Three-Dimensional Unsteady Flow Nature in the Vocal Tract during Human Phonation

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Introduction

The quality of the human voice during phonation is strongly related to the three-dimensional (3D), unsteady flow field in the vocal tract downstream of the vocal folds. A slight pathological change of the vocal fold's geometry and/or their movement may have already a strong effect on the flow field and thereby on the flow-induced noise (sources) which is a parameter that characterizes the voice quality. In this study the unsteady flow field in a dynamical model of the vocal folds is simulated numerically and visualized with the same boundary conditions in the experiment. In particular a comparison between the flow dynamics with and without model ventricular folds, which build a second constriction in the test channel, is shown. This work is integrated in the DFG funded research group FOR894 with the aim to study the "Physical Fundamentals of the Human Voice".

Vocal Folds Model and Test Section

The used dynamical (driven) model of the glottal cycle as adapted from [1] is illustrated in Figure 1 in its current configuration.

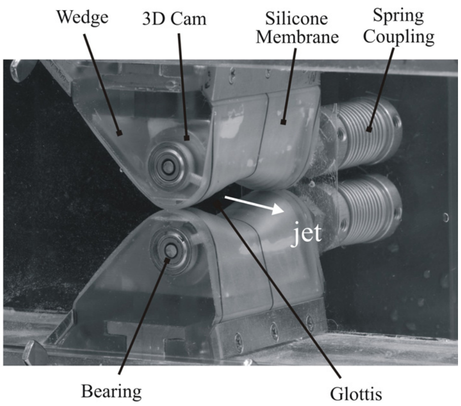

Figure 1: The cam model.

The complexity to mimic a high-frequency variation of the glottis cross-section and the limitations inherent to time-resolved high resolution flow measurements led us to an enlarged 3:1 scaled-up model with use of the medium water. This configuration allows us to study in experiment the flow field downstream of the glottis in slow motion with spatial and temporal detail. The relevant flow similarity parameters are the Reynolds, the Strouhal and the Euler numbers from which the model-to-real flow velocity (u), frequency (f) and pressure (Δp) ratios can be derived as shown in Table 1.

Similarity Parameters		
Re	Sr	Eu
u_{model}/u_{real}	f_{model}/f_{real}	$\Delta p_{model}/\Delta p_{real}$
1:45	1:135	1:2

Table 1: Main dimensionless flow similarity parameters.

The main characteristic of the model is the reproduction of the glottal cycle [2] by the use of two counter-rotating 3D shaped cams with elliptic cross-section which are mounted on wedges and continuously deform a stretched silicone membrane during rotation ω. Thus the glottis contour changes during one cycle from a convergent and over a uniform form into a divergent closing form considering at the same time the lens-like glottal opening shaped by the 3D contoured cams as indicated in Figure 2.

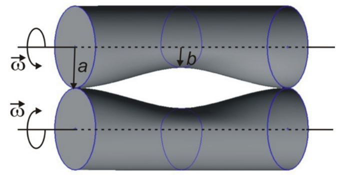

Figure 2: Optimized cam profiles: semi-axes a and b.

The cams geometry and shape are derived from clinical and in-vitro test observations with excised animal vocal folds. The vertical and lateral motions of the vocal folds are mapped through a systematic optimization process onto the 3D cams according to the given boundary conditions of the cam glottal model. The resulting optimized cams are then 3D machined, inserted into the vocal folds module and placed in a square test section for the purpose of flow visualization. Our cam model can be extended by two water-filled Perspex ventricular folds downstream of the glottis [3], which build a second constriction in the test section. The channel has one reservoir at each end, so we are able to prescribe an exact transglottal pressure difference, from which a characteristic time-dependent volume flow rate results for the glottal cycle. In the present study we prescribe a realistic pre-phonatory transglottal pressure difference and time-varying motion and profile of the glottis during the normal phonatory cycle. The open quotient is set by the cams shape and has a value of 0.5. These boundary condition settings are also given into a numerical vocal fold model.

Flow Field Visualizations

The experimental set-up allows full optical accessibility into the region of interest shown in Figure 3 for the recording of flow. The medium in the downstream region of the glottis is seeded with fluorescent particles and a laser sheet illuminates the characteristic midplanes in the near-glottal region: the coronal plane (x-y) and the sagittal plane (x-z).

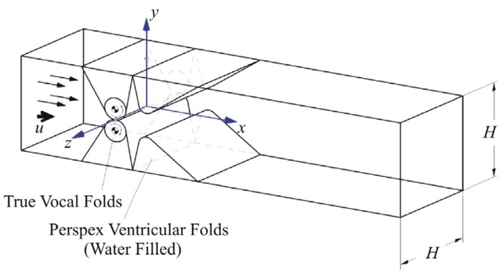

Figure 3: Region of interest, H_{model} = 60 mm.

