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INFLUENCE OF THE NASAL CAVITIES TO HUMAN VOICE QUALITY

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Abstract: *Nasal cavities (NC) form the side branches of the human vocal tract and exhibit antiresonance and resonance properties which influence the produced voice quality. This study investigates the possibility of these resonances to contribute to the speaker's or singer's formant cluster around 3 – 5 kHz. A reduced finite element (FE) model was created which allows numerical simulation of the effects of changing the volumes of NC on the acoustic resonance and antiresonance characteristics of the vocal tract. This model, created from an accurate three-dimensional (3D) FE model of the human vocal tract for vowel [a:] and [i:] is computationally-effective and allows parametric changes of the volume connecting the nasal tract with the human vocal tract. Developed FE models of acoustic spaces of nasal and vocal tract for vowels /a:/ and /i:/ are used to study the influence of (NC) on phonation of these vowels. Acoustics frequency-modal characteristics are studied by modal analysis and numerical simulation of acoustic signals in time domain is performed by transient analysis of the FE models.*

Keywords: Human vocal tract, Nasal cavities, Human voice quality, Self-exciting vibration, Bio-acoustic, FE parametric model, Velopharyngeal insufficiency.

1. Introduction

Velopharyngeal insufficiency (VPI) is an insufficient closing of nasal cavity (nasopharynx) and its airproof separation from the oral cavity (oropharynx). VPI leads to open nasality (rhinolalia aperta) affecting all oral speech sounds that should not be nasal. Small defects of the velopharyngeal closure become evident first by a different timber of the voice, bigger defects influence formant structure of vowels. According to the literature (Carney et al., 1971) the VPI influence in particular the production of vowels /i:/ and on the other hand its influence on the production of vowel /a:/ is smaller. Several types of nasal speech are not easily diagnosed even specialized physicians are often not fully aware of the differences. Acoustic analysis of VPI are oriented mainly on differences in voice timbre because the resonant changes are the most essential. While the influence of the vocal tract on vocal out-put has been studied rather extensively, the influence of side cavities of human vocal tract, such as the nasal cavities (NC) has received less attention. Generally, these cavities have been re-ported to cause antiresonances in the resulting vocal spectrum, i.e., largely decreasing radiation of some of the spectral frequencies out of the mouth, particularly those around 4 – 5 kHz (Dang et al., 1997). As such, their role for the resulting vocal intensity may be considered undesirable, since it contradicts the general goal of enhancing vocal output with the smallest vocal effort. However, newest studies with perceptual evaluations of sounds produced using 3D mathematical and physical models of the singers' vocal tracts revealed that the voice quality is perceived as being better when side branches are present (Mokhtari et al., 2008). Furthermore, spectral analysis of singers indicates that the formant structure around 3 – 5 kHz is more complex than usually expected. A more detailed analysis shows that besides the antiresonances there are also new resonances which occur due to these side cavities. In technical terms, the side cavities create zero-pole, i.e. antiresonance-resonance pairs in the overall transfer function of the vocal tract.

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2. Computational model

The construction of the FE model of the female vocal tract from the CT images was described in the previous papers of the authors and the mathematical background for finite element analysis of the acoustic eigenfrequencies and eigenmodes of the human supraglottal acoustic spaces of the human vocal tract can be found in (Vampola et al., 2008). The sophisticated accurate 3D FE models of the vocal tract are, however, problematic to use for investigating the effect of vocal tract shape modifications on the changes in acoustic resonance properties since the calculations of each single configuration takes many hours of time. Simple 1D models based on the knowledge of the cross-sectional area of the vocal tract are more advantageous for this purpose since they allow a fast online computer simulation of phonation. The analysis of the resonance and antiresonance characteristics and of the acoustic mode shapes is based on a three-dimensional (3D) finite element (FE) model of the human vocal tract constructed from the CT measurements of a subject phonating on [a:] and /i:/ vowel. Then, a reduced FE model is created which includes the side cavities and its resonance and antiresonance frequencies are tuned to correspond to those of the full FE model. This reduced model is then used for analyzing the antiresonances, resonances and the pressure transfer function of the vocal tract. The accuracy of the results obtained using the reduced model is examined by comparing these to the results obtained with the full 3D FE model. Then the effect of the volume changes of the nasal cavities on the acoustic pressure transfer function is studied.

The basic mathematical description governing equations for acoustic pressure in an acoustic cavity can be written in the FE formulation as

$$\mathbf{M}\ddot{\mathbf{p}} + \mathbf{B}\dot{\mathbf{p}} + \mathbf{K}\mathbf{p} = \mathbf{0} \tag{1}$$

where **M**, **B** and **K** represent global (N xN) mass, damping and stiness matrices, **p** is vector of nodal pressures in N nodes inside the vocal tract, and the dot and double dots above the pressure denote the first and second time derivatives, respectively.

