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EXPERIMENTAL INVESTIGATION OF ACOUSTIC CHARACTERISTICS OF 3D HUMAN VOCAL TRACT MODEL WITH NASAL CAVITIES

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Abstract: *The following experiments were carried out to be later used in the verification of a complex mathematical model of human voice production. Acoustic resonance characteristics of a 3D human vocal tract model without and with nasal and paranasal cavities were measured in two different ways: The excitation was realized by (1) self-oscillating vocal folds replica and (2) by sine-tone sweeps from an earphone placed instead of the vocal folds. The resulting resonance and antiresonance frequencies were found to be comparable for both excitation signals.*

Keywords: formant frequencies, modelling of phonation, biomechanics of voice

1. Introduction

Human voice is generated by self-oscillating vocal folds excited by air flowing from the lungs. The vocal folds vibration modulates the stream of air producing the primary sound of voice. This sound signal propagates inside the supraglottal cavities (i.e., in the vocal tract) from the vocal folds to the lips and the nostrils which modify its quality. The acoustic resonances of the vocal tract create so-called formants, which occur as peaks in the envelope of the voice spectrum. The formants define vowels and the voice timbre. The final sound quality of human voice is thus given both by characteristics of the vocal fold vibration and by vocal tract properties (Sundberg, 1987).

In the present paper effects of nasal cavities together with all paranasal cavities of the vocal tract are studied. The nasality or so-called velopharyngeal insufficiency is modeled by interconnecting acoustic cavities of the nasal tract with the vocal tract model at the velum (soft palate). The objective of the experimental modelling is to offer data that can be used for verification of a complex mathematical model of phonation.

2. Methods

A three-dimensional (3D) model of the vocal tract (VT) for the vowel [a:] was created from the Computer Tomography (CT) measurement of a female subject during phonation, see Vampola et al. (2015). The complex 3D volume model of acoustic nasal cavities was developed from a detailed CT investigation of the head of another subject of the same gender, similar age and size. The physical model was made from the volume model by 3D printing, see Fig. 1.

Two kinds of excitation of acoustic cavities were realized. First by self-oscillating vocal folds replica and second by an earphone placed instead of the vocal folds. The acoustic pressure inside the mouth was measured with a B&K 4138 miniature microphone (range 6.5 Hz - 140 kHz) 3 mm from the lips and a special B&K 4182 microphone probe (range 1 Hz - 20 kHz) measured the sound 3 mm from the nostril

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inside the nasal cavity. Acoustic signal outside the vocal tract model was recorded with a sound level meter B&K 2239. All the measured signals were simultaneously sampled by the frequency of 16.4 kHz and registered by the measurement system Brüel & Kjaer PULSE type 3560 C, controlled by a personal computer equipped by the SW PULSE LabShop Version 10.

