SIMULATION OF THE INFLUENCE OF A CLEFT ON ACOUSTIC CHARACTERISTICS OF HUMAN SUPRAGLOTTAL SPACES

PACS : 43.70 Bk

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ABSTRACT

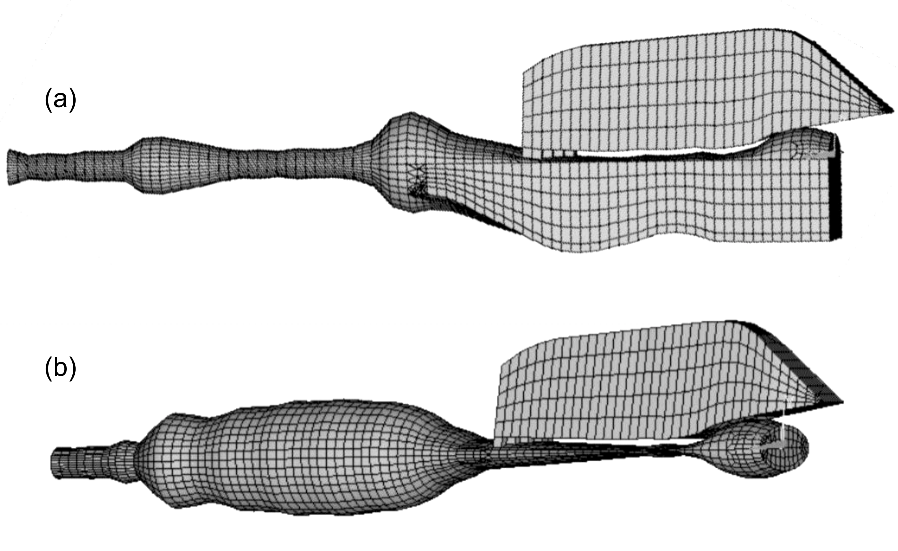
Approximate finite element (FE) models of acoustic spaces corresponding to the human vocal and nasal tracts were created according to the geometrical data published in literature. The FE models for English vowels / *a* / and / *i* / were analyzed for increasing size of a cleft, which joints both acoustic spaces. The influence of the cleft palate on the pronunciation of the vowels / *a* / and / *i* / is analyzed by using modal and transient analysis of the FE models. The pulse excitation of the vocal tract is realized by the time dependent displacement of a small circular plate moving at the position of the vocal folds. The time response and frequency response functions are calculated at several points in the supraglottal spaces, near the lips and the vocal folds, and in the nasopharynx. The results of numerical solution are in reasonable agreement with clinical observations of handicapped children.

FINITE ELEMENT MODELS OF SUPRAGLOTTAL SPACES

The contribution is a continuation of previously published papers [1,2] of the authors where the acoustic frequency modal characteristics of the vocal tract of a healthy human were studied by using FE modelling. The simplified FE models of male vocal tract for the English vowels / *a* / and / *i* / were developed according to the MRI data published by Story *et al.* [3]. Recently, a simplified FE model of the nasopharynx and the nasal cavity was added to the original FE models, and the influence of the cleft palate connecting both acoustic spaces on the formant frequencies for the the vowel /*a* / was modelled [4]. Here the study is extended to the time domain analysis and to the analysis of FE models for both vowels, /a/ and / i /. The designed FE models approximating the human supraglottal acoustic spaces are presented in Fig. 1. The total length of the vocal tract from the vocal folds (on the left side) to the lips (on the right) was 174.58 mm.

The acoustic transient and modal analysis were realized by the finite element software system ANSYS 5.7 using the acoustic finite elements FLUID30 considering the speed of sound c_0 = 353 ms^{-1} and the air density ρ_0 = 1.2 kgm^{-3}. Zero acoustic pressure (p = 0) was assumed in the nodes that belong to the areas of lips and nostrils. The other boundary walls of the acoustic spaces were supposed as acoustically hard and no absorption was considered.

The pulse excitation of the supraglottal spaces was realized by a small rigid circular plate (a piston) translating in the axial direction along the axes z . The plate was situated in the position of the vocal folds, and its diameter was equal to 1/3 of the diameter of the cross-section area of the FE model of the acoustic space at this point. The translation motion of the plate in time was given by integration of the flux (volume) velocity that corresponds to the airflow throw the vocal folds [3]. The interaction between the plate and the acoustic space was realized by the interactive acoustic FE elements.



