Sensitivity of Aeroacoustic Source Distribution for Different Glottal Motion Patterns

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Introduction

The modulation of the air-flow resulting from the oscillation pattern of the human vocal folds represents the main acoustic source in human voice generation. The present investigation uses a three-dimensional numerical model of the vocal folds and shows the relationship between glottal motion pattern, the supraglottal flow field and the flow induced acoustic field. In a hybrid approach the Navier-Stokes equations for incompressible fluid flow are numerically solved and the aeroacoustic source terms for the inhomogeneous wave equation are determined by Lighthill's acoustic analogy. Coherent flow structures generated in the shear layer of the supraglottal jet flow and small-scale fluctuations occurring during the turbulent decay of the jet contribute to the acoustic source terms in the supraglottal flow field. In case of asymmetric vocal folds movement during the phonation cycle the supraglottal jet is deflected out of the central axis and shows a stronger interaction with the walls of the vocal tract. It is assumed that these interactions result in a change of the harmonic to noise ratio (HNR) in the generated primary voice signal. The HNR is used as a voice quality indicator.

Computational Model

The pressure driven pulsating air flow through the glottal constriction during the phonation process is characterized by its mean Reynolds number $Re_m = (u_m h)/\nu$, Strouhal number $Sr = (f_0 h)/u_m$, Euler number $Eu = \Delta p / \left(\rho u_m^2\right)$ and Mach-number $Ma = u_m/a$ with maximum opening of the constriction h, mean flow velocity u_m, fundamental frequency f_0 of the air-flow modulation, driving transglottal pressure head Δp, density ρ and viscosity ν of air. Corresponding values for Re, Sr and Eu are given in table 1. The Mach number is in the order of $\mathcal{O}(10^{-1})$. Therefore the flow field can be considered as incompressible and the flow calculation is decoupled from the aeroacoustic calculation.

The equations of mass (1) and momentum (2) conservation are solved numerically using the Finite-Volume-Mehtod (FVM) for three dimensional, time-dependent, incompressible fluid flow.

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u} \tag{2}$$

Table 1: Characteristic values, similartity parameters and scaling factors between air flow and up-scaled water flow in the larygeal channel.

typical values for glottal airflow [1]	similartity parameters
$u_m = 30$ m/s	$Re_m = 5000$
$h = 2$ mm	
$f_0 = 135$ Hz	$Sr = 0.01$
$\Delta p = 1400$ Pa	$Eu = 1$

The acoustic pressure distribution is calculated in a separate step from the inhomogeneous wave equation (3). It reads

$$\frac{1}{c^2} \frac{\partial^2 p'}{\partial t^2} - \Delta p' = \nabla \cdot (\nabla \cdot \mathbf{T}) \tag{3}$$

with p' the acoustic pressure, c the speed of sound and $\mathbf{T}$ the Lighthill tensor. It is assumed that heat conduction and the viscous stresses may be neglected. Therefore an approximation for $\mathbf{T}$ can be given as

$$\mathbf{T} \approx \rho \mathbf{u}\mathbf{u} \tag{4}$$

The wave equation (3) is discretized using the Finite-Element Method (FEM) on the same computational grid as used for the CFD calculation.

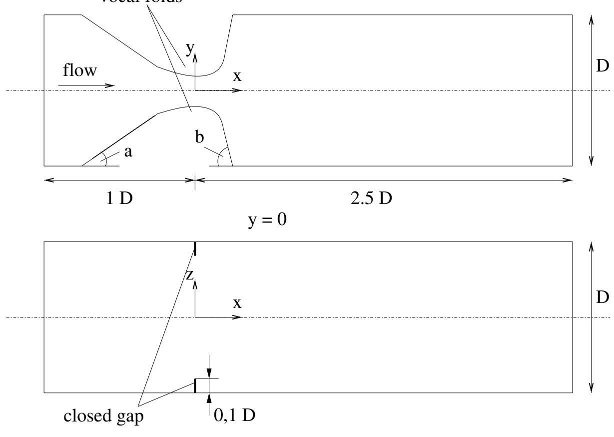

Figure 1: Sketch of the computational domain in accordance to the experimental set-up in [3], mid-coronal (upper) and mid-sagittal (lower) cross-section at the state of the fully openend glottal constriction (cycle time $t/T_0 = 0.25$)

Results

Flow fields

The computed flow field is characteristic for elliptic jet flows and has strong three-dimensional nature as already shown in experiments [3]. The visualization of the flow field by a massless scalar tracer (figure 2) shows a significant influence of the opening modulation on the supraglottal flow field. A strong deflection of the jet flow in the the mid-coronal cross-section is observed for asymmetric movement of the vocal folds.

