EXPERIMENTAL MODELLING OF THE INFLUENCE OF VOCAL FOLDS COMPLIANCE ON HUMAN VOCAL TRACT ACOUSTIC PROPERTIES

Vojtěch Radolf*, Jaromír Horáček*,
Anne-Maria Laukkanen**

* Institute of Thermomechanics, Academy of Sciences, Prague, Czech Republic

** Speech and Voice Research Laboratory, Tampere University, Tampere, Finland

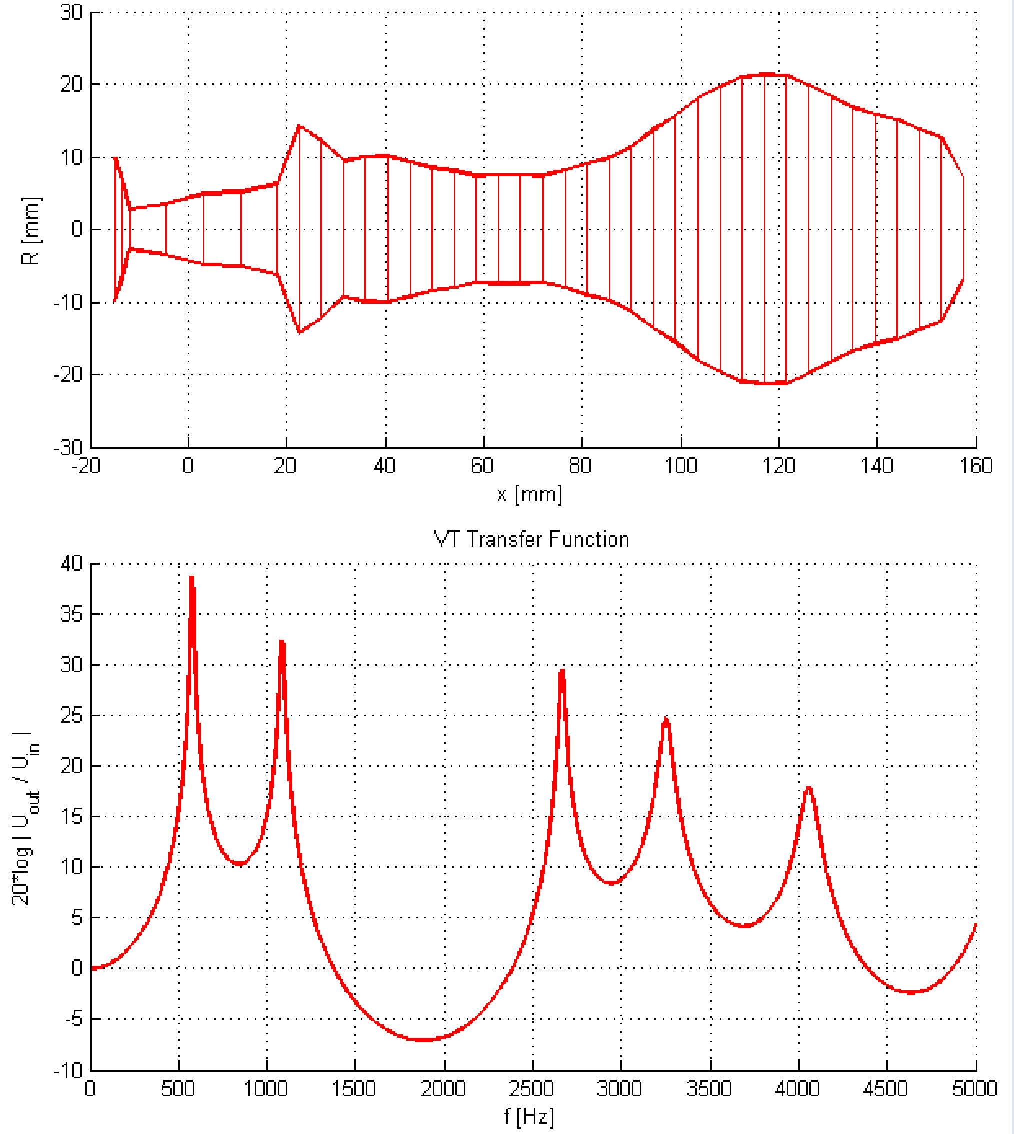
INTRODUCTION

Transfer function of VT

– describe acoustic resonance properties of this filter:
primary sound source --> voice sound radiated from the mouth.

– dependent on boundary conditions (open x closed VF, closure done by soft tissue x hard wall).

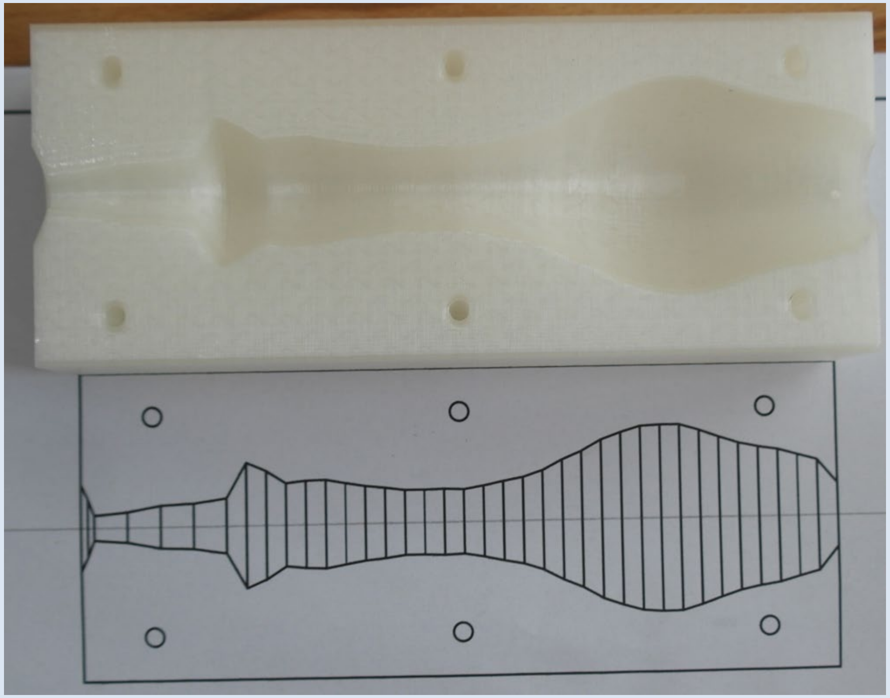
Modelling of these two problems properly resolved?



METHODS

3D VT model created from CT examination of a female subject during phonation [a:], see [1].

- simplified VT model with circular cross-sections was 3D printed using an acoustically hard material.

