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EXPERIMENTAL MODELLING OF THE INFLUENCE OF VOCAL FOLDS STIFFNESS ON ACOUSTIC RESPONSE SPECTRA OF THE HUMAN VOCAL TRACT

Radolf V.[1], Košina J.[1], Horáček J.[1]

Abstract: *The acoustic volume velocity transfer function of a vocal tract characterizes its acoustic resonance properties, which are important for human voice production. In this paper, the computed and measured transfer functions of the vocal tract model are compared. The procedure of measuring the transfer function is then applied to the vocal tract model completely closed by the silicone vocal folds model. The influence of the vocal folds' stiffness on the vocal tract transfer function and also on the acoustic response spectra during simulated phonation was found to be very important - especially in higher frequency regions.*

Keywords: Vocal tract transfer function, Vocal folds silicone model, Yielding walls

1. Introduction

The transfer function of a vocal tract is commonly used to describe resonance properties of this acoustic filter changing the primary sound source to the voice sound radiated from the mouth. These properties are, however, strongly dependent on the boundary conditions of the vocal tract. The input boundary conditions, i.e., the vocal folds, change the state from open to closed during phonation. Moreover, closure is done by soft tissue instead of a hard wall that is usually considered in numerical simulations. Computational as well as experimental modelling of these two problems is still not properly resolved. Therefore, we proceeded to measure and compute the transfer functions of the vocal tract model connected to vocal folds replica made of silicone, which has been used for experimental investigation of voice in our laboratory for several years, see, e.g., (Laukkanen et al., 2021). For the measurements we used the recently published methodology developed by Fleischer et al. (2018). A computational analysis of the vocal tract acoustics was done using a previously published transmission line model by Radolf et al. (2016) in a frequency domain

$$\begin{bmatrix} p_L \\ U_L \end{bmatrix} = \mathbf{T_{VT}} \cdot \begin{bmatrix} p_G \\ U_G \end{bmatrix} = \begin{bmatrix} A_{VT} & B_{VT} \\ C_{VT} & D_{VT} \end{bmatrix} \cdot \begin{bmatrix} p_G \\ U_G \end{bmatrix}, \tag{1}$$

where p and U are acoustic pressure and volume velocity respectively, $\mathbf{T_{VT}}$ is a transfer matrix of the vocal tract obtained by multiplying transfer matrices of all conical elements from the glottis to lips (see Fig. 1), and the indices G, L respectively mean the position of glottis (vocal folds) and lips.

In addition, we compare the spectra of the simulated phonation, i.e., the self-excited oscillations of the vocal folds model, with the transfer functions.

2. Methods

The simplified vocal tract (VT) model with circular cross sections was 3D printed using an acoustically hard material. Its main geometric configuration was taken from a 3D volume model obtained from CT examination for the vowel [a:], see (Vampola et al., 2011). However, the VT shape was slightly modified, as described by Radolf et al. (2024), see Fig. 1.

[1] Ing. Vojtěch Radolf, Ph.D., Ing. Jaromír Horáček, DrSc., Ing. Jan Košina: Institute of Thermomechanics of the Czech Academy of Sciences, Dolejškova 1402/5, 182 00 Prague, Czech Republic, radolf@it.cas.cz

The volume velocity transfer function of the VT model was measured using the method described by Fleischer et al. (2018). This utilizes excitation of the VT model with an external sound source in front of the lips and measurement of the sound pressure inside the model at the closed glottal end. Thus the pressure P_1 is measured at the glottis while the mouth is open and then the pressure P_3 is measured directly in front of the closed lips. The pressure ratio P_1/P_3 is exactly the volume velocity transfer function, which reflects resonances of the VT open at the lips and closed at the glottis with a hard wall.

However, the input boundary condition of a real human VT is more complex compared to that of a hard wall, because the vocal folds created by soft tissue can be very compliant. To model this phenomenon, we applied the experimental method (Fleischer, 2018) using the silicone model of vocal folds created from Ecoflex 00-10. The pressure P_1 was measured with a special B&K 4182 microphone probe with a diameter of 1.25 mm inserted between the left and right parts of the three-layer vocal fold (VF) model, which was connected to the VT model. The transfer function was then measured for several conditions of VF filled either with pressurized air or water. Changing the medium and its pressure in the middle layer between models of epithelium and body layers inside the VF replica simulated its various dynamic stiffnesses.

