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INFLUENCE OF STEADY FLOW ON THE POSITION OF RESONANT FREQUENCIES OF HUMAN VOICE

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Abstract: *This study aimed to evaluate the influence of steady flow on the position of resonant peaks of human voice for phonation of vowel [a:] and its use for the energy redistribution in the frequency spectrum during the singing. The study applied 3D volume models of the vocal tract based on computer tomography (CT) images of a female speaker converted to the simplified 1D model assembled from the cylindrical elements. The 1D model considers the acoustic energy dissipation due to friction losses inside the vocal tract and emitting energy from the mouth. The steady flow higher than 3 l/s shift resonance F3 and F4 to the lower values and increases positively the amount of acoustic energy in the frequency interval 2.5-4 kHz and can influence support the stronger voice production.*

Keywords: singing voice, vocal efficiency, vocal loading, vocal tract, finite element modelling

1. Introduction

The very detailed three-dimensional finite element models (3D FE) of the human vocal tract (VT) can be assembled based on computer tomography (CT) images including all the side cavities like the piriform sinuses, valleculae and by the nasal tract (NT), see e.g. (Vampola et al, 2020; Vampola et al, 2021 and Vampola et al, 2024). The complexity of these computational models having millions of degrees of freedom demand using supercomputers or high-performance computational systems. In case of evaluating the influence of the steady flow, turbulent losses or stiffness of boundary tissues the 3D models are extremely time consuming. These models cannot be used for easy geometric modification because their conversion to the fully parametric models is due to their complexity problematic. Therefore, deriving simplified one-dimensional (1D) computational models involving all significant physical phenomena is still a suitable approach for sensitivity analysis or optimization calculations of the VT.

2. Vocal tract models

The geometric configuration of 1D models of the VT is based on the CT images of a female subject. The CT images were transformed into 3D volume models which were subsequently divided into separate segments. The parallel cavities of the piriform sinuses, valleculae were modeled by means of Helmholtz' resonators where their definition parameters (volume, area and length of neck) were taken from the 3D volume models. Figure 1 and Table 1 shows the definition of cross-sections areas of the vowel. Table 2 defines the parameters of Helmholtz' resonators.

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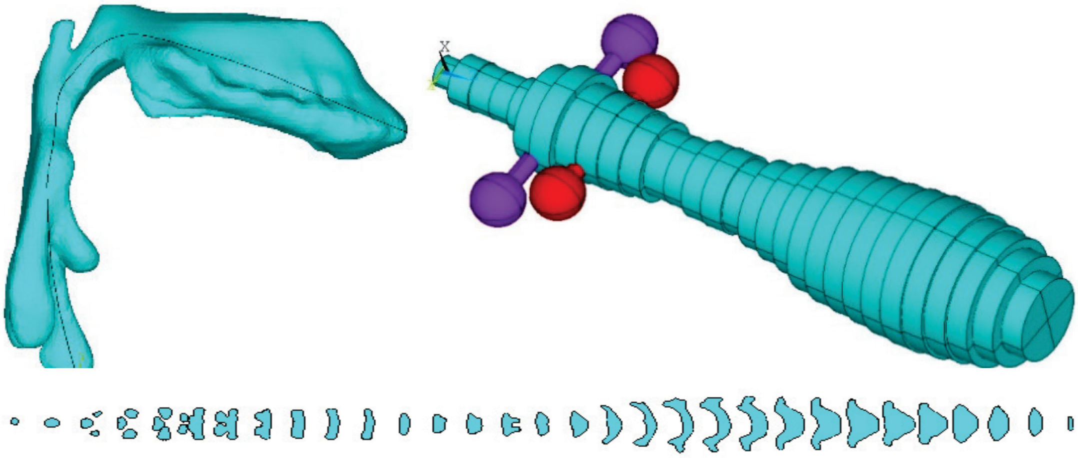


Fig. 1: 3D and 1D model of vocal tract for vowel [a:]

Tab. 1: Cross sections areas for vowel of 1D model [a:].