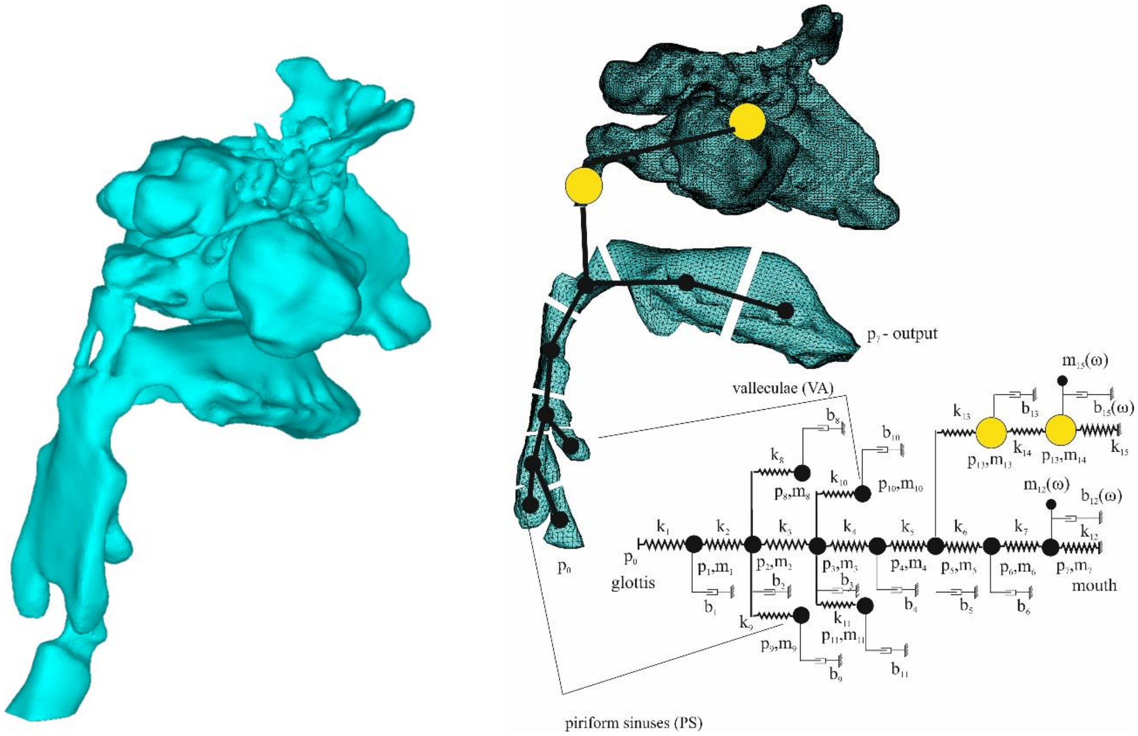

Fig. 1: Volume model of the human vocal tract for vowel/a:/ (left);
Simplified computational model of the human vocal tract for vowel/a:/ (right).

2.1. Acoustic modal analysis

The acoustic frequency - modal characteristics of the FE models were studied by the modal analysis considering air density ρ_0 = 1.2 kg.m^{-3}, sound speed c_0 = 350 m.s^{-1}, co-efficient of the boundary admittance $\mu = r / \rho_0 . c_0$ = 0.005, where r is the real component of the specific acoustic impedance (Vampola et al., 2015) and the pressure $p = 0\ Pa$ at the lips and nose.

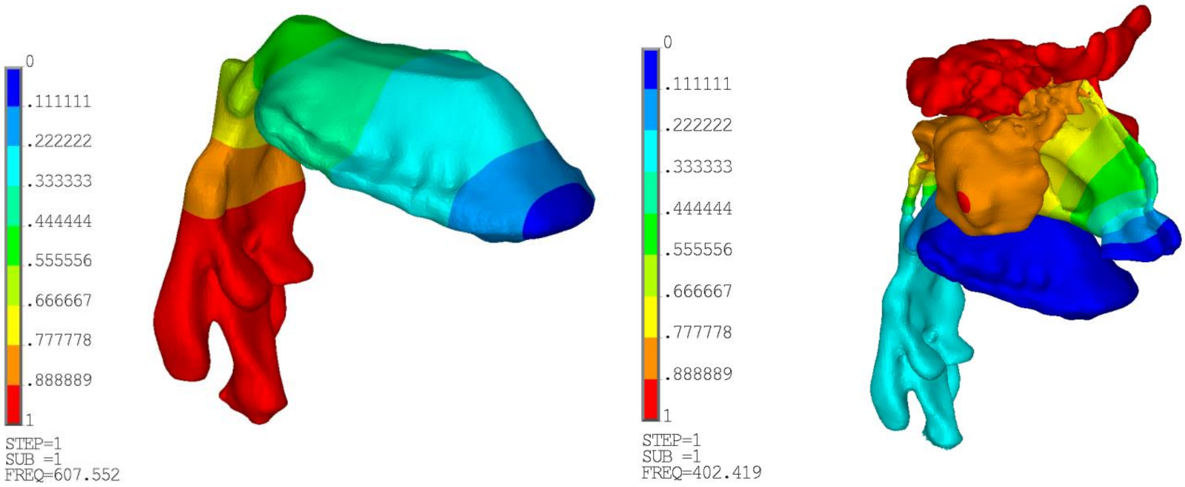

Fig. 2: The first oral mode of the human vocal fold – vowel /a:/ without nasal cavities (left, 607 [Hz]) and with nasal cavities (right, 402 [Hz]).