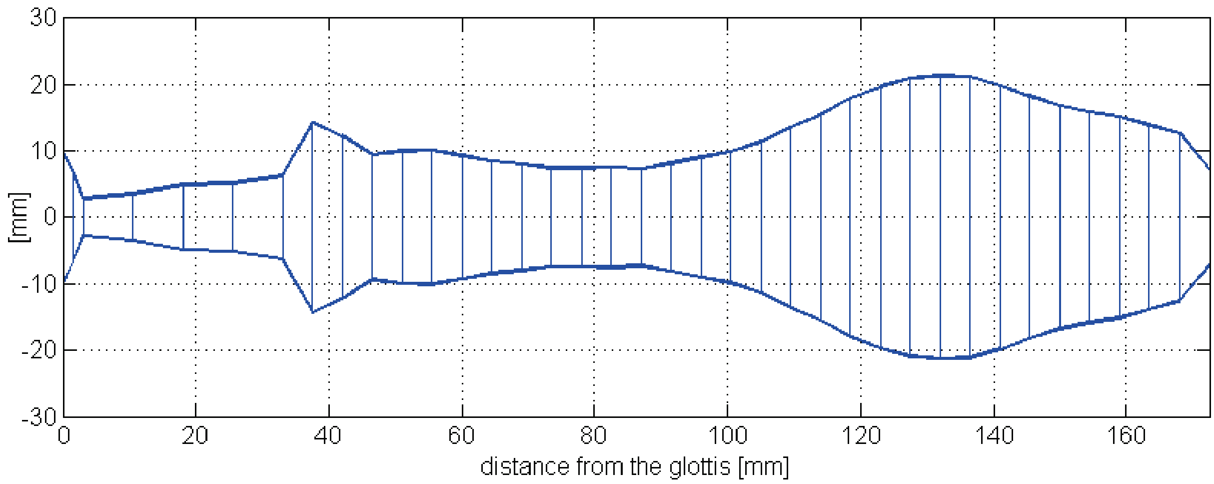

Fig. 1: Geometry of the acoustically analysed vocal tract model for vowel [a:].

3. Results

Spectra of measured pressure signals and the transfer function resulting from the above-mentioned measurement procedure are plotted in Fig. 2. The transfer function (thin green line) was filtered (averaged) to better emphasize its character and peaks. The resulting filtered spectra (thick green line) were obtained by using frequency bands (windows) of 50 Hz and shifting them by a frequency step of 5 Hz. In each window the mean value of the level was calculated and plotted in the middle of the frequency range of the window. The location of maxima of the filtered spectra can be compared to the mathematically-modelled transfer function (dotted black line). The calculated third resonance frequency differs from the measured one by 7.2 %. Other resonances up to 5 kHz differ from the measured ones by less than 3 %.

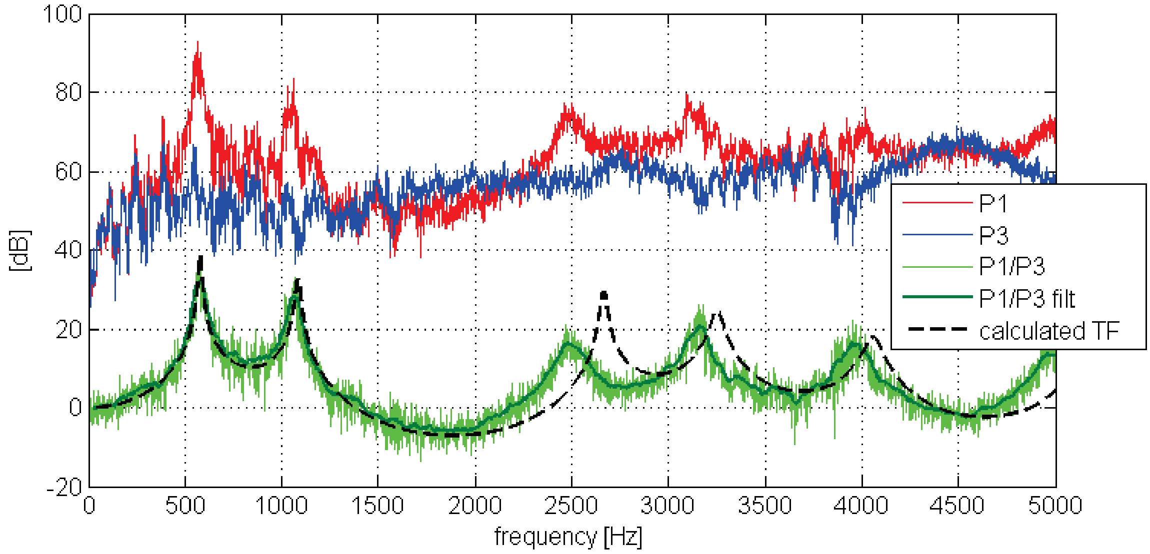

Fig. 2: Spectra of pressure signals measured at the glottis closed with a hard wall (P_1) and in front of the closed mouth (P_3), transfer function (TF) P_1/P_3 resulted from the measured signals and from the computational analysis.

Figure 3 shows the final version of the measured transfer functions for a hard wall instead of VF and for VF filled with water with an internal pressure of 10 mbar. It can be seen that varying the VF stiffness changes the resonances both in frequency and level. A substantial difference between hard wall and compliant VF is evident mainly above 2 kHz. The transfer functions can be compared with spectra of the acoustic signal recorded during simulated phonation when VF model filled with water was driven by an airflow rate of 0.25 l/s and self-oscillated with a fundamental frequency of 186 Hz. It is clear that the transfer function of the hard wall tract does not match the spectrum from phonation. This spectrum is, on the contrary, well characterized by the transfer function measured with VF in the static position.

