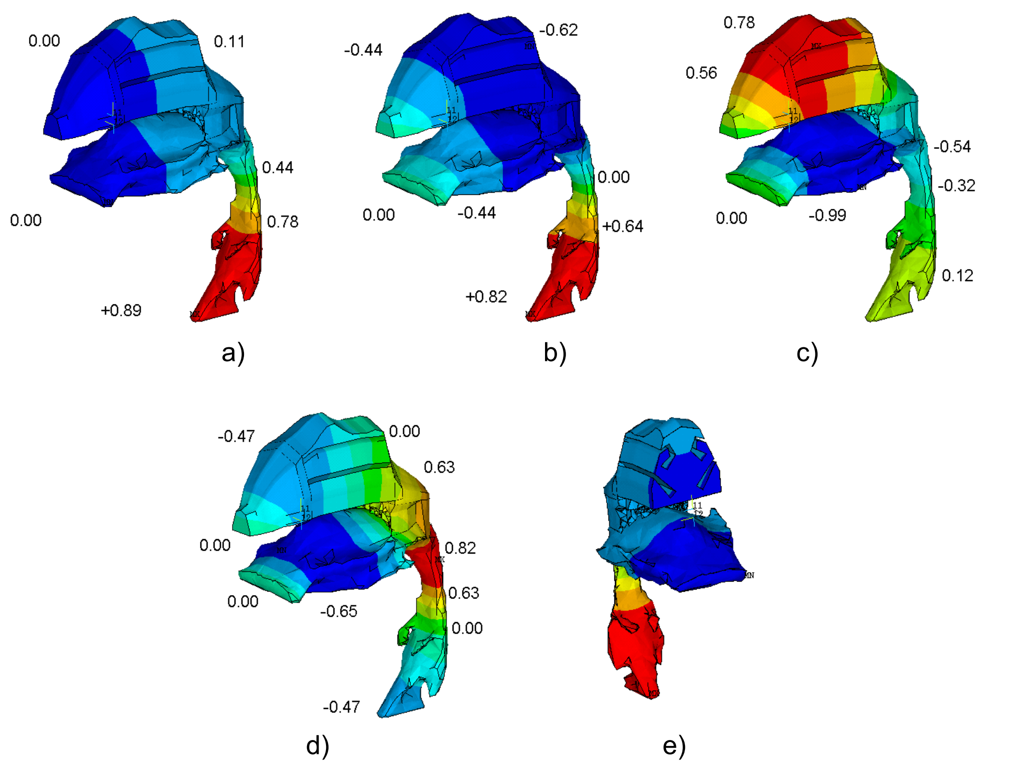


Fig. 7 Normalised acoustic mode shapes for Czech vowel / *a* / - newly designed FE model:
a) F1 = 654,8 Hz; b) F2 = 953,3 Hz; c) $f_{nasopharynx}$ = 1 789,5 Hz; d) F3 = 2 845,7 Hz;
e) illustration of FE modelling of *concha nasalis media* and *concha nasalis inferior*
(for F1 and 3rd variant of the solution N_r = 20).

CONCLUSIONS

Two FE models of male vocal tract are presented in the paper. The original FE model corresponds to the English vowel / *a* /, the new FE model belongs to the real male vocal tract and it was designed by using MRI data files taken for the Czech vowel / *a* /.

Agreement between the calculated acoustic natural frequencies of the vocal tract without the cleft palate and the first two formant frequencies F1 and F2 refereed in literature (see [9,10]) for the English and the Czech vowel / *a* / is very good. The FE model for the Czech vowel / *a* /, designed by the direct method for MRI data transformation to the mesh of finite elements, corresponds to the FE model developed according to the Story data. The calculated formant frequencies F1, F2 are in reasonable agreement with the data known from Czech phonetics [10].

From the results of modal analysis of both FE models arise that the influence of magnitude of cleft palate on formant frequencies F1 – F3 for the vowel / *a* / is very small. After a sudden but small jump of the acoustic natural frequencies for a very small cleft palate the formant frequencies F1 and F2 are changed by increasing the size of the cleft only very slightly Whereas, the higher formant frequency F3 increase with increasing area of the cleft palate. This is in a reasonable agreement with the experience resulted from clinical observations.

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