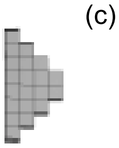


Fig. 1 FE models of English vowels / *a* / and / *i* / considering the cleft palate with N_r = 20 acoustic finite elements connecting acoustic spaces of the nasal tract with the vocal tract: a) FE model for the vowel / *a* /; b) FE model for the vowel / *i* /, c) area of the cleft for N_r = 20.

NUMERICAL SOLUTION AND RESULTS

The main aim of numerical solution was to obtain the transfer functions given generally as

$$H_{sr} = X_s(\omega)/F_r(\omega), \qquad (1)$$

where $X_s(\omega)$ and $F_r(\omega)$ are the Fourier images corresponding to a force excitation $f_r(t)$ applied in the point *r* and $x_s(t)$ is the time response of the system investigated in the point *s*. The results of the transient dynamic analysis of the FE models were the time responses of the acoustic pressure in selected points. The first point was on the axis of symmetry of the FE model of supraglottal space near the plain of lips, the second point was situated near the vocal folds and the third in the nasopharynx. Because the results of the ANSYS transient analysis were obtained in the form of extensive data files, an optimal choice of the time step and the computed time interval was very important for successful calculation of the transfer functions concerning the computation time and the computer memory capacity. The FFT images of the exciting acoustic pressure pulses and the pressure time responses were afterwards calculated by MATLAB.

The Fig. 2 presents the excitation pulse of the airflow volume velocity in the time domain as well as the corresponding displacement of the rigid plate and the velocity of the air flowing throw the glottis. The last graph shows the autospectrum of this pulse used for excitation of the FE models. The pulse signal covers a sufficiently wide frequency bandwidth of the excitation relating to the formants F1-F3 of both vowels investigated.

The results of transient analysis of the FE models for English vowels /*a* / and / *i* / are presented in Figs. 3, 4 and 5.

The Fig. 3 shows the results of numerical solution that corresponds to the FE models with separated acoustic spaces of the nasal and vocal tracts, i.e., for the models without the cleft palate (N_r = 0). Calculated acoustic pressures near the lips are presented here in the time and frequency domains. The resonant frequencies of the nasopharynx are not embodied in the frequency response functions among the formant frequencies F1-F3, because the nasal tract was completely separated, and thus it was not excited in this case. The level of the acoustic pressure in the time response for the vowel /i/ is approximately two times higher than the pressure response calculated for the vowel /a/.