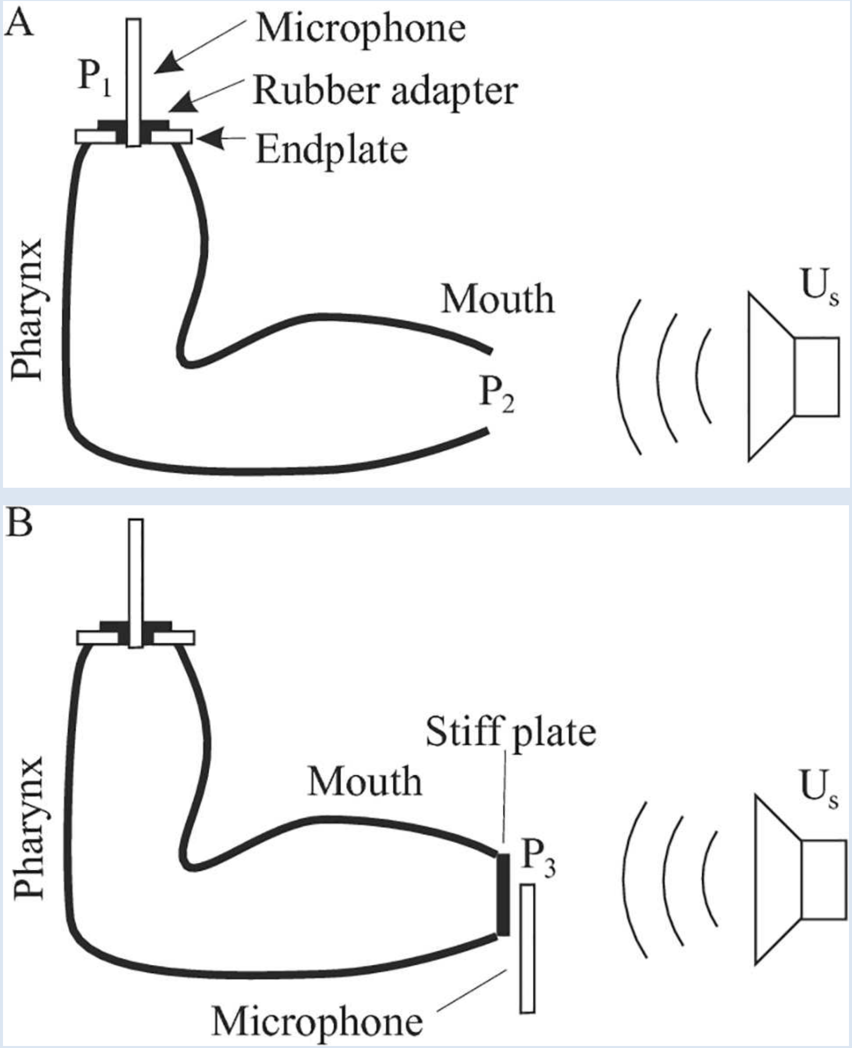


[1] Vampola T., Laukkanen A-M., Horáček J., Švec J.G.: Vocal tract changes caused by phonation into a tube: A case study using computer tomography and finite-element modeling. J. Acoust. Soc. Am. 129 (1), 2011, 310-315.

METHODS – MEASUREMENT SET UP

Volume velocity transfer function of the VT model was measured using the method described in [2]:

- excitation of the VT model with an external sound source in front of the lips,
- pressure P_1 is measured at the closed glottis while the mouth is open,
- pressure P_3 is measured right in front of the closed lips.
- P_1/P_3 = volume velocity transfer function U_2/U_1



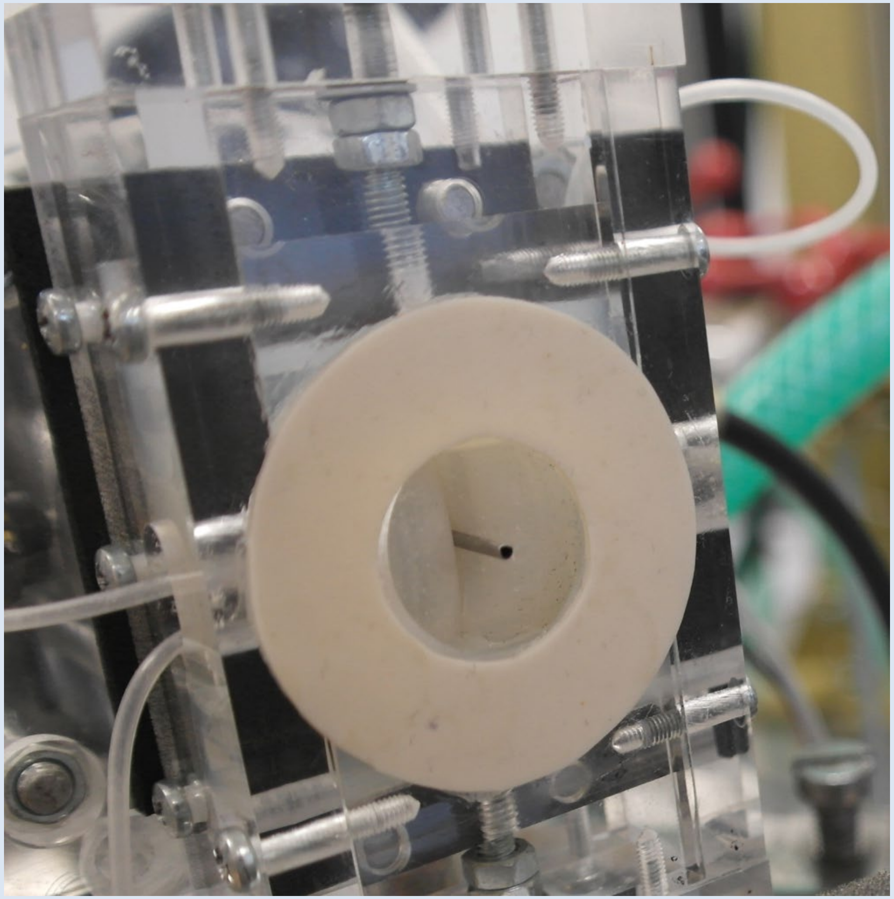
[2] Fleischer M., Mainka A., Kürbis S., Birkholz P.: How to precisely measure the volume velocity transfer function of physical vocal tract models by external excitation. PLoS ONE 13(3), 2018, e0193708.

METHODS – MEASUREMENT SET UP

We applied the experimental method [2] using the the three-layer model of vocal folds (silicone Ecoflex 00-10).

- Microphone probe inserted between the left and right part of VF model (connected to VT).
- Transfer function measured for several conditions of VF filled either with pressurized air or water.

- Loudspeaker 170 mm, 8 Ohm, 150 W, white noise signal.



[2] Fleischer M., Mainka A., Kürbis S., Birkholz P.: How to precisely measure the volume velocity transfer function of physical vocal tract models by external excitation. PLoS ONE 13(3): e0193708.

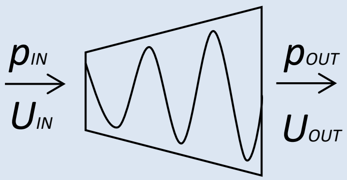
METHODS – MATHEMATICAL MODEL

Wave equation of an acoustic duct

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

Transfer matrix of a conical acoustic duct

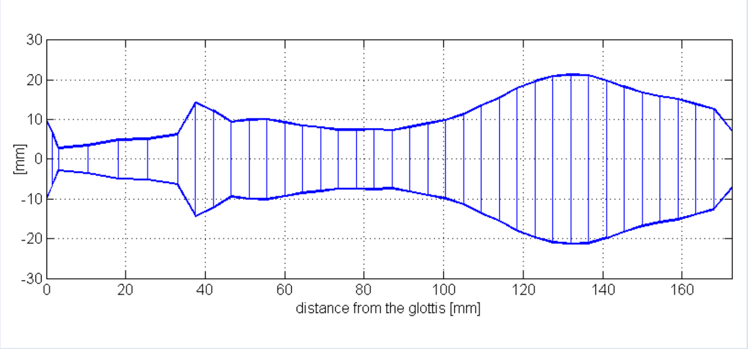
$$\begin{bmatrix} p_{OUT} \\ U_{OUT} \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \cdot \begin{bmatrix} p_{IN} \\ U_{IN} \end{bmatrix}$$