Tab. 1: Vowel /a:/ (ON-oral-nasal frequency, O-oral frequency, N-nasal frequency).

<table>
<tr><td></td><td colspan="2">F_1 [Hz]</td><td colspan="2">F_2 [Hz]</td></tr>
<tr><td>Without nasal cavities</td><td colspan="2">607</td><td colspan="2">1233</td></tr>
<tr><td>With nasal cavities</td><td>ON
402</td><td>O
708</td><td>N
1096
1240</td><td>ON
1440</td></tr>
</table>

Due to the velopharyngeal insufficiency the oro-nasal frequencies fnaso for vowels /a:/ appear below the first formant (fnaso < F1) and between the first and second formants (F1 < fnaso < F2. The first pure oral frequency is shifted to second formant. For the vowel /i:/, the oro-nasal frequencies appear between the first and second formants (F1 < fnaso < F2) of the normal voice and between the second and third formants (F2 < fnaso < F3). The first pure oral frequency disappeared.

2.2. Acoustic transient analysis

The FE models of the supraglottal spaces were excited in time domain at the position of the vocal folds and the sound radiation looses were modeled at the lips and nose. The broad band frequency pulse was used for excitation of the resonant frequencies of the acoustic spaces for simulation of phonation in time domain. The Newmark method for integration of the governing equations for the pressure in FE formulation was used. The interconnection of the acoustic spaces diminishes the pressure level at the lips. This pressure decrease is more considerable for vowels and /i:/ than for the vowel /a:/. The decrease of the pressure level at the lips due to the VPI for the vowel /a:/ is much smaller value than the decrease of for the vowels /i:/. The results support the clinical observations (Carney et al., 1971), the VPI influence more substantially the phonation of vowels /i:/ than the vowel /a:/. However, the increasing size of the interconnecting area has only small influence on the level of the pressure at the lips and thus a quantification of a degree of connecting the vocal and nasal tract on such basis is difficult.

3. Conclusion

The results show that the human vocal tract is a very complex resonator. Side branches are generally known to cause antiresonances, i.e., sharp local minima in the resulting transfer function. In speech research the antiresonance phenomenon is well known from the studies of nasalized vowels where the nose acts as the side branch of the vocal tract (Hattori et al., 1958). The NS cavities act as antiresonators which severely decrease the sound level radiating out of the mouth around the antiresonance frequency. Simultaneously, however, they act also as resonators which amplify the acoustic output at different frequencies. The larger the volume of the NS cavities, the lower their antiresonance and resonance frequencies are. There has been good evidence that humans can willingly change the size of these cavities. These findings suggest that the NS cavities may play a beneficial role in producing the "resonant voice".

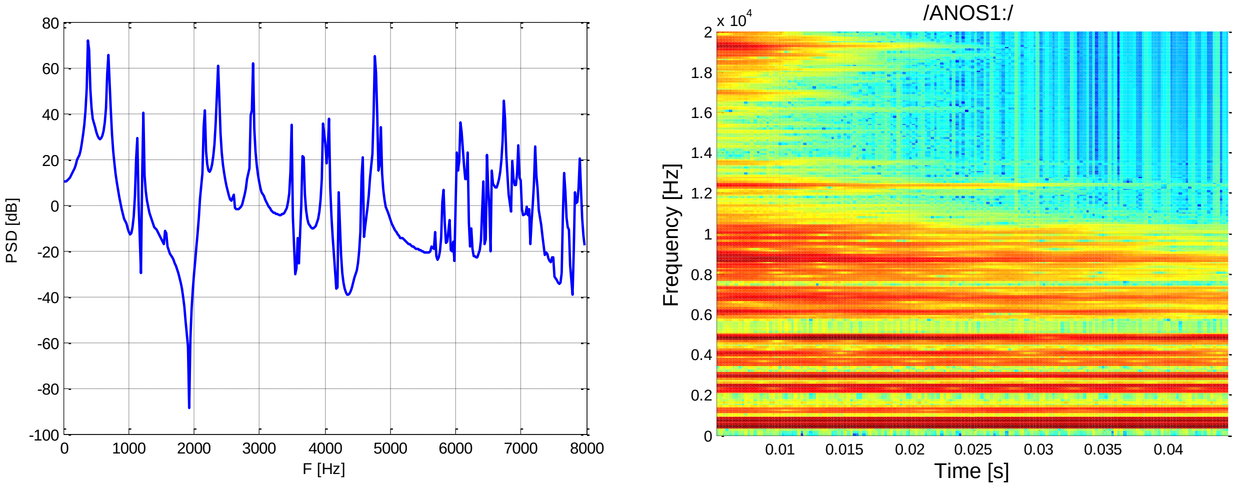

Fig. 3: Acoustic pressure response computed at the lips (left), spectrogram of the computed acoustic pressure of the lips using the simplified model with VPI harmonically excited (right).

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