Numerical Modelling of Production of Czech Vowel /a/ based on FE Model of the Vocal Tract

Pavel Švancara[1], *Jaromír Horáček*[2], *Luděk Pešek*[2]

[1]Institute of Solid Mechanics, Mechatronics and Biomechanics,
Brno University of Technology, Czech Republic, `svancara@umt.fme.vutbr.cz`
[2]Institute of Thermomechanics, Academy of Sciences of the Czech Republic
`jaromirh@it.cas.cz`

Abstract

Finite element (FE) model of the acoustic space corresponding to the human vocal tract for Czech vowel /a/ and acoustic space around the human head was used for numerical simulations. The resonant characteristics of the FE model are studied using modal and transient analyses. The production of vowel /a/ is simulated in time domain using transient analysis of FE model excited by Liljencrants-Fant's (LF) glottal signal model. Three different wave shapes of differential glottal airflow are used corresponding to nearly breathy, intermediate and normal phonation. The time and frequency response functions are calculated near the lips, at distance 0.2 m in front of the lips and near the inner surface of the hollow sphere at a position of ear. The results of numerical simulations are in good agreement with experimental data known from literature. Solution in the time domain allows to create sound files for an acoustic verification of the quality of numerically produced vowel by listening. Designed FE model allows also observing radiation of acoustic waves from the lips to the outer acoustic space.

1. Introduction

In previous papers of the authors [1,2] acoustic characteristics of the human vocal tract of a healthy man and man with a cleft was studied by FE modelling. Here the FE model is modified to obtain radiation boundary condition outside of the lips and Liljencrants-Fant's (LF) model is used as a glottal signal model. FE model of the acoustic space of the vocal tract of a healthy male for Czech vowel /a/ was created using magnetic resonance imaging (MRI) technique [1]. 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. A slice through 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.

The acoustic transient and modal analysis were realized by the system SYSNOISE 5.5 considering the speed of sound $c_0 = 353\ \mathrm{ms^{-1}}$ and the air density $\rho_0 = 1.2\ \mathrm{kgm^{-3}}$. Boundary walls of the vocal tract were considered acoustically absorptive. For modelling the acoustic damping the boundary condition of normal impedance $Z = 83\,666\ \mathrm{kgm^{-2}s^{-1}}$ was applied on the boundary walls (for assumed soft tissue material with Young modulus $E = 5$ MPa and density $\rho = 1400\ \mathrm{kgm^{-3}}$ [3]).

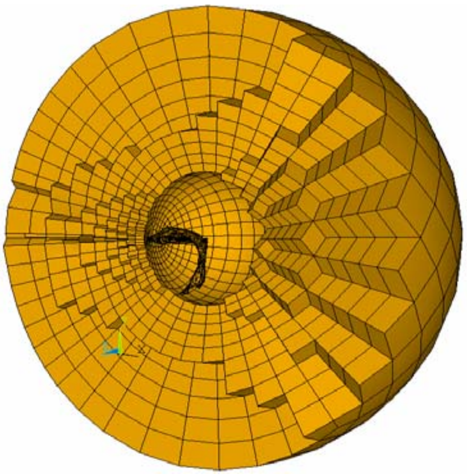

Figure 1: *A slice trough the FE model of the vocal tract for the vowel /a/ including an acoustic space around the head.*

2. Mathematical formulation

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, 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

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

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 of solution in time was used.

3. Frequency modal analysis

Firstly the resonant characteristics of the FE model were studied using transient analysis in time domain. The FE model was excited by very short pulse of differential glottal flow (duration 0.25 ms) at the faces of FE elements in position of the vocal folds and autospectrum of the sound pressure near the lips was calculated. Then the eigenfrequencies of the FE model of the vocal tract were computed by modal analysis, assuming zero acoustic pressure at the nodes belonging to the area of the lips, and acoustically hard boundary walls with no absorption were considered. Calculated eigenfrequencies and formant frequencies detected in autospectra resulted from transient analysis are summarized in Table 1. Results calculated by both methods are close and are in good agreement with experimental data known from literature [4,5].

#	Transient [Hz]	Modal [Hz]
1.	678	687
2.	1095	1161
3.	2910	2951
4.	4016	4076
5.	-	4310
6.	4480	4498

Table 1: Resonant frequencies evaluated from the transient analysis and the eigenfrequencies obtained by modal analysis of the FE model.