Transfer matrix of the vocal tract

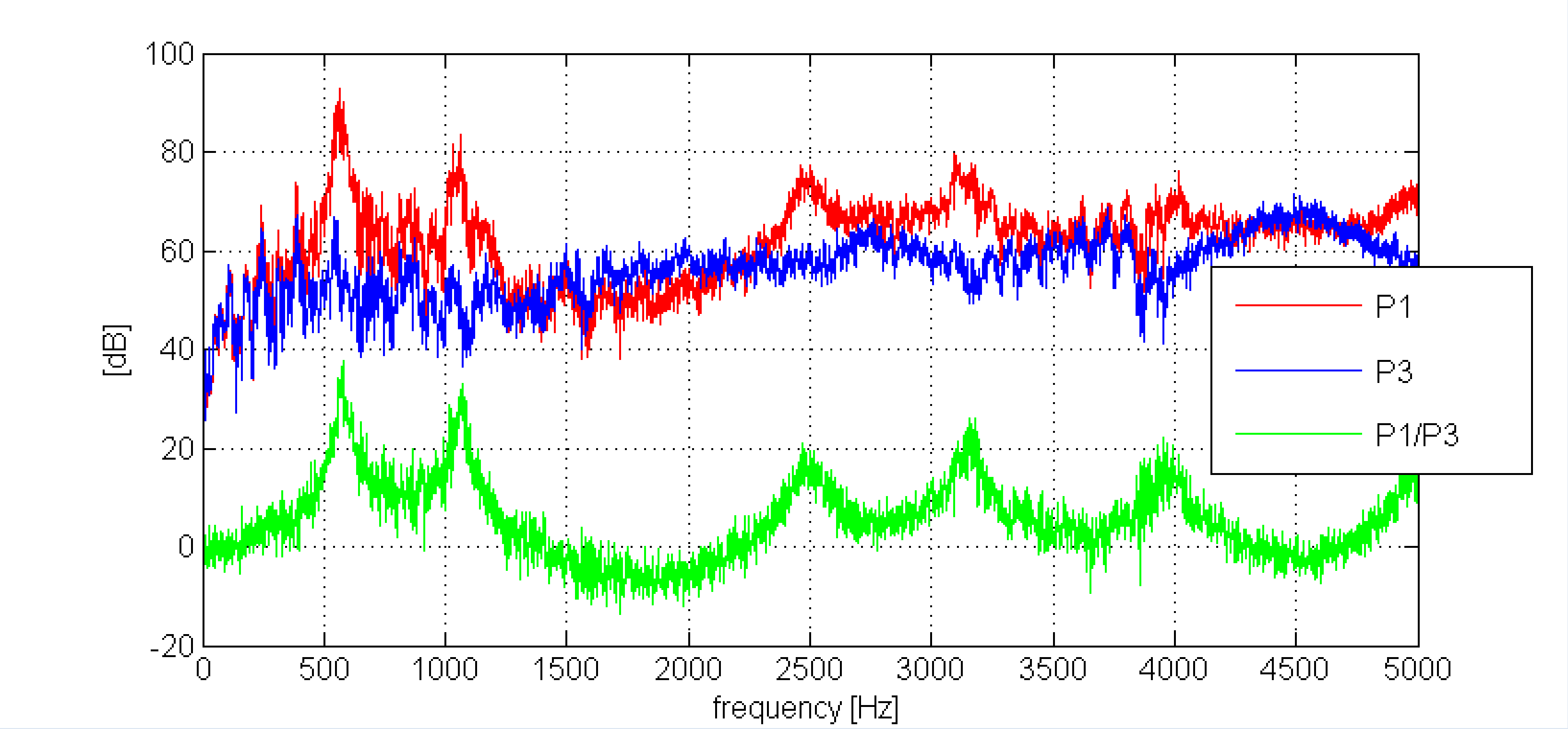
$$\begin{bmatrix} p_{LIP} \\ U_{LIP} \end{bmatrix} = \mathbf{T}_{VT} \cdot \begin{bmatrix} p_{GLOT} \\ U_{GLOT} \end{bmatrix}$$

$$\mathbf{T}_{VT} = \begin{bmatrix} a_{VT} & b_{VT} \\ c_{VT} & d_{VT} \end{bmatrix} = \mathbf{T}_{N_e+1,N_e} \cdot \mathbf{T}_{N_e,N_e-1} \cdot \ldots \cdot \mathbf{T}_{3,2} \cdot \mathbf{T}_{2,1}$$



RESULTS

- **Spectra of pressure signals and the transfer function**
  - hard wall closure at the glottis



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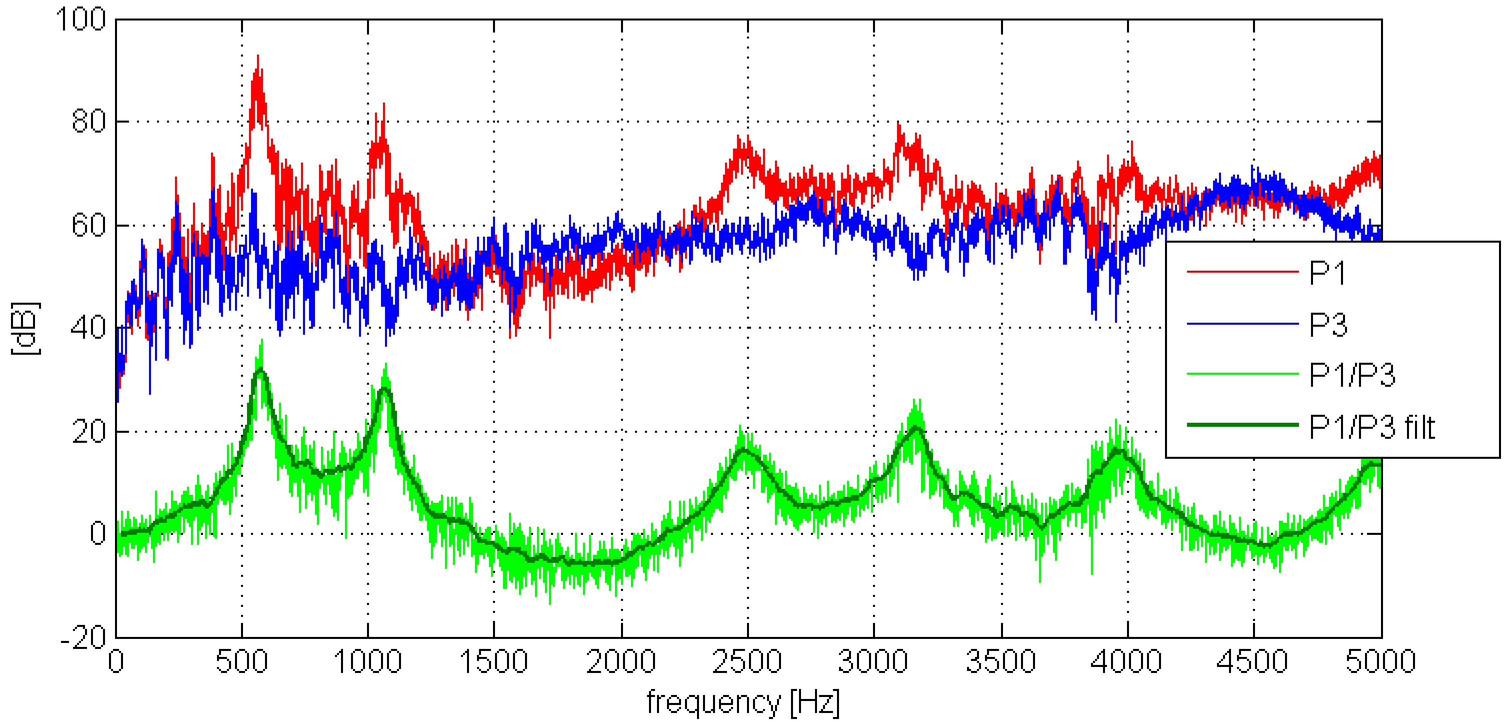