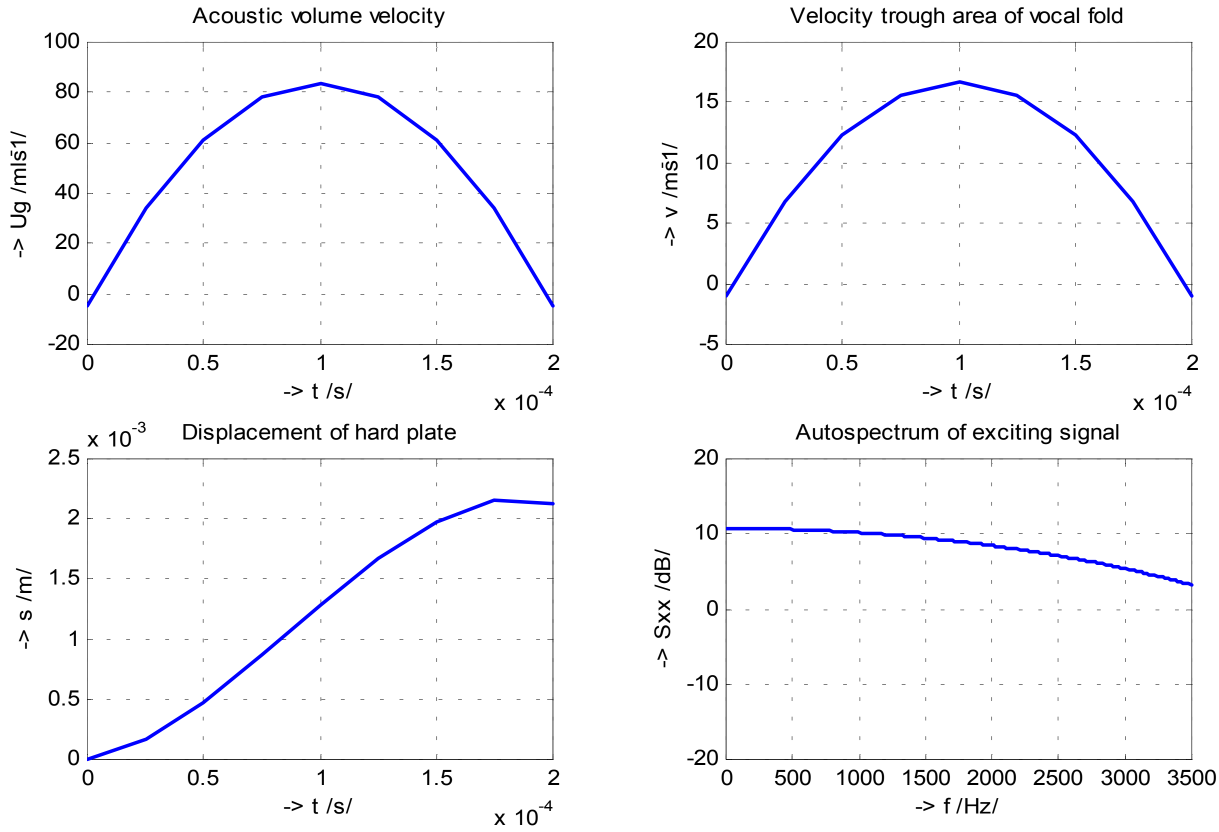


Fig. 2 Characteristics of the pulse excitation: airflow volume velocity, translation of the rigid plate, air flow velocity in the glottis and the autospectrum of the pulse.

Similarly, the Fig. 4 presents the results of transient analysis of the FE models for the magnitude of the cleft area equal to N_r = 20 elements. The resonant frequencies of the nasal tract f_{nas} are now visible in the frequency response functions between the formant frequencies F2 and F3 for the vowel /*a* /, and between the formant frequencies F1 and F2 for the vowel /*i* /, respectively. Comparing the results in Fig. 4 with the previous results presented in Fig.3 for N_r = 0, it can be concluded, that the influence of the cleft on the pronunciation of the vowel /i/ is much more significant than for the vowel /a/. The reasons for this conclusion are as follows:

- for the vowel /a/, the first eigenfrequency f_{nas} of the nasal tract is much higher than the lowest formant frequencies F1 and F2, and simultaneously the corresponding peak in the frequency response function near the frequency f_{nas} is small,
- on the other hand for the vowel /i/, the resonance peak in the frequency response function near the frequency f_{nas} is considerably more significant than for the vowel /a/, and it is between the lowest formant frequencies F1 and F2. In addition, a deep antiresonance appears in the spectrum near 400 Hz due to the cleft, and the amplitude of the pressure in the time response is nearly two times smaller than the acoustic pressure near the lips for the case N_r = 0. It is probably caused by a higher relative leakage of the acoustic energy trough the cleft and afterwards through the nostrils out of the vocal tract.

The time responses of the acoustic pressure calculated in three different nodes of the FE models with the cleft for the vowels /*a*/ and /*i*/ are shown in Fig. 5; for the nodes: a) near the vocal folds, b) near the lips and c) in the space of nasopharynx. The pressure levels near the vocal folds are much higher than the acoustic pressur near the lips; more than ten times higher for the vowel /a/ - see the responses 1 in Fig. 5 on the left side, and more than four times higher for the vowel /i/ - see the responses 2 in Fig. 5 on the right side.