Cross section 1-8 [cm²]	Cross section 9-16 [cm²]	Cross section 17-24 [cm²]	Cross section 25-31 [cm²]
0.3762	3.091	2.962	8.591
0.9527	2.819	3.649	8.090
0.8577	2.477	4.308	7.287
0.8565	1.734	5.958	6.519
1.080	1.772	6.772	4.808
3.539	2.252	7.202	2.683
4.697	2.400	7.670	0.4807
3.310	2.099	8.242	

Tab. 2: Parameters of Helmholtz' resonators for vowel [a:].

	Volume [m³]	Area [m²]	Length [m]
piriform sinus -left/right	0.9817E-06	0.10475e-3	0.001
	0.9253E-06	0.1144e-3	0.001
vallecuale – left/right	0.3695E-06	0.09559e-3	0.001
	0.5889E-06	0.11882e-3	0.001

3. Analytical 1D model

The wave equation (Munjal, 2014) for a movable viscous compressible fluid of constant temperature can be assembled in the form

$$-\frac{1}{c_0^2}\left(\frac{\partial^2 p_T}{\partial t^2}+2u_0\frac{\partial^2 p_T}{\partial x\partial t}+u_0^2\frac{\partial^2 p_T}{\partial x^2}\right)+\frac{\partial^2 p_T}{\partial x^2}-\frac{r}{\rho_0 c_0^2}\frac{\partial p_T}{\partial t}=0. \tag{1}$$

Where $p_T(x,t)=p_0+p(x,t)$, $\rho_T(x,t)=\rho_0+\rho(x,t)$ and $u_T(x,t)=u_0+u(x,t)$. Parameters ρ_0, p_0 are constant components of density and pressure corresponding to the atmospheric values at the given temperature, u_0 is the steady state flow value and c_0 is speed of sound in the vocal tract. Since sound pressure $p(x,t)$ and particle velocity $u(x,t)$ have been considered as a function of spatial coordinate and time, it can be by the method of separation variables split into the two independent functions, where time function is expressed as a harmonical signal

$$p(x,t)=P(x)T(t)=P(x)e^{j\omega t}, u(x,t)=U(x)T(t)=U(x)e^{j\omega t}. \tag{2}$$

After substitution Eq.(2) into Eq.(1) and using a Mach number $M=\frac{u_0}{c_0}$, a real wave number $k_0=\frac{\omega}{c_0}$ and a resistance coefficient $\beta=\frac{r}{\rho_0 c_0}$ normalized by the basic wave resistance can be found the wave equation for the cylindric element in the form

$$\left((1-M^2)\frac{\partial^2 P}{\partial x^2}+(-j2Mk_0)\frac{\partial P}{\partial x}+(k_0^2-j\ \beta k_0)P\right)e^{j\omega t}=0. \tag{3}$$

Its solution is

$$p(x,t)=\left(C_1e^{\lambda_1 x}+C_2e^{\lambda_2 x}\right)e^{j\omega t}, \tag{4}$$

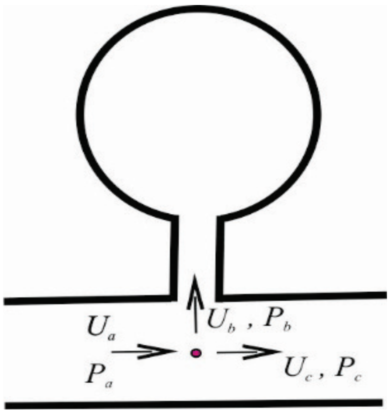
with

$$\lambda_{1,2}=(1-M^2)^{-1}\left(jMk_0\mp\sqrt{-k_0^2+j\ \beta k_0(1-M^2)}\right). \tag{5}$$

The velocity of the mass particle can be derived from the continuity equation in the form

$$u(x,t)=(j\omega\rho+r)^{-1}\left(j\ Mk_0\ P+(M^2-1)\frac{\partial P}{\partial x}\right)e^{j\omega t}. \tag{6}$$

Mach number expresses the influence of the steady state flow and β defines the dissipation of the acoustic energy.



$$p_a=p_b=p_c=p$$

$$w_a=w_b+w_c$$

$$\frac{w_a}{p}=\frac{w_b}{p}+\frac{w_c}{p}$$

$$\frac{1}{Z_a}=\frac{1}{Z_b}+\frac{1}{Z_c}$$

Fig. 2: Helmholtz's resonator

The simplified 1D model is assembled from the boundary conditions for pressures and impedances of individual cylindrical segment. The parallel cavities of the VT in the 1D model were modeled by the acoustic impedance of Helmholtz's resonators (Fig. 2)

$$Z_a(\omega)=j\omega m_a+r_a+\frac{1}{j\omega c_a}=r_a+j\left(\omega m_a-\frac{1}{\omega c_a}\right), \tag{7}$$

where the definition of the acoustic mass m_a, resistance r_a and compliance c_a is in (Munjal, 2014).