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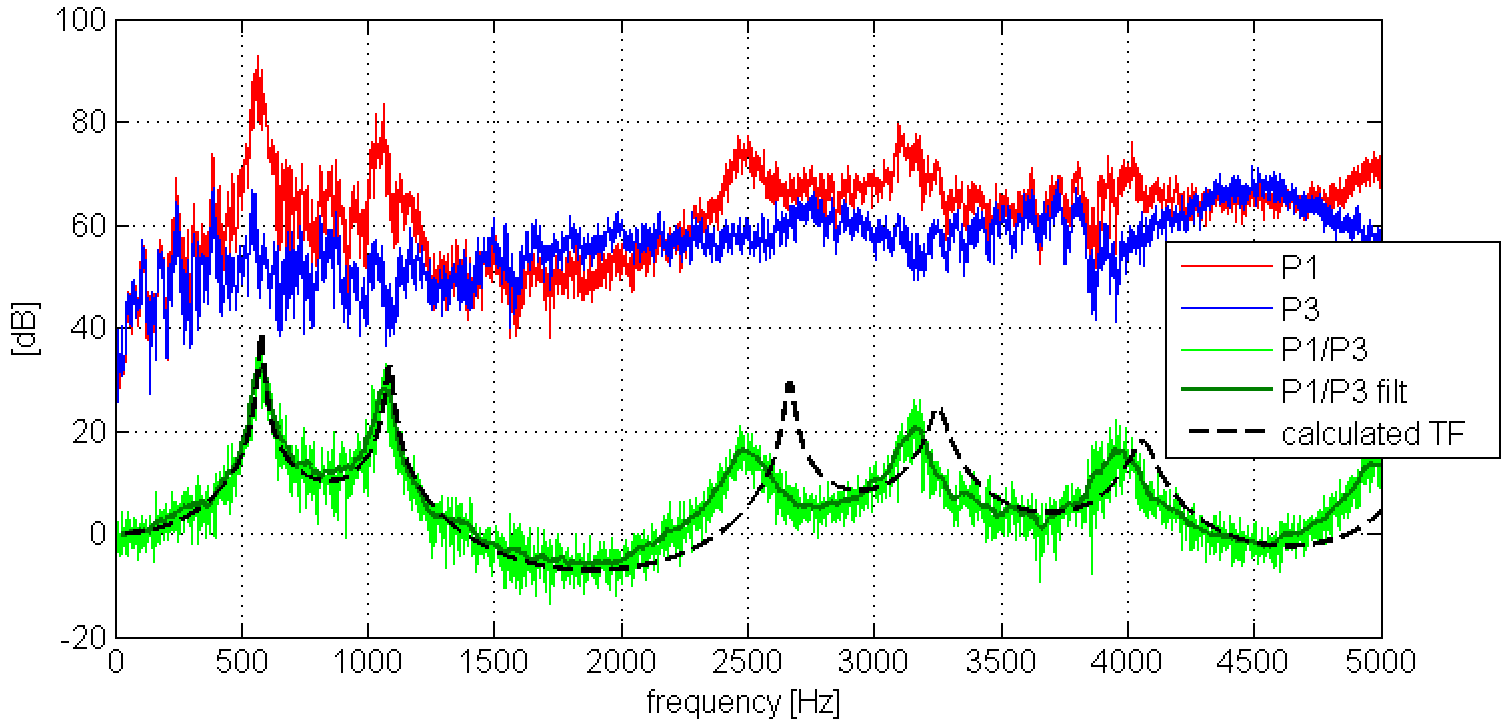
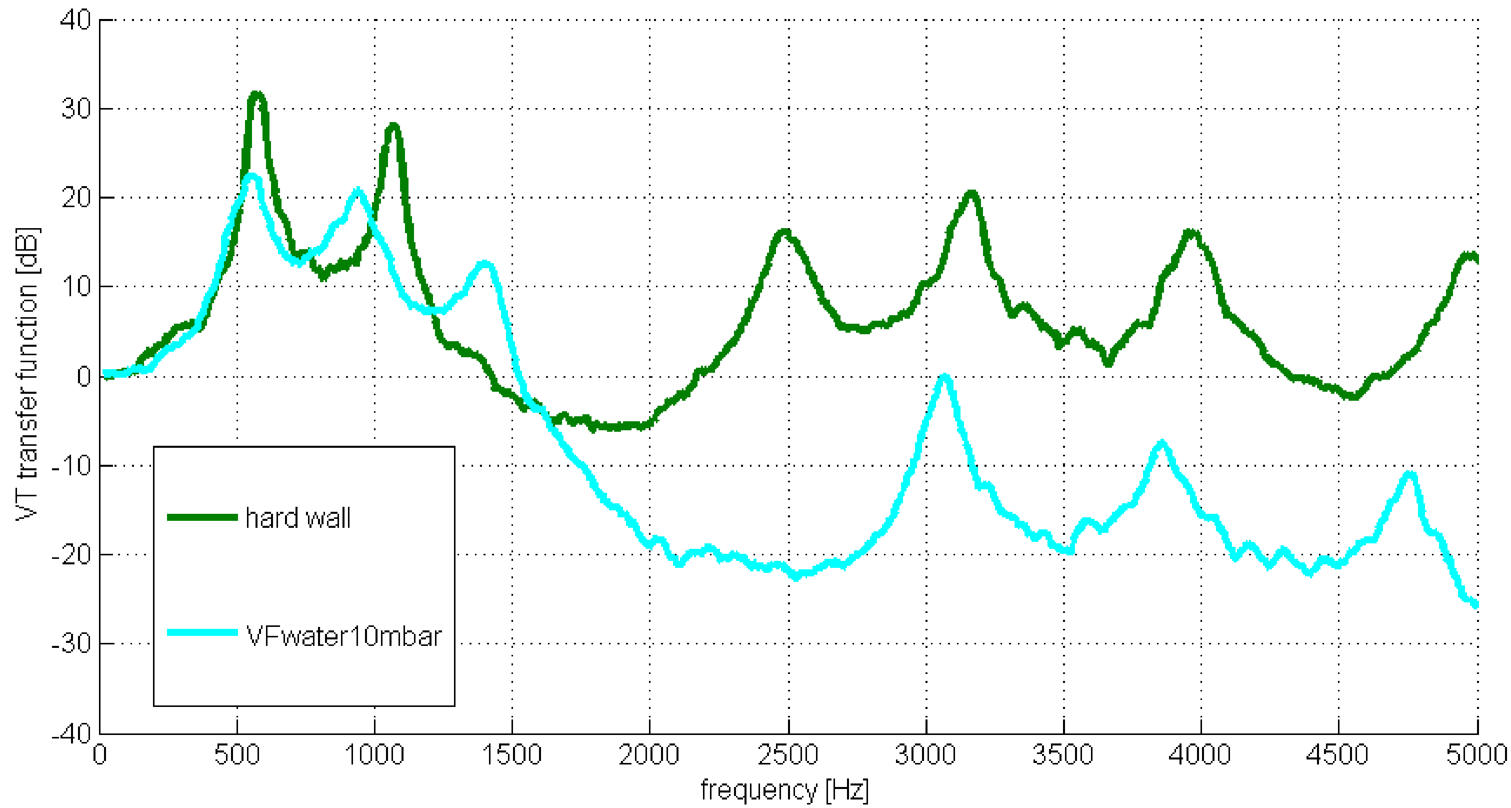


RESULTS

- **The transfer function measured for different vocal folds stiffness**



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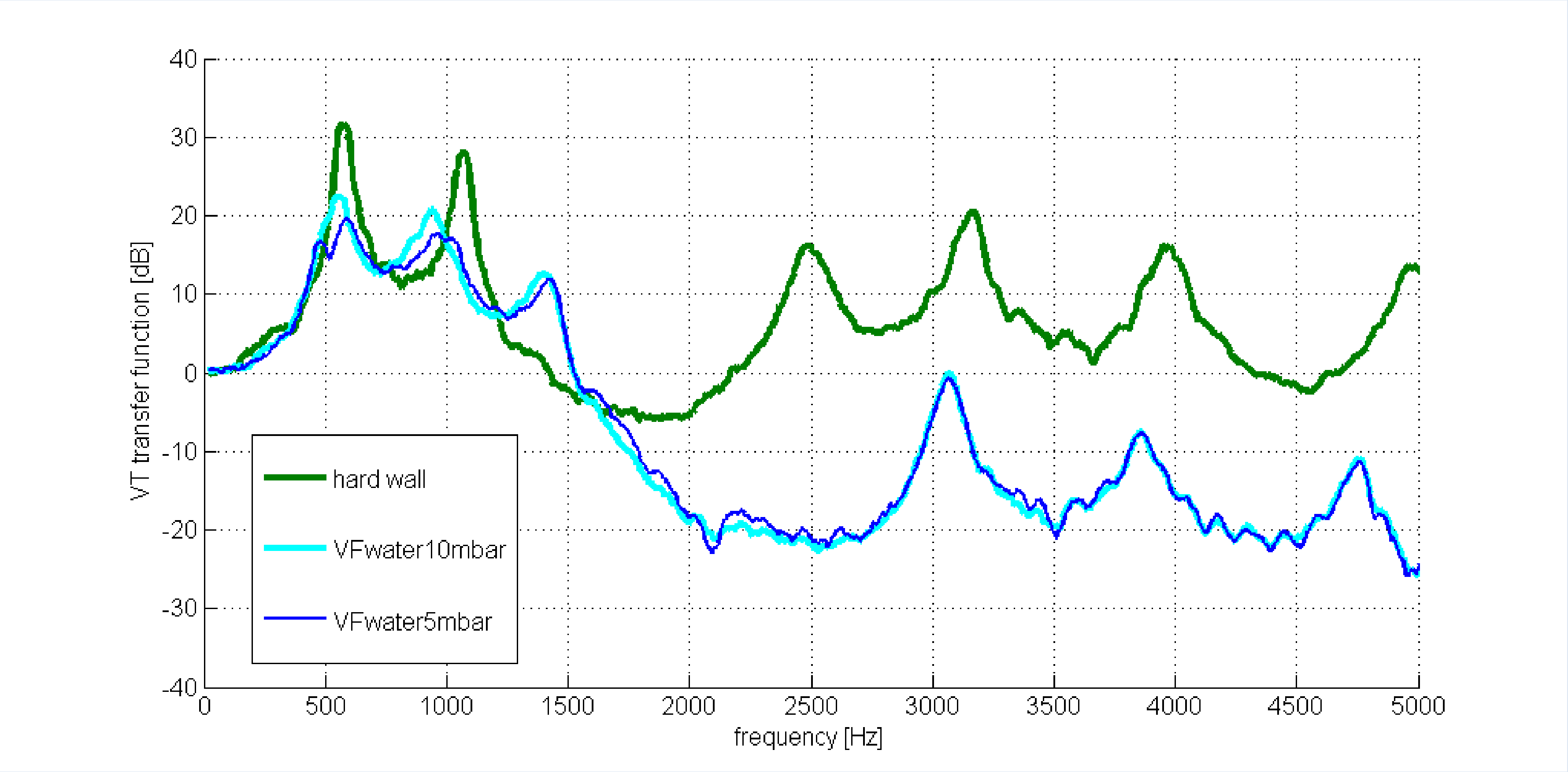

