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Mathematical Modelling of the Sensitivity of Acoustic Resonance Properties to a Change in Volume of Lateral Cavities of the Human Vocal Tract

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Abstract: An analysis of acoustic resonant properties of the human vocal tract including piriform sinuses was done using 1D mathematical model. Resulted changes caused by the lateral cavities correspond to recent findings of 3D computational models.

Introduction

Lateral cavities of the human vocal tract (VT) play specific role in the speech spectra. It was shown by several authors that piriform sinuses (PS), side branches in the bottom part of the pharynx, decrease formant frequencies in the lower frequency region. Besides, these cavities cause spectral minima in a region of 4 to 5 kHz as was proved by Dang and Honda in [1]. Detailed computational analysis of 3D acoustical mode shapes done by Vampola et al. [2] revealed that PS additionally contribute extra resonances. In this paper a simplified mathematical model is used to describe this issue.

Mathematical Model

The acoustical system was described by the wave equation of an acoustical duct with variable cross-section A and viscosity losses (specific acoustic resistance r_N)

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{1}{A} \cdot \frac{\partial A}{\partial x} \cdot \frac{\partial \phi}{\partial x} - \frac{1}{c_0^2} \cdot \left(\frac{\partial^2 \phi}{\partial t^2} + c_0 \cdot r_N \cdot \frac{\partial \phi}{\partial t} \right) = 0 . \tag{1}$$

The system was modelled in frequency domain using conical acoustical ducts, considering the radiation impedance at lips. Geometry of the model has been derived from CT images of the human vocal cavities for vowel /a:/, see [3]. The following values of fluid density, dynamic air viscosity, and speed of sound were used, respectively: $c_0 = 353\, ms^{-1}$; $\rho = 1.2\, kgm^{-3}$, $\mu = 1.8 \cdot 10^{-5}\, kgm^{-1} s^{-1}$.

Results

Geometry of the computational model including PS of nominal volume size is depicted in the upper panel of Fig. 1. Corresponding transfer functions from the glottis to the position of lips and to the closed ends of PS are shown below. Moreover the transfer function of the VT model without PS is plotted with black dashed line. The volume of PS was changed from zero to the nominal value for which the normalized volume was $V_N = 1$, the length of both PS kept constant at 20 mm. New pair of resonances around 5 kHz followed by an antiresonance frequency were detected in the results. The formant frequencies lying below the first new resonance of PS lowered with increasing PS volume, whereas the others increased, see Fig. 2.

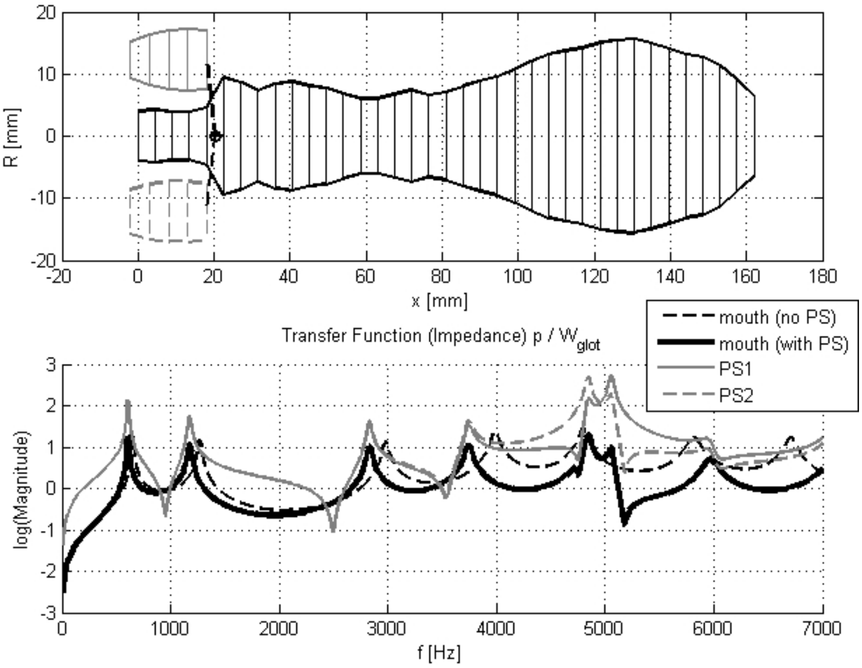

Fig. 1: Top: Geometry of the VT model with PS of normalized volume $V_N = 1$.
Bottom: Transfer function from glottis
a) to lips without PS (black dashed),
b) to lips including PS (black solid),
c) to PS1 cavity (grey solid),
d) to PS2 cavity (grey dashed).

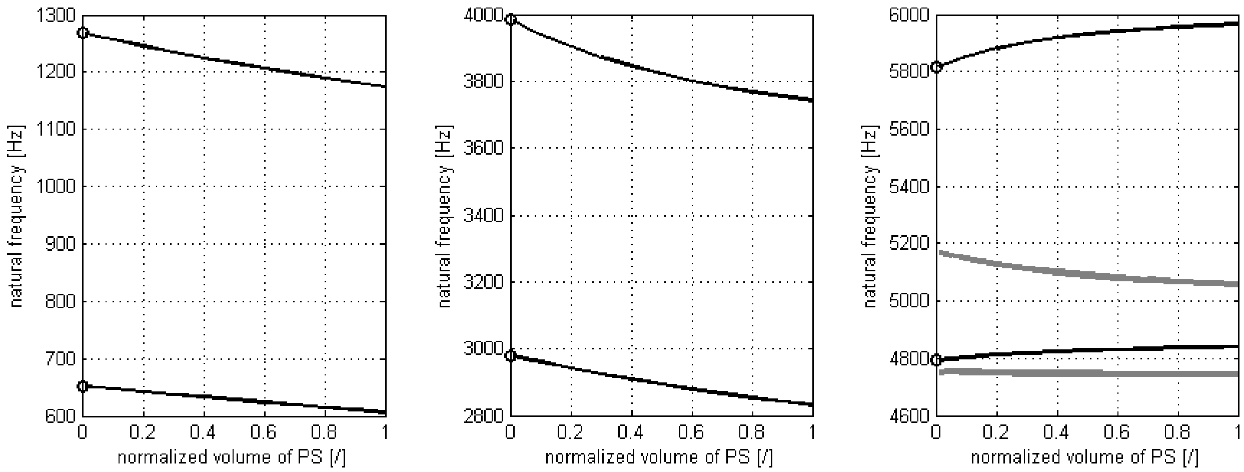

Fig. 2: Natural frequencies of the VT model in dependence on normalized volume of PS. Grey lines depict resonances that disappear when $V_N = 0$.

Summary

Although the simplified 1D model cannot capture higher-frequency transversal mode shapes, the resulted changes caused by PS correspond to recent findings of 3D computational models [3].

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