4. Numerical simulations of vowel production

The production of the vowel /a/ was simulated using transient analysis of FE model in time domain with Liljencrants-Fant's (LF) glottal signal model [6]. The LF model describes differentiated airflow in time domain. Each fundamental period of the glottal signal can be expressed as

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

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 2 illustrates these waveshape parameters. The other parameters in equation (3) are derived from the waveshape parameters. In this work the following normalized parameters are 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 a fundamental period T_0 to t_p .

Three different wave shapes of differential glottal flow are used (see Fig. 2), corresponding to nearly breathy phonation (with $R_a = 0.2$), intermediate ($R_a = 0.1$) and normal phonation ($R_a = 0.05$ ms). Remaining three timing parameters were the same for all three wave shapes considered ($R_k = 0.34$, $R_g = 1.12$, $E_e = 0.4\ m^3s^{-2}$). Autospectra of these wave shapes are shown in Figure 3. The FE model is 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 time responses – sound pressures and their autospectra are calculated near the lips, at distance 0.2 m in front of the lips (see Figs. 4 and 5) and near the inner surface of the hollow sphere at a position of ear.

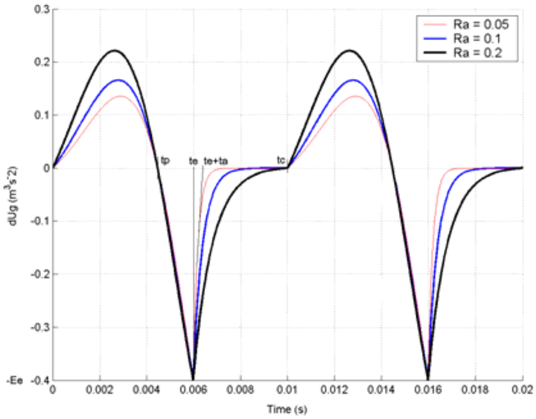

Figure 2: *Derivative glottal flow wave shapes used for acoustic excitation of the vocal tract.*

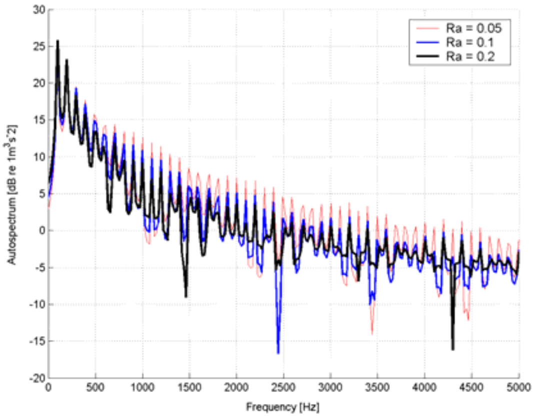

Figure 3: *Autospectra of derivative glottal flow wave shapes.*

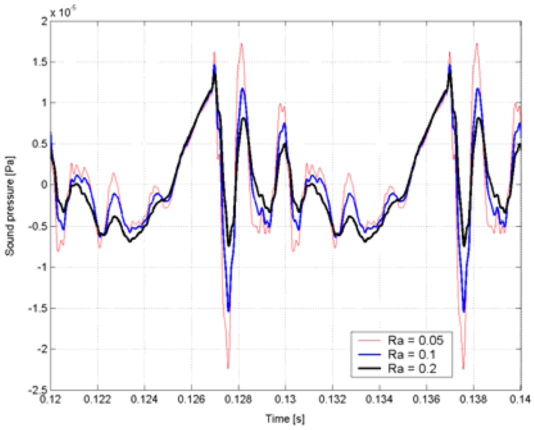

Figure 4*: Calculated sound pressure at the distance 0.2m in the front of the lips from time 0.12s to 0.14s*

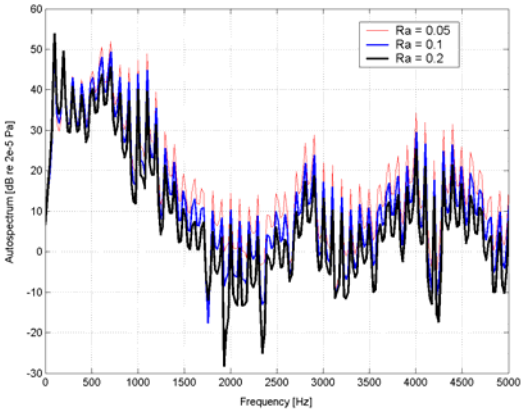

Figure 5*: Autospectra of calculated sound pressures at the distance 0.2m in the front of the lips.*