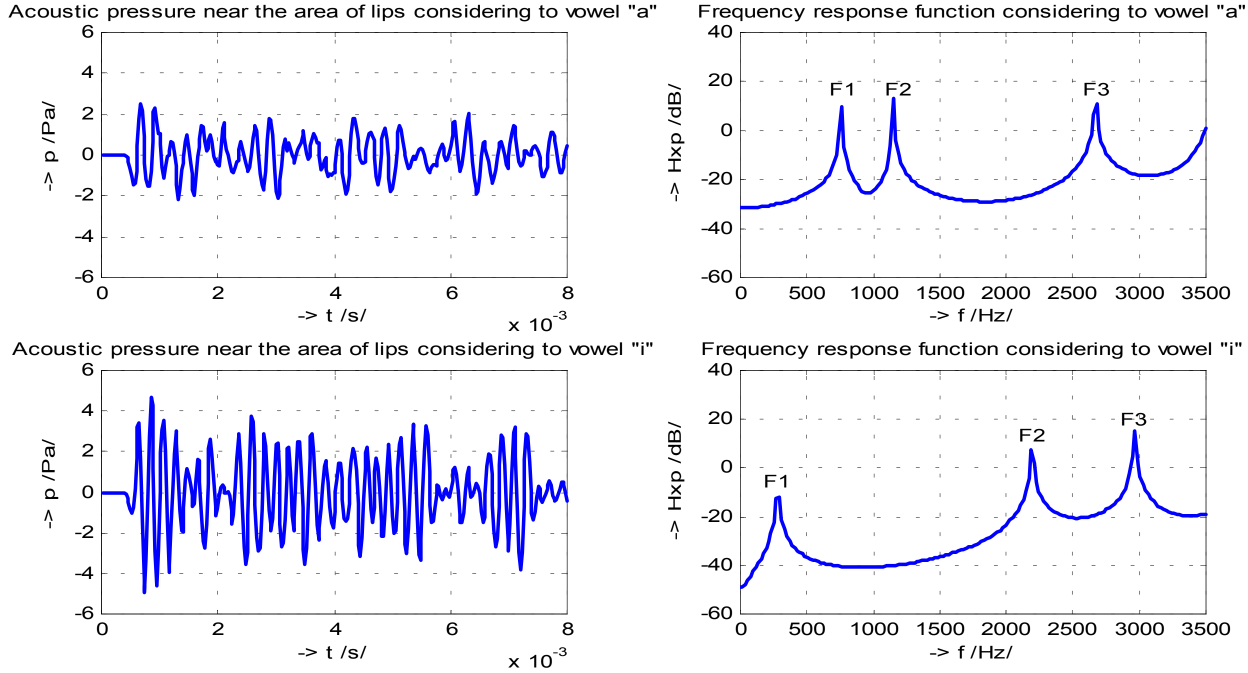


Fig. 3 Time and frequency response functions for the acoustic pressure near the lips calculated for the FE models of vowels / *a* / and / *i* / without any cleft (N_r = 0).