4. Acoustic energy dissipation

The acoustic energy losses, caused by the radiation of the sound from the mouth to the free field, was modeled by a circular plate oscillating in an infinite wall. The frequency-dependent acoustic impedance was implemented for this case earlier (Vampola et al, 2024)

$$\hat{Z}_a=\frac{c_0\rho_0}{S}\ (E+iF),\ E=1-\frac{J_1(2kR)}{kR},\ F=\frac{H_1(2kR)}{kR}, \tag{8}$$

where R is an equivalent radius of the vibrating plate calculated from the cross-section areas A of the VT model at the lips and J_1 and H_1 are the Bessel and Struve functions. The equation of motion (1) was derived under the assumption that there is no relative motion of the individual fluid layers in the cross-sections of the vocal tract. In other words, the acoustic wave remains planar, and the energy dissipation is possible between the boundary walls of the vocal tract and the layer of fluid wetting these boundaries, then the acoustic resistance of a cylindrical element of constant cross-section R of a given length l can be expressed as a real part of the acoustic impedance in the form of the Hagen-Poiseuille's law valid for the laminar type of flow (Munjal, 2014).

$$r_a = Re(Z_a) \doteq \frac{8\mu l}{\pi R^4} \tag{9}$$

5. Numerical analyses

The following material parameters for numerical analyses were used, speed of sound c_0=350 m/s, air density ρ_0=1.2 kg/m^3, and the steady state flow up to $u_0 = 8\ l/s$. The velocity of sound was selected to facilitate comparison with physical laboratory models. Results are shown in figure 3 and table 3.

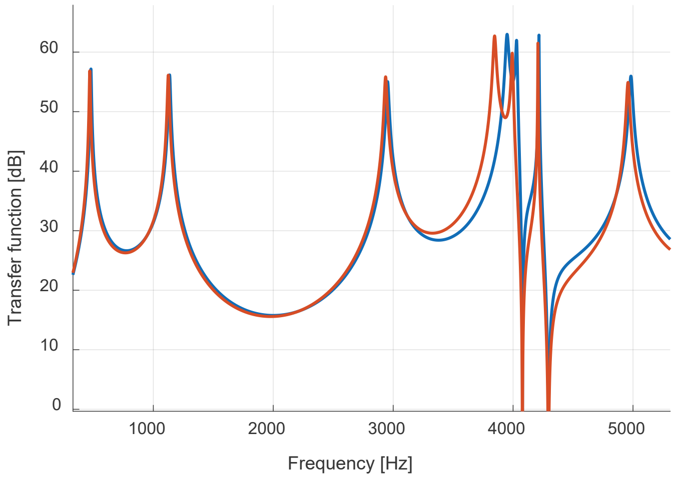


Fig. 3: Transfer function of the human vocal fold for $u_0 = 0\ l/s$ (blue curve) and for $u_0 = 6\ l/s$ (red curve)

Tab. 3: Eigenvalues for vowel [a:]

Res.	$\lambda_{1,2}$	$\Delta\omega/2\pi$ [Hz]
f_{R1}	-40.9 ±j 526.1	-46
f_{R2}	-35.6 ±j 1107.9	28
f_{R3}	-40.5 ±j 2650.7	304
f_{R4}	-49.7 ±j 3458.3	492

6. Conclusions

- The accordance of the lower resonant peaks positions for 1D and 3D model are in good agreement.
- The influence of steady flow $u_0 = 0 - 3l/s$ is negligible for resonant peaks positions.
- The steady flow $u_0 = 3l/s$ and higher causes redistribution of acoustic energy in the frequency span 3-4 kHz.
- The steady flow $u_0 = 3l/s$ and higher increases the third resonant peak about 0.8 dB.
- The steady flow $u_0 = 3l/s$ increases the total acoustic output energy at the lips in frequency range from 300Hz to 4kHz by 6%

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