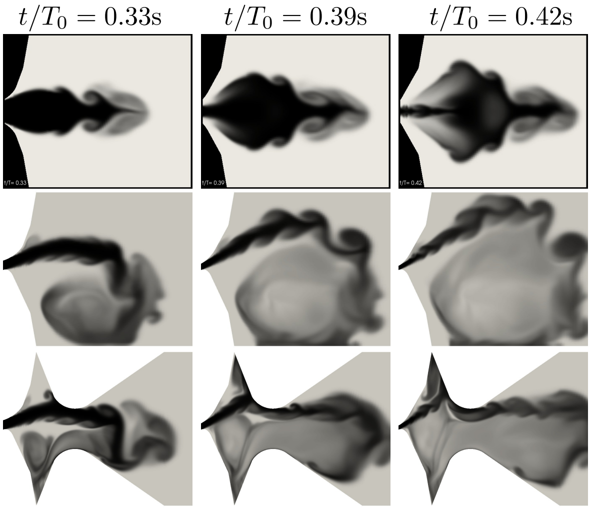

Figure 2: Visualization of the supraglottal flow field in the mid-coronal cross-section (see figure 1), top row: symmetric movement of the vocal folds, mid row: asymmetric movement, bottom row: asymmetric movement with supraglottal structures (ventricular folds), the driving transglottal pressure head is given as in natural phonation with Δp=6 cm *H_2O*

Figure 3 shows the three-dimensional flow field by an isovalue of the Q-criterion. The interaction of the leading vortex convecting at low speed and the vortical structures generated by Kelvin-Helmholtz instabilities in the shear layer of the core-flow leads to vortex pairing and disintegration and disspation of the jet front [3].

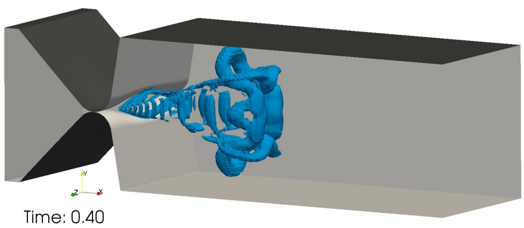

Figure 3: Visualization of the three-dimensional vortical flow structures by an isovalue of the Q-criterion [2] at cycle time $t/T_0 = 0.4$ (closing phase of the glottal gap)

Acoustic Results

Figure 4 shows the computed aeroacoustic sound pressure level at a fixed point one channel width downstrem of the glottal orifice. The applied fundamental frequency $f_0 = 135$Hz results from the modulated volume flow rate and is the dominant part of the supraglottal sound pressure spectrum. The most interesting frequency range is above $10f_0$. The occuring frequencies in this range arise from the vortical flow structures generated in the jet shear layer, their interaction among each other (vortex pairing), their interaction with the supraglottal structures (ventricular folds) and with the channel walls. So for the asymmetric case with supraglottal structures a signifcant higher sound pressure level in the range above $10f_0$ is observed.

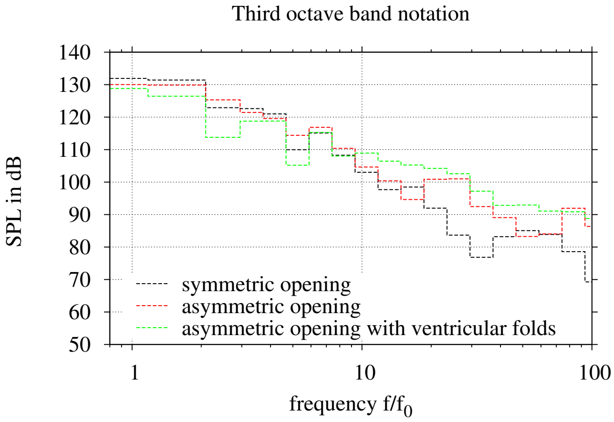

Figure 4: Third octave band notation of sound pressure level in supraglottal region

Conclusion

Further grid refinement studies of the numerical calculations will be made. The local resolution of the computational grid used for the CFD calculation determines the smallest flow structures that are resolved. Their influence on the composition of the resulting sound pressure spectrum, especially in the range above $10f_0$, will be pointed out.

Acknowledgements

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