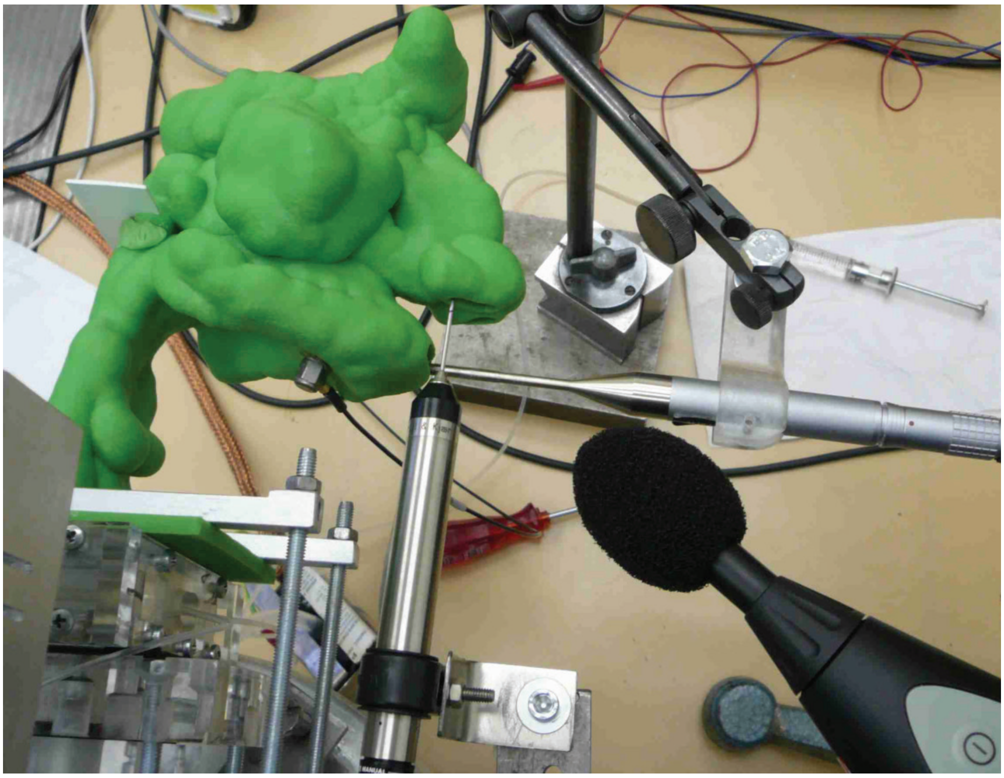

Fig. 1: Measurement set-up for nasalized vocal tract model excited by artificial vocal folds.

2.1. Excitation by the earphone

An earphone with a diameter of 15 mm was placed and sealed in the input of the vocal tract, i.e. instead of the vocal folds. Uni-directional sine sweep, range 150-5155 Hz, constant speed of 715 Hz/s, was exciting acoustic waves in VT model for the duration of 14 s. Nonlinear characteristics of the earphone were measured in a free space (without VT model) and subtracted from the measured spectra. The sound level meter B&K 2239 was installed at the distance of 3 cm from the mouth of the vocal tract model.

2.2. Excitation by the self-oscillating vocal folds model

The developed simplified model of the human lungs, which includes splitting of the airways up to the fourth order branching, was built in the subglottic part of the experimental facility; see e.g. Horáček et al. (2017). The air was flowing through the model of the lungs to the trachea. Total trachea length was 23 cm and inner diameter 18 mm.

The measurements were performed with a 1:1 scaled three layer vocal folds model (Horáček et al., 2017). The vocal folds were excited by airflow coming from the trachea. The mean airflow rate Q was set to 0.12 l/s which caused self-oscillations of the vocal folds with the fundamental frequency f_0 of 81 Hz. The sound level meter B&K 2239 was installed at the distance of 7 cm from the mouth of the vocal tract model. Sound pressure level of this signal was recalculated to the level at the distance of 3 cm from the mouth as it was in previous case of excitation.

3. Main results

Spectra of signals measured in mouth and outside the mouth for the vocal tract without nasal cavities are shown in Fig. 2. The upper solid curves demonstrate responses to sine sweep excitation. Spectra of the raw signal excited by vocal folds and after filtering out f_0 and higher harmonics are represented by the lower thin and thick curves, respectively.