In the following Figures 4 and 5 we show selected visualization images without inclusion of model ventricular folds at a realistic fundamental frequency of f_0 = 135 Hz and a transglottal pressure of Δp = 6 cmH_2O.

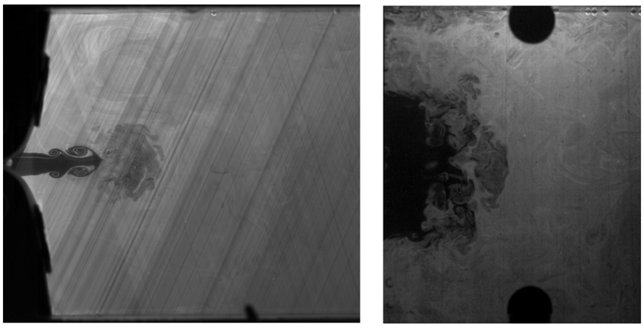

Figure 4: Snap-shot of the jet in x-y (left) and x-z (right) planes at t/T = 0.125 of the glottal cycle.

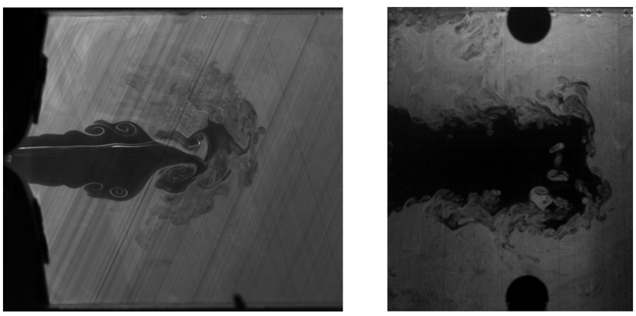

Figure 5: Snap-shot of the jet in x-y (left) and x-z (right) planes at t/T = 0.25 of the glottal cycle.

The temporal and 3D spatial evolution of the jet is very characteristic. The roll-up of the jet edge into Kelvin-Helmholtz type vortices is clearly visible. Part of these large scale vortices interact and merge. The visualization in the x-z plane evidences the axis-switching of the jet during the glottal cycle.

Including the model ventricular folds the jet front is seen to be stabilized (Figure 6).

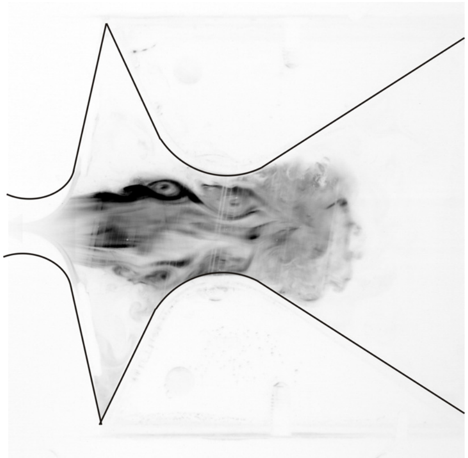

Figure 6: Snap shot of the jet in x-y plane at t/T = 0.25 of the glottal cycle, model ventricular folds included.

The 3D unsteady incompressible flow field is solved with the finite volume method based code OpenFOAM. Exemplarily we show in Figure 7 the flow visualization by means of a passive scalar in the x-y and x-z planes for the instant of maximum glottal opening. In the numerical simulation of the glottal flow global and local flow structures are observed to be similar as in experiment.

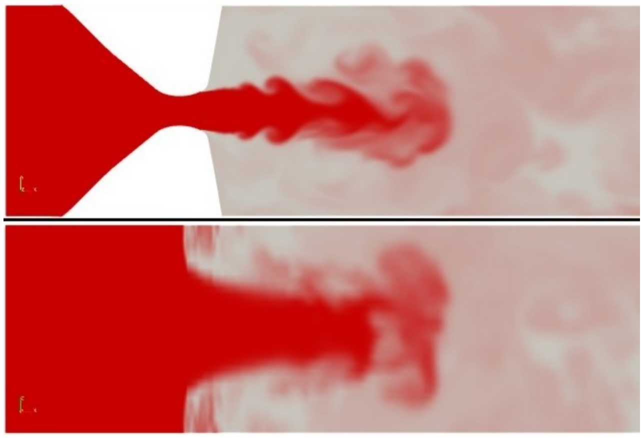

Figure 7: Flow visualization in the x-y (top) and x-z (bottom) planes for instant of maximum glottal opening t/T = 0.25.

Conclusions

We conclude that the flow field in the presented vocal tract model is of 3D unsteady nature and that it is important to consider in general the 3 dimensionality of the vocal folds. The main flow structures have been visualized.

The aim of the continued study is the comparison of the flow fields of irregular cam cases, such as observed in medical practice against the regular convex cam case illustrated here. In particular the noise generation (acoustic sources) are extracted from the computed flow field such that the impact on the voice quality can be quantified and a possible pathology assessment will be feasible.

Acknowledgements

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