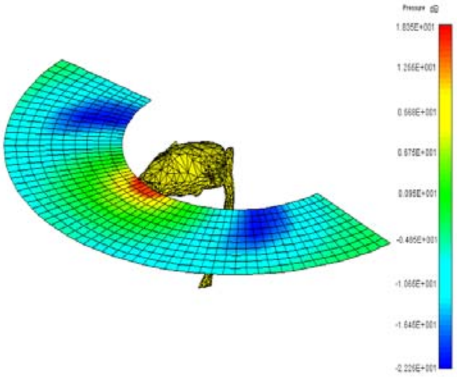

Figure 6: *Sound pressure isosurfaces in front of the lips in time 0.046*

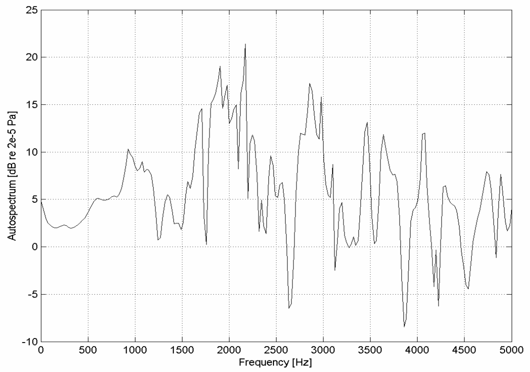

Figure 7: *Difference between calculated autospectra at the distance 0.2m in the front of lips and at the position of the ear.*

5. Discussion

Formant frequencies determined from the calculated autospectra are in good agreement with the experimental data known for the formants from literature [4, 5] as well as with the results of the modal analysis. Comparison of computed results for three different wave shapes of differential glottal flow show, that by increasing the parameter R_a the amplitudes of higher frequencies are decreasing. Solution in the time domain allows creating sound files for an acoustic checking of the quality of numerically produced vowel by listening. To achieve longer time duration of the sound files, computed time sequences of sound pressure are repeated many times. Designed FE model allows also observing radiation of acoustic waves from the lips to the outer acoustic space (see Fig. 6). One of the example is also shown in Figure 7, where the difference between the autospectrum calculated at the distance 0.2 m in front of the lips and the autospectrum at the position of the ear is plotted.

6. Conclusions

Finite element (FE) model of the acoustic space corresponding to the human vocal tract for Czech vowel /a/ and acoustic space around the human head was created and the production of the vowel /a/ was simulated using transient analysis in time domain with Liljencrants-Fant's (LF) glottal signal model. The formant frequencies evaluated from calculated autospectra are in good agreement with experimental data known from the literature as well as with the results of the modal analysis performed. Time domain solution allows to create sound files for verification of the quality of numerically produced vowel by listening. FE model allows also observing radiation of acoustic waves to the outer acoustic space.

7. References

[1] Dedouch, K.; Horáček, J.; Vampola, T.; Švec, J.G.; Kršek, P.; Havlík, R., 2002. Acoustic modal analysis of male vocal tract for Czech vowels. In *Interaction and Feedbacks'2002*, Prague, Nov. 26-27, 2002, IT ASCR, 13-20, ISBN 80-85918-75-7.

[2] Dedouch, K.; Horáček, J.; Vampola, T.; Vokřál, J., 2003. Velofaryngeal insufficiency studied using finite element models of male vocal tract with experimental verification. In 3^{rd} *Int. Workshop MAVEBA*. Firenze, Italy, 229-232.

[3] Abé, A.; Hayashi, K.; Sato, M., 1996. *Data Book of Mechanical Properties of Living Cells, Tissues and Organs*. Tokyo: Springer-Verlag.

[4] Palková, Z., 1994. *Phonetics and Phonology of the CzechLanguage.* Prague: Charles University – Karolinum (in Czech).

[5] Novák, A., 1996. *Phoniatrics and pedaudiology. Voice disorders – principles of voice physiology, diagnostics, treatment, reeducation and rehabilitation.* Prague: Unitisk s.r.o. (in Czech).

[6] Fant, G.; Liljencrants, J.; Lin, Q., 1985. A Four Parameter Model of Glottal Flow. In *STL-QPSR 4*, Sweden, 1-13.

Acknowledgement. This research is supported by the Grant Agency of the Czech Republic by project No 106/04/1025 *"Modelling of vibroacoustic systems focusing on human vocal tract"*.