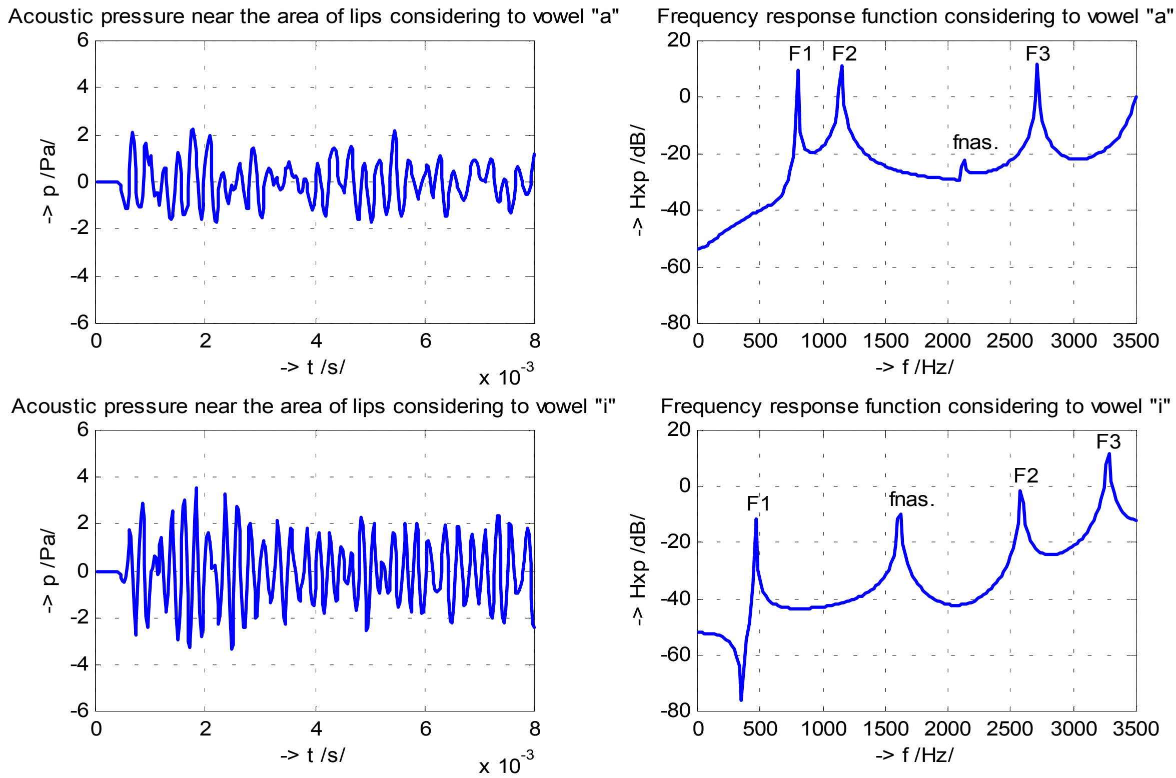


Fig. 4 Time and frequency response functions for the acoustic pressure near the lips calculated for the FE models of vowels / *a* / and / *i* / with the cleft palate for N_r = 20 elements connecting nasal tract with the vocal tract.