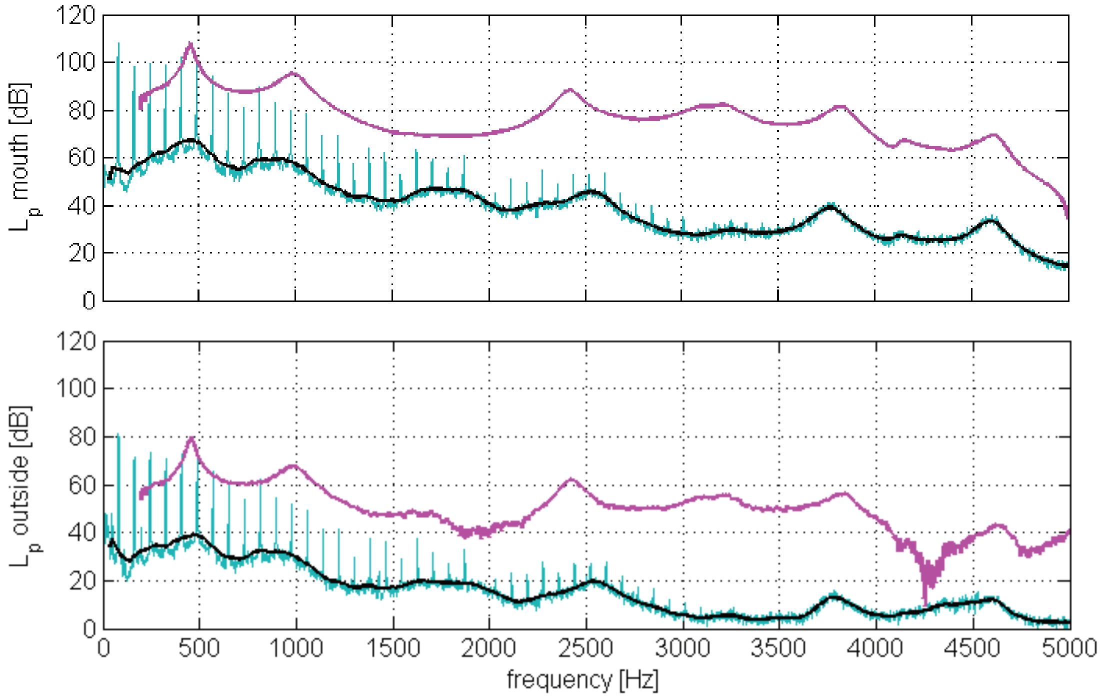

Fig. 2: Sound pressure spectrum levels of the vocal tract without nasal cavities inside and outside the mouth.