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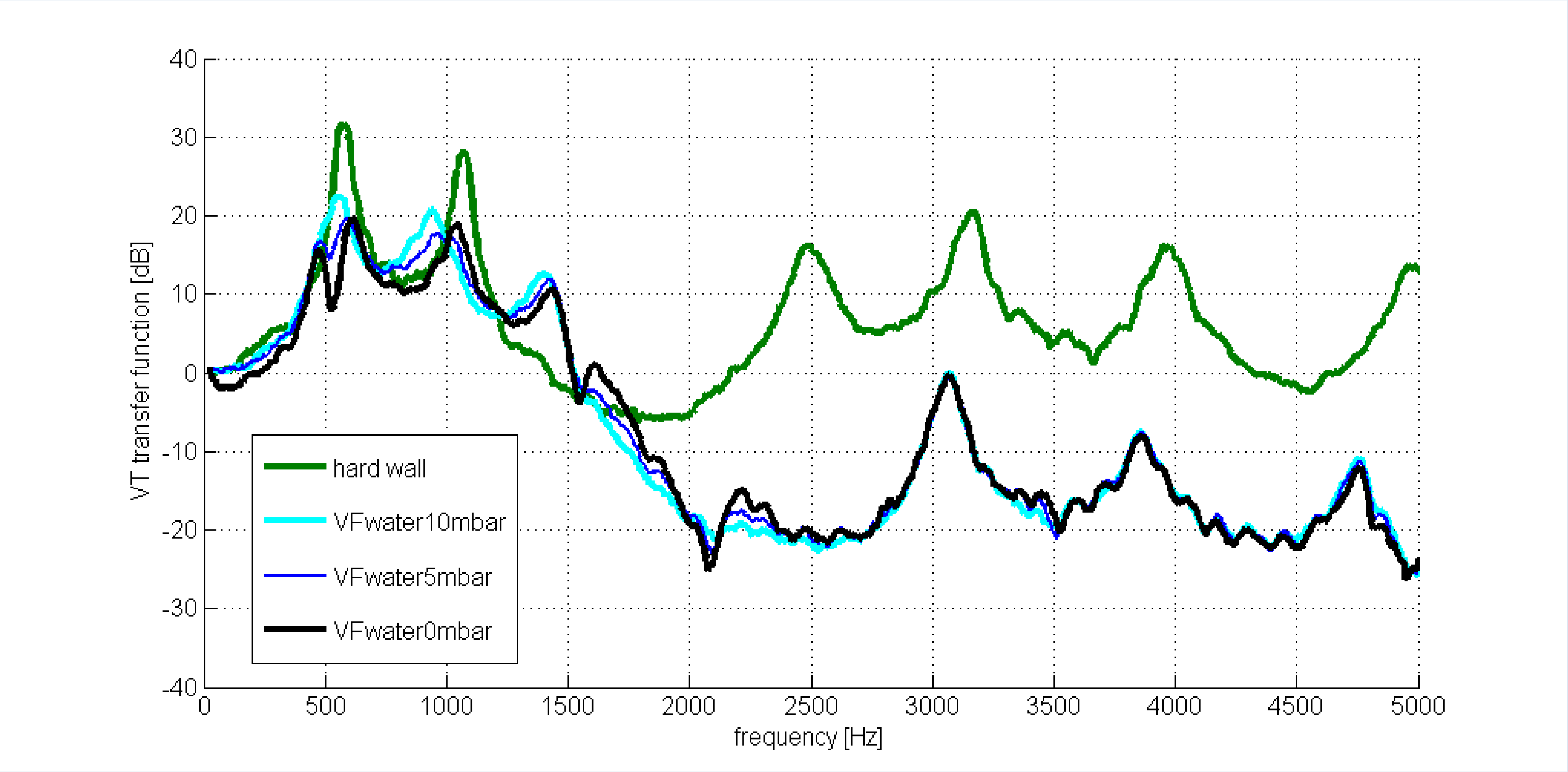

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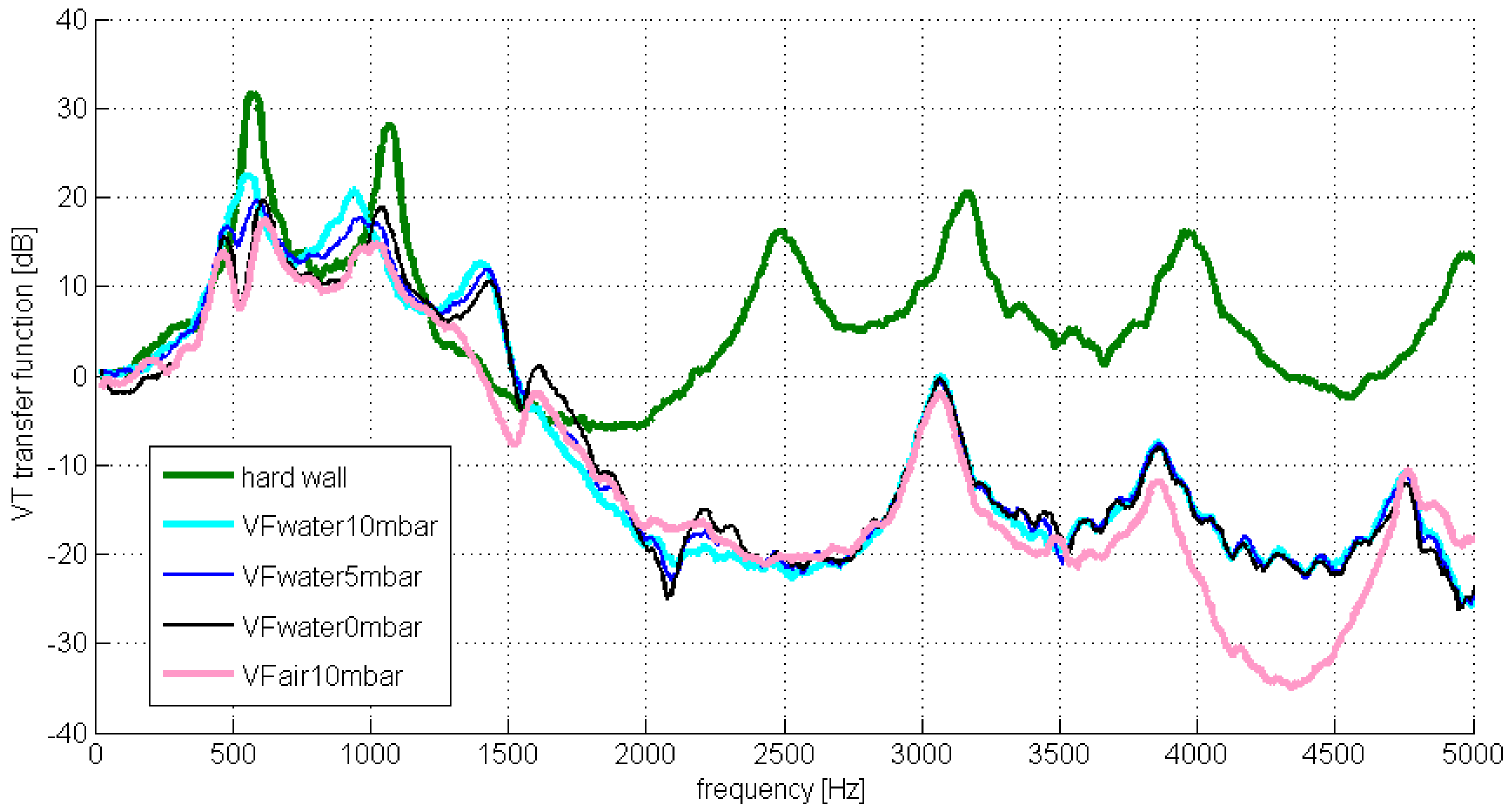