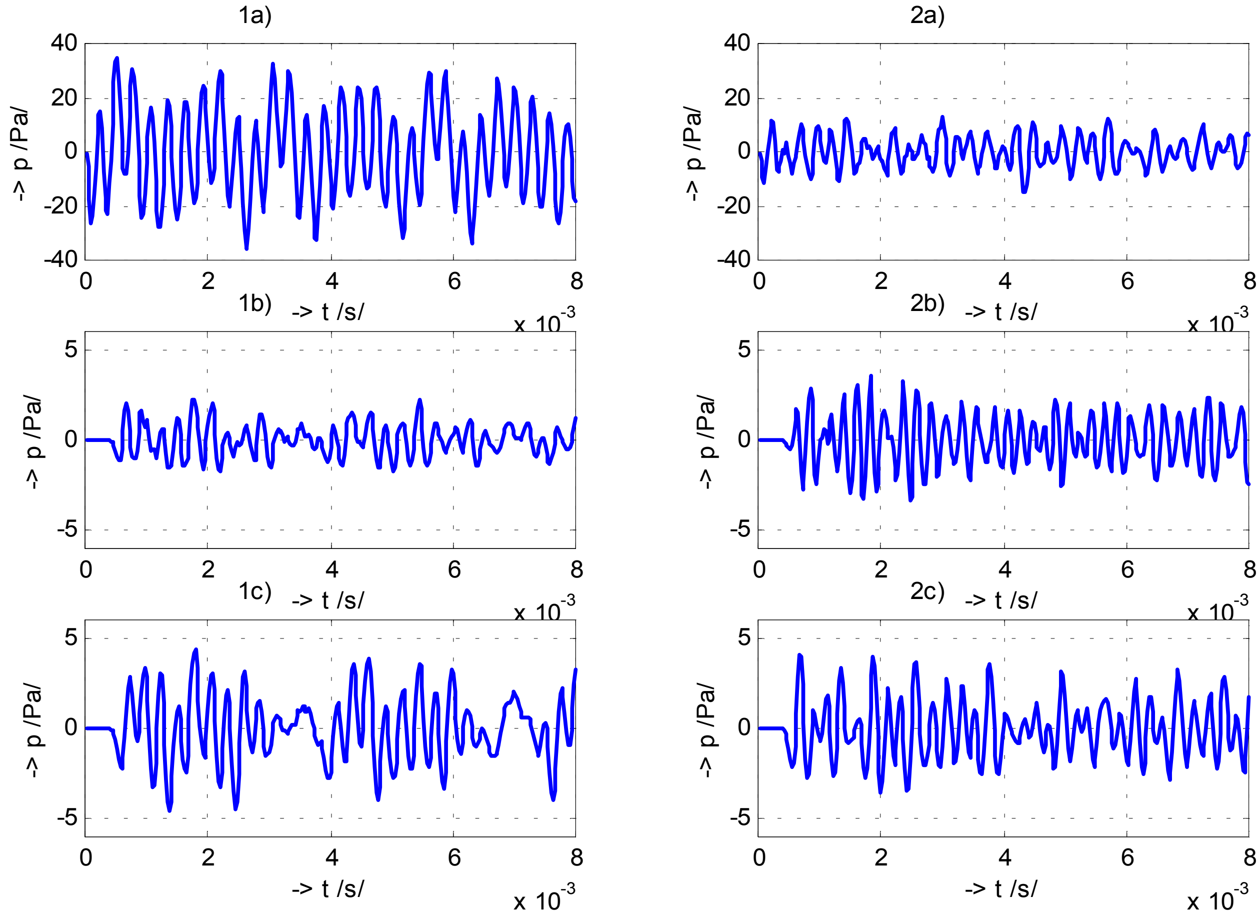


Fig. 5 Time responses of the acoustic pressure for the FE models with the cleft palate ($N_r = 20$) for the vowel /*a* / - see the variants 1 shown on the left, and for the vowel / *i* / - see the variants 2 shown on the right, calculated in three different nodes for the acoustic pressure: a) near the vocal folds; b) near the lips; c) in the space of nasopharynx.

The frequencies F1, F2, F3 and f_{nas} resulting from the transient analysis are compared in Tab. 1 with the eigenfrequencies computed by using the acoustic modal analysis. The results of both types of analysis, used for all FE models of the vowels / *a* / and / *i* / , either with or without the cleft, are in reasonable agreement.

vowel	number of elements in cleft	resonant and eigenfrequencies [Hz]							
		F1		F2		F3		f_{nas}	
		TRAN	MOD	TRAN	MOD	TRAN	MOD	TRAN	MOD
/ *a* /	$N_r = 0$	760	759	1 152	1158	2 670	2708	-	1060
	$N_r = 20$	800	796	1 145	1133	2 714	2736	2 121	2065
/ *i* /	$N_r = 0$	282	283	2 195	2216	2 968	3020	-	1282
	$N_r = 20$	467	471	2 585	2621	3 276	3348	1 612	1621

Tab. 1 Resonant frequencies evaluated from the transient analysis (TRAN) and the eigenfrequencies calculated by the modal analysis (MOD) of the FE models for the English vowels / *a* / and / *i* / , without ($N_r = 0$) and with ($N_r = 20$) the cleft palate.

CONCLUSIONS

Investigation of the acoustic transfer functions corresponding to simplified FE models of English vowels / *a* / and / *i* / considering the cleft palate is presented in the paper. The computed data files, essential for further analysis of the transfer functions, were obtained as the results of the transient analysis of the FE models by finite element system ANSYS 5.7. The FE models were excited by a transient translation motion of a small rigid plate situated in the area of the vocal folds and driven by a time signal that corresponds to a volume velocity of the air flowing through the vocal folds during phonation.

The main conclusions resulting from the numerical simulations are as follows:

- the frequency bandwidth, which corresponds to the pressure pulse excitation used, was sufficient for excitation of the first three formants considering the frequency range of a normal human voice for both modeled vowels,
- the formant frequencies F1 and F2 evaluated from the resonances of the calculated frequency response functions for the pressure are in good agreement with the experimental data known for the formants from the literature [8,9] as well as with the results of the modal analysis performed,
- the influence of the cleft on the pronunciation of the vowel / a / was found to be much smaller than the influence of the cleft palate on the sound produced during pronunciation of the vowel / i / .

The last and probably the most important conclusion resulting from the FE modeling presented here is in good agreement with the data published in literature dealing with the velopharyngeal insufficiency [5] as well as with the clinical observations of handicapped children with the cleft palate.

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The research is supported by the Grant Agency of the Czech Republic by the project No 106/98/K019 Methods of Mathematical-Physical Modelling of Vibroacoustics Systems Important in Biomechanics of Voice and Hearing.