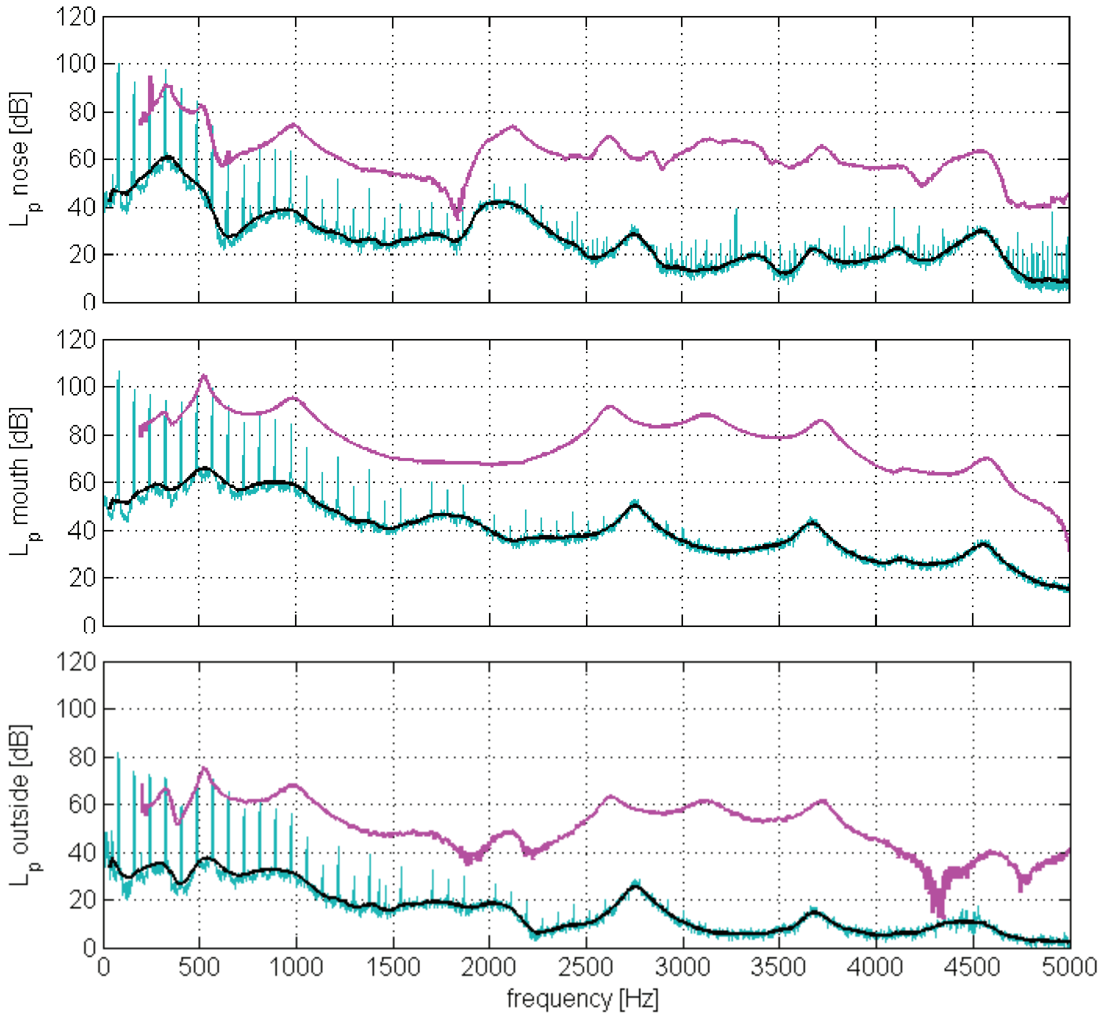

Fig. 3: Sound pressure spectrum levels of the vocal tract with nasal cavities inside the nose and the mouth and outside the mouth.

The spectra of the vocal tract with nasal cavities measured in nose, in mouth and outside the mouth are shown in Fig. 2. Resonance (formant) frequencies are summarized in Tab. 1.

Tab. 1: Resonance frequencies of the vocal tract model with and without nasal cavities measured in mouth and outside the mouth

Without nasal cavities		F_{1nasal}	F_1	F_2	F_{2nasal}	F_3	F_4	F_5
Mouth	Earphone	/	455	984	/	2420	3222	3831
	Vocal folds	/	460	930	/	2530	3250	3770
	Difference [%]	/	-1.1	5.8	/	-4.4	-0.9	1.6
Outside	Earphone	/	456	980	/	2425	3222	3831
	Vocal folds	/	480	840	/	2530	3220	3780
	Difference [%]	/	-5.0	16.7	/	-4.2	0.1	1.4
With nasal cavities								
Mouth	Earphone	320	525	984	/	2627	3128	3720
	Vocal folds	280	530	910	/	2750	/	3670
	Difference [%]	14.3	-0.9	8.1	/	-4.5	/	1.2
Outside	Earphone	326	526	971	2100	2627	3120	3723
	Vocal folds	300	540	850	2010	2760	/	3680
	Difference [%]	8.7	-2.6	14.2	4.5	-4.8	/	1.2

4. Conclusions

Resonance frequencies measured with the earphone are mostly in good agreement with the resonances measured with vibrating vocal folds. The highest differences are for the second resonance F_2 measured outside the vocal tract model. Differences can be caused by a longer input cavity (glottis) and by a periodical change of an input boundary condition in case of excitation with self-oscillating vocal folds periodically closing the glottis.

Both types of experiments (earphone and vocal folds) show the same qualitative change of resonance frequencies after connecting nasal cavities into the human vocal tract model: an increase of F_1, a decrease of the difference (F_5 - F_3) and formation of new nasal resonances F_{1nasal} and F_{2nasal}. Also the new antiresonance frequencies at about 400 Hz and 2200 Hz agree for both types of excitation.

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