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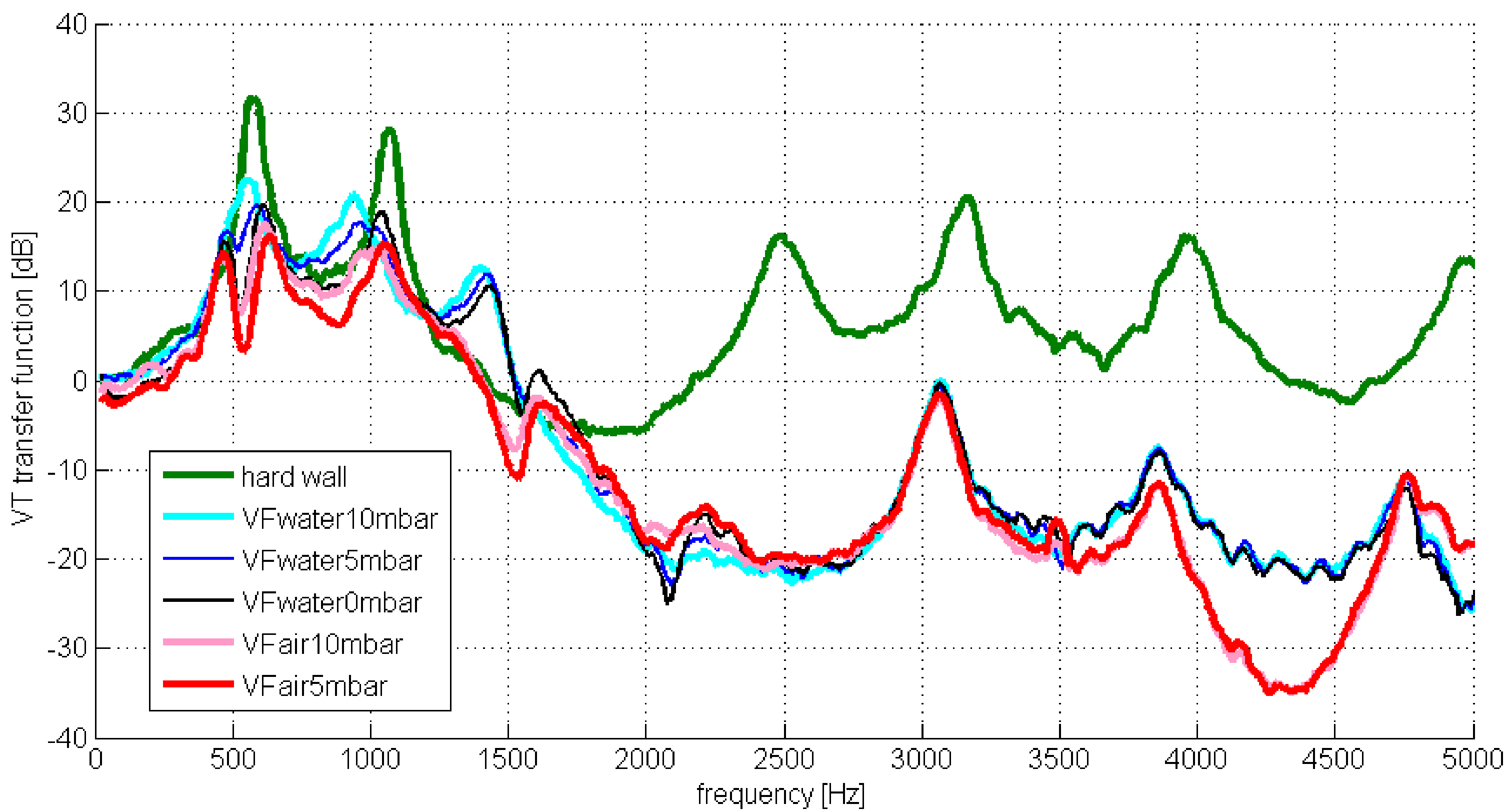

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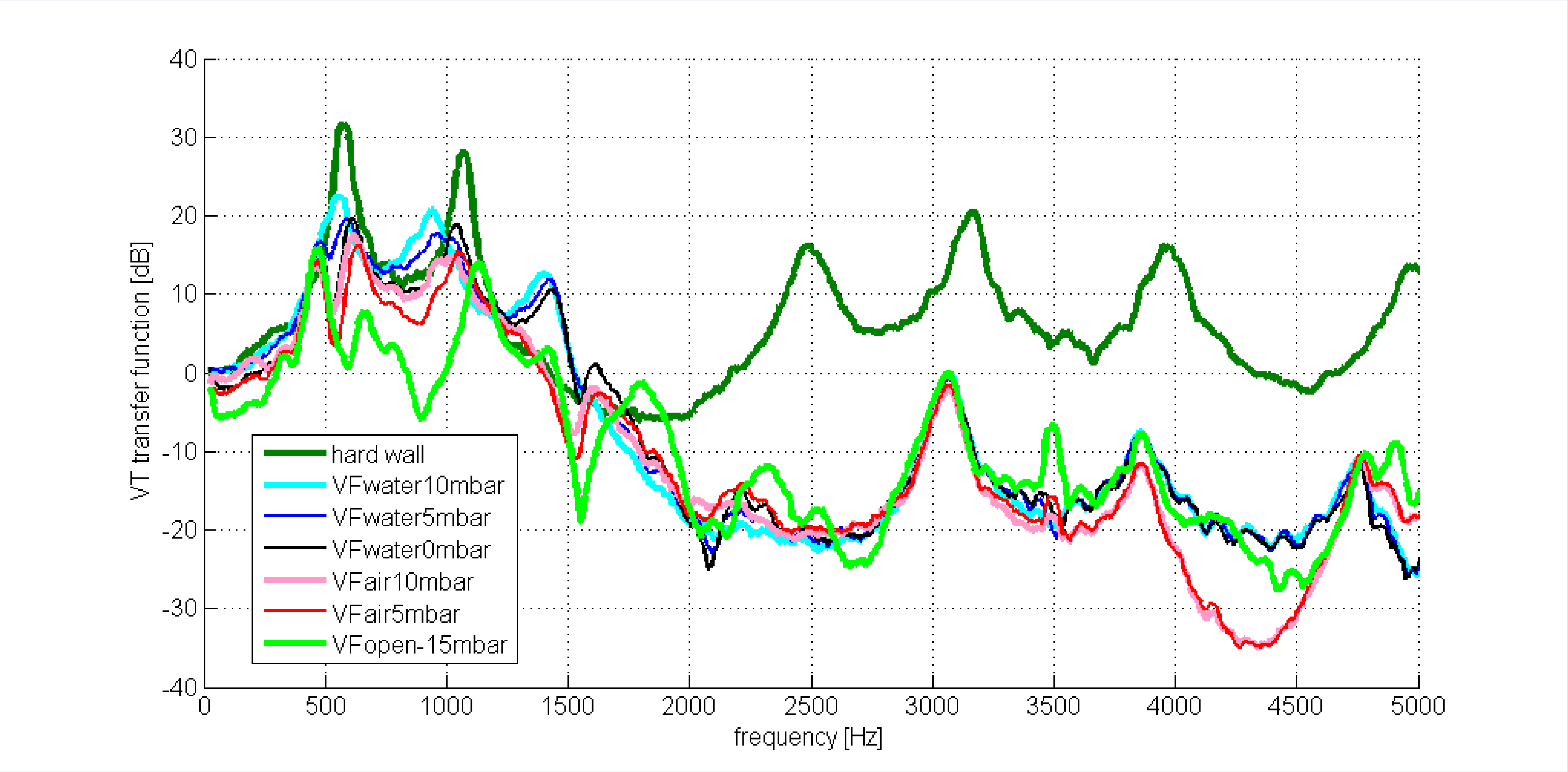

DISCUSSION AND CONCLUSION

The calculated and measured transfer function of VT model with “hard-walled vocal folds” was compared. Calculated resonance frequencies differ from the measured ones by less than 7.2 %.