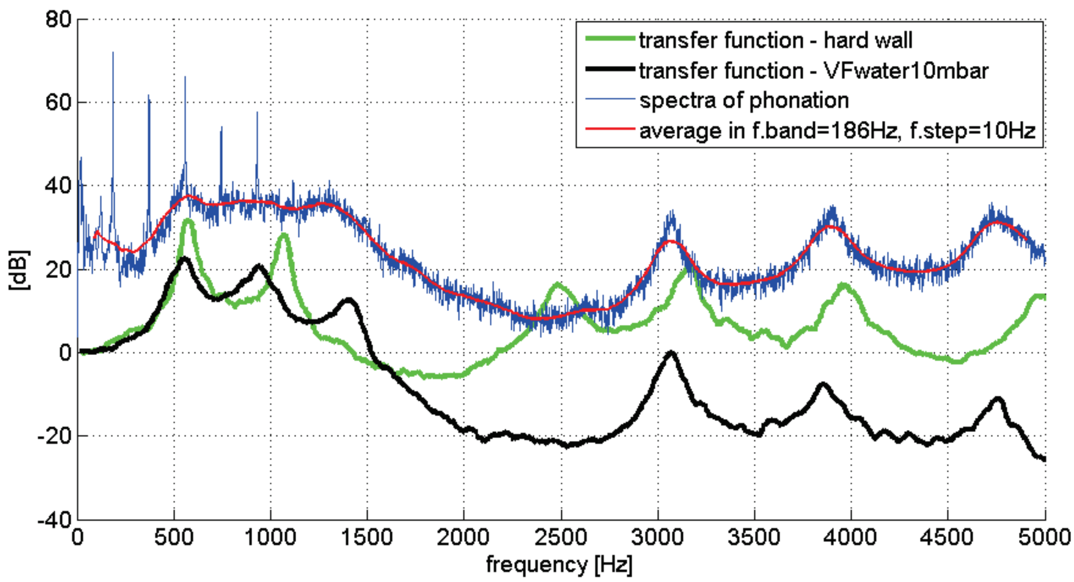

Fig. 3: The volume velocity transfer function measured for the hard wall at the position of the vocal folds and for VF model filled with water; spectra of the acoustic signal measured 20 cm from the lips during self-oscillation of the VF model filled with water.

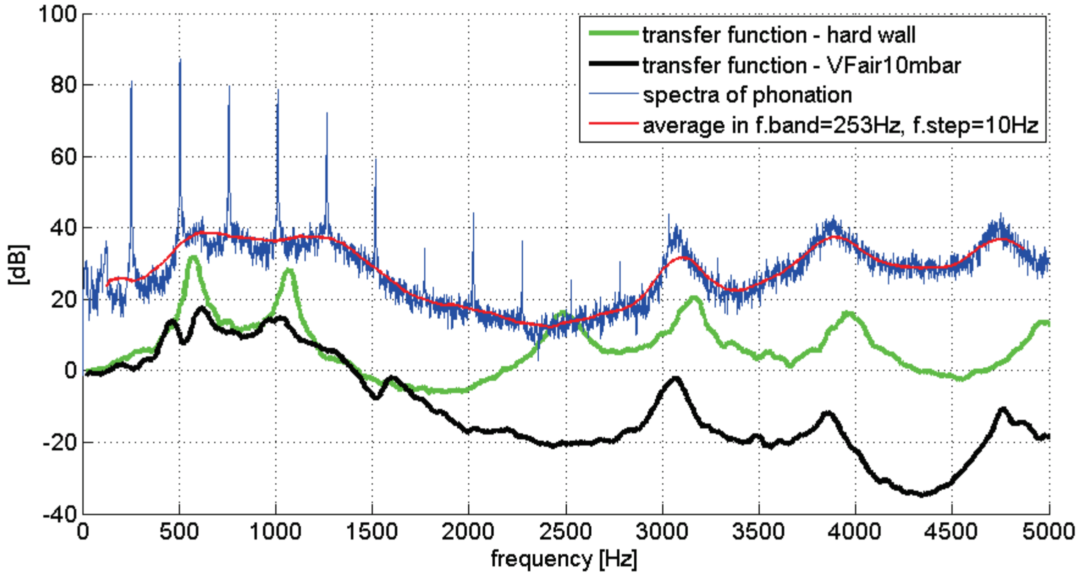

Fig. 4: The volume velocity transfer function measured for the hard wall at the position of the vocal folds and for VF model filled with air; spectra of the acoustic signal measured 20 cm from the lips during self-oscillation of the VF model filled with air.

Figure 4 compares the measured transfer functions for hard wall and for VF filled with air with an internal pressure of 10 mbar. Spectra of the acoustic signal recorded during self-oscillations of the VF model filled with air, with the fundamental frequency of 253 Hz and the airflow rate of 0.3 l/s again correspond much better to the transfer function with VF model.

4. Conclusions

The stiffness and viscous properties of the vocal folds can significantly change the vocal tract frequency-modal and damping acoustic characteristics, especially in the frequency range above 2 kHz. We can note that a smaller contact quotient (CQ) means a longer time for open glottis and thus the evaluated resonances might correspond rather to this case.

Acknowledgement

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