The stiffness and viscous properties of VFs can significantly change the VT frequency-modal and damping acoustic characteristics, especially in the frequency range above 2 kHz.

In future work, this phenomenon should be modelled mathematically.

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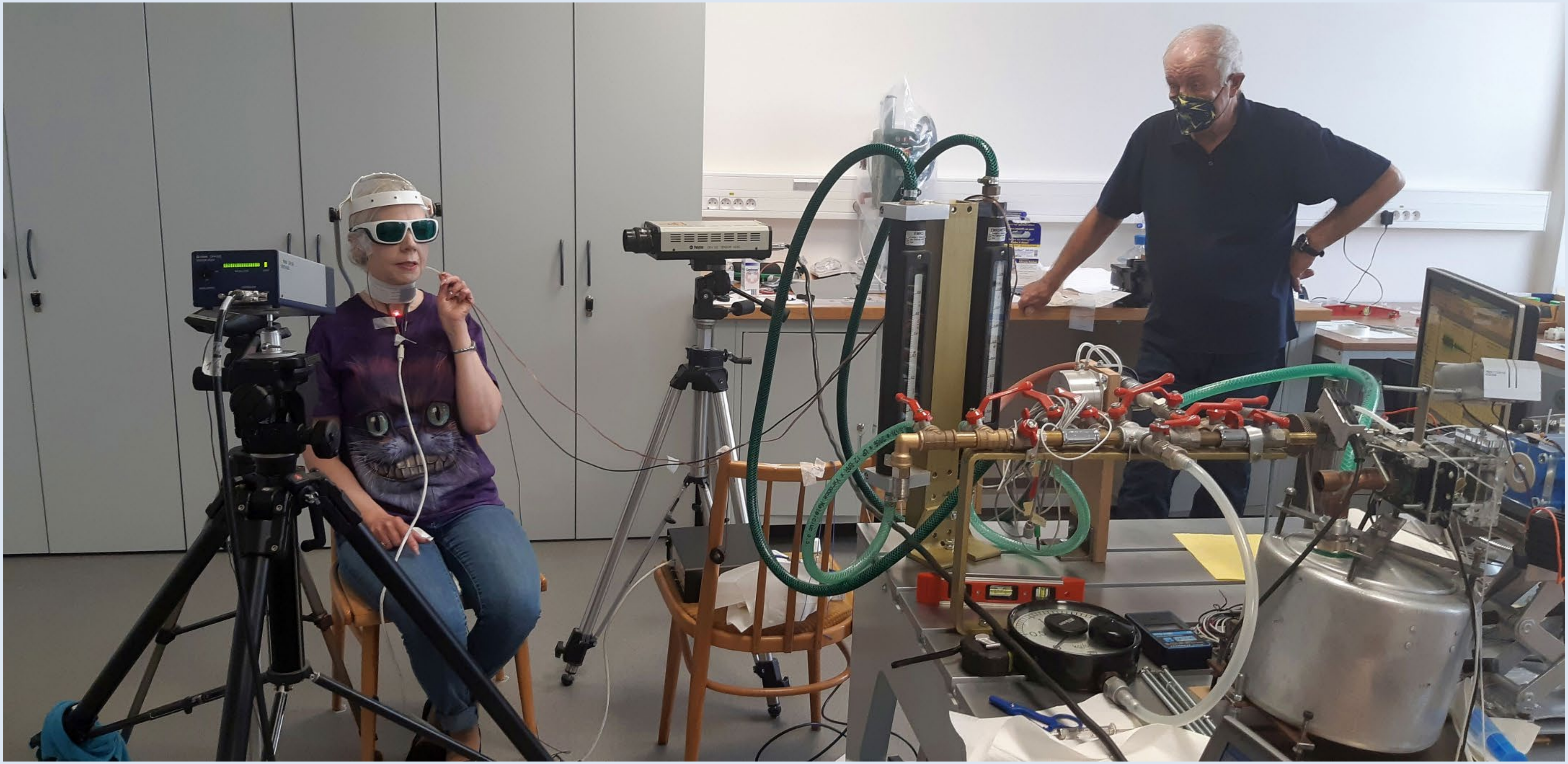
and by the Academy of Finland (grant no. 356528).

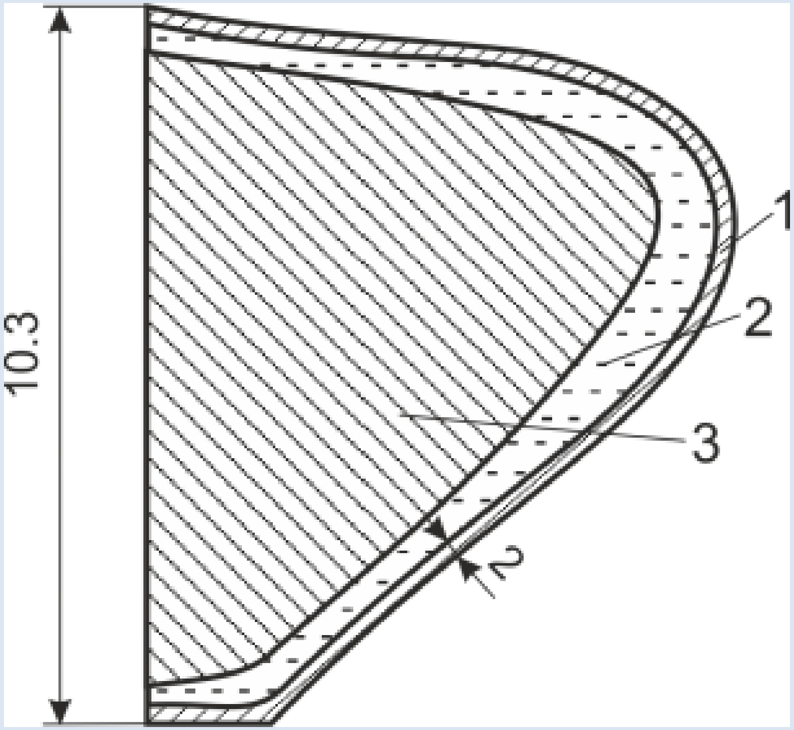
GREETINGS FROM CO-AUTHORS

Anne-Maria Laukkanen **Jaromír Horáček**



Appendix - MEASUREMENT SET UP

1:1 scaled three layer vocal folds model



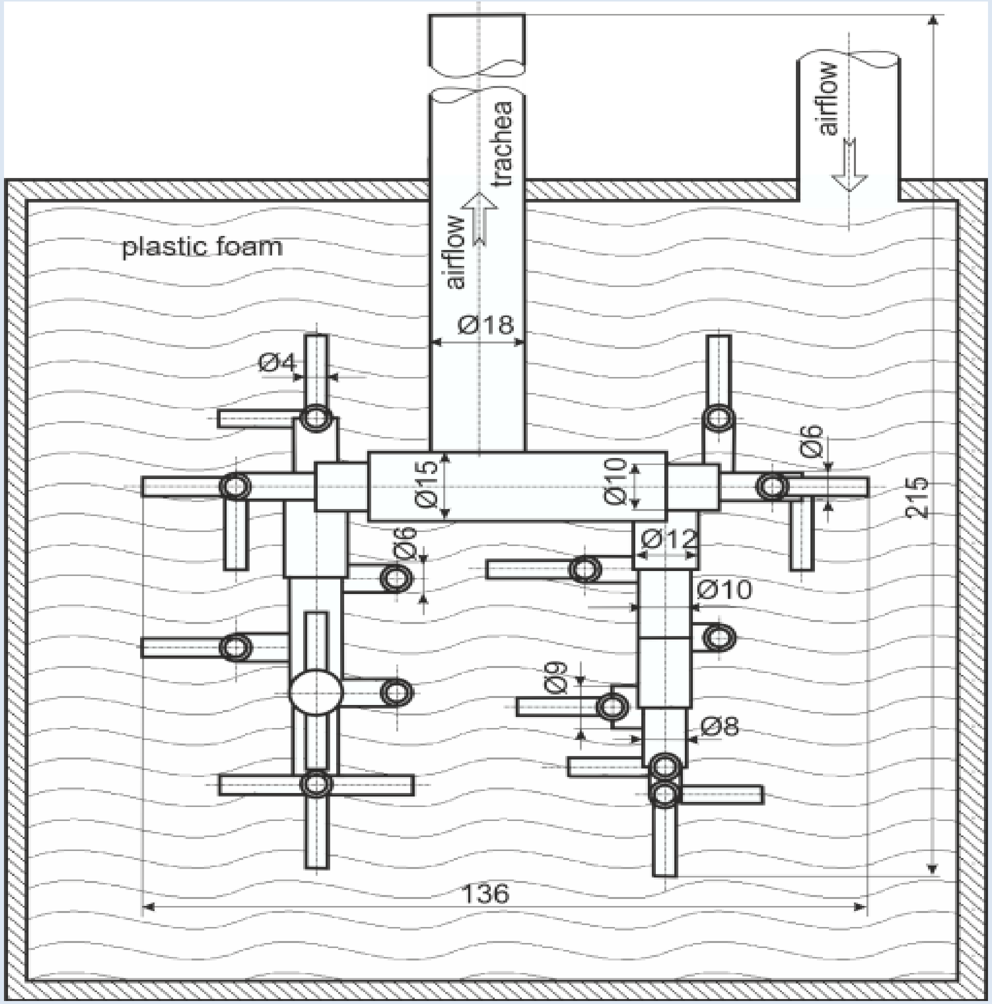
Thin silicon rubber cover

Liquid layer (lamina propria)

Silicon rubber wedge (vocal fold body)

Appendix - MEASUREMENT SET UP

- **Schema of the lungs model**



splitting of the airways
up to the
4th order branching

Appendix - 1D modelling

- Wave equation of an acoustic duct with a variable cross section *A(x)*

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{1}{A}\frac{\partial A}{\partial x}\frac{\partial \phi}{\partial x} - \frac{1}{c_0^2}\left(\frac{\partial^2 \phi}{\partial t^2} + \frac{r_S}{\rho}\frac{\partial \phi}{\partial t}\right) = 0$$

- velocity potential	ϕ	$\left[m^2\, s^{-1}\right]$
- speed of sound	c_0	$\left[m\, s^{-1}\right]$
- specific acoustic resistance	$r_S = 2\pi\sqrt{f\mu\rho / A}$	$\left[kg\, m^{-3}\, s^{-1}\right]$
- fluid density	ρ	$\left[kg\, m^{-3}\right]$
- fluid dynamic viscosity	μ	$\left[kg\, m^{-1}\, s^{-1}\right]$
- frequency	f	$\left[Hz\right]$

- acoustic pressure	$p = -\rho\frac{\partial \phi}{\partial t} - r_S\,\phi$	$\left[kg\, m^{-1}\, s^{-2} = Pa\right]$
- acoustic velocity	$v = \frac{\partial \phi}{\partial x}$	$\left[m\, s^{-1}\right]$
- volume velocity	$U = v\,A$	$\left[m^3\, s^{-1}\right]$

Appendix - 1D modelling

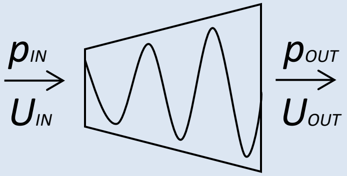
- 1D wave equation with variable cross-sectional area *A(x)* and viscous damping.

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

- Analytical solution in frequency domain for a conical shape element.
- The form of transfer matrices for acoustic pressure p and volume velocity U.

$$\begin{bmatrix} p_{OUT} \\ U_{OUT} \end{bmatrix}=\begin{bmatrix} a & b \\ c & d \end{bmatrix}\cdot\begin{bmatrix} p_{IN} \\ U_{IN} \end{bmatrix}$$

(Radolf, 2010)
(Leino et al., 2011)



$$a=\frac{\xi_0}{\xi_0+L}\cdot\left(\cosh(\gamma L)+\frac{1}{\gamma\,\xi_0}\cdot\sinh(\gamma L)\right)$$

$$b=-\frac{z_0(r_N+jk)\cdot\xi_0}{A_{IN}\cdot\gamma(\xi_0+L)}\cdot\sinh(\gamma L)$$

$$c=A_{OUT}\cdot\frac{\left(1-\gamma^2\xi_0(\xi_0+L)\right)\cdot\sinh(\gamma L)-\gamma L\cdot\cosh(\gamma L)}{\gamma(\xi_0+L)^2\cdot z_0(r_N+jk)}$$

$$d=\frac{A_{OUT}}{A_{IN}}\frac{\xi_0}{\xi_0+L}\cdot\left(\cosh(\gamma L)-\frac{1}{\gamma(\xi_0+L)}\cdot\sinh(\gamma L)\right)$$

$$\xi_0=\frac{R_{IN}}{R_{OUT}-R_{IN}}\cdot L$$

$$r_N=\frac{1}{R}\cdot\sqrt{2k\mu/c_0\rho_0}$$

$$k=\omega/c_0$$

$$\gamma=\alpha+j\beta$$

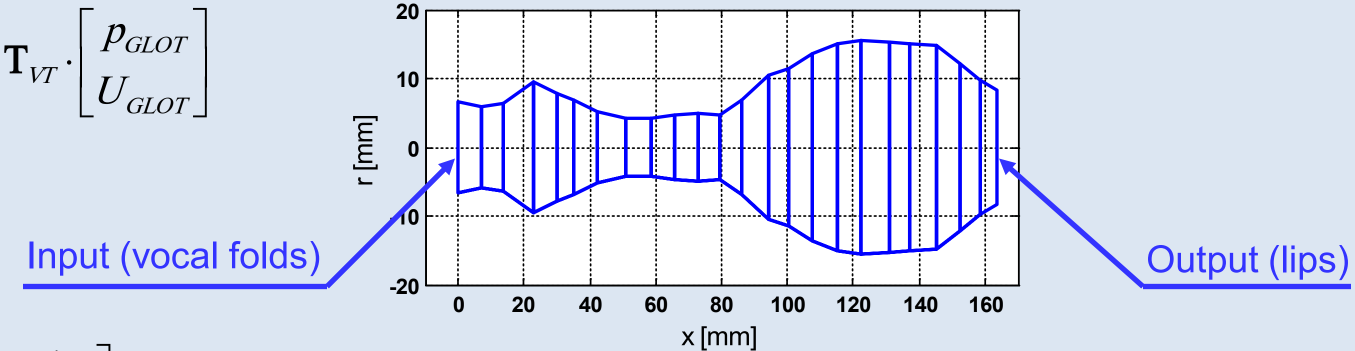
$$\alpha=\frac{r_N}{\sqrt{2+2\cdot\sqrt{1+(r_N/k)^2}}}$$

$$\beta=\frac{k}{2}\cdot\sqrt{2+2\cdot\sqrt{1+(r_N/k)^2}}$$

Appendix - 1D modelling

- Acoustic properties of the whole vocal tract

$$\begin{bmatrix} p_{LIP} \\ U_{LIP} \end{bmatrix} = \mathbf{T}_{VT} \cdot \begin{bmatrix} p_{GLOT} \\ U_{GLOT} \end{bmatrix}$$



$$\mathbf{T}_{VT} = \begin{bmatrix} a_{VT} & b_{VT} \\ c_{VT} & d_{VT} \end{bmatrix} = \mathbf{T}_{N_e+1,N_e} \cdot \mathbf{T}_{N_e,N_e-1} \cdot \ldots \cdot \mathbf{T}_{3,2} \cdot \mathbf{T}_{2,1}$$

- Acoustic radiation impedance

$$Z_{A\,rad} = \frac{c_0 \rho_0}{\pi R^2} \cdot \left[1 - \frac{J_1(2kR)}{kR} + j\frac{H_1(2kR)}{kR} \right] = \frac{p_{LIP}}{U_{LIP}}$$

(Škvor 2001)

- Eigenfrequency calculation

$$U_{GLOT} = 0 \quad \Rightarrow \quad a_{VT} - Z_{A\,rad} \cdot c_{VT} = 0$$

- Acoustic pressure at the lips

$$p_{LIP} = \frac{a_{VT} \cdot d_{VT} - b_{VT} \cdot c_{VT}}{a_{VT} - Z_{A\,rad} \cdot c_{VT}} \cdot Z_{A\,rad} \cdot U_{GLOT}$$