FLOW-STRUCTURE-ACOUSTIC INTERACTION IN A HUMAN VOICE MODEL

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ABSTRACT

For the investigation of the physical processes of the human phonation a fluid-structure-coupled in-vitro model was developed, which constitutes a copy of the human voice. With that model one was able to reproduce manlike process of sound production.

The model made it possible to enforce extensive observations of the flow-induced vocal folds vibrations. Many measurement techniques were applied like flow visualization, Particel Image Velocimetry (PIV) of the time-dependent flow field, unsteady pressure measurement, vibration measurement by a Laser-Scanning-Vibrometer as well as the measurement of the acoustic field. Furthermore correlations were done between the acoustic field and the flow velocity and the movement of the structure.

The results support the existence of the Coanda-effect during phonation. The flow attaches to one vocal fold just past the glottis and forms a spacious vortex behind the vocal folds. That behavior is not linked to one vocal fold and changes stochastically. The sound production is presumed to be produced by oscillations of the vocal folds and the involved oscillating volume flow rate.

INTRODUCTION

Human voice production arises from oscillations of the two opposing vocal folds within the larynx. The opening between the vocal folds is called glottis. Increased subglottal pressure causes an airstream through the glottis and excites vocal fold oscillations (figure 1). Hence, the airstream is modulated and forms the primary voice signal. Subsequently, the voice signal is filtered by the vocal tract and emitted as acoustic signal through the mouth.

The objective of these investigations is to understand the physical mechanism of the voice production in detail.

For example the knowledge of the mechanism of human phonation might lead in the far future to the development of synthetic vocal fold implants for people who lost their vocal folds in succession of larynx cancer. In the near future that knowledge will help a surgeon to form remaining tissue of mucosa in a better way, so that such patients will possess a voice after the surgery without any learning how to use common devices. A synthetic model of the vocal folds would allow many observations, which cannot be applied to a living human being. On that way certain disease patterns could be reproduced, their effects observed and adapted and gentle surgery techniques developed.

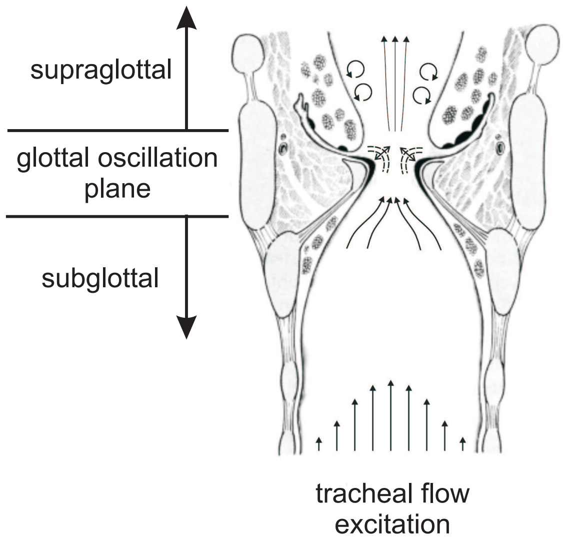

Figure 1: Schematically sketch of the vocal tract

Previous works can be divided into investigations on rigid configurations of vocal folds with a constant and modulated volume flow rate, respectively, and into experiments with oscillating vocal folds. In the second case one has to distinguish between impressed vocal fold movements and flow-induced oscillations of the vocal folds. The advantage of rigid geometries of vocal folds ([1], [2], [3], [4], [5]) consists in a better accessibility. In that case the vocal folds can be constructed of transparent materials, which allow optical research in the area of the glottis. Often only single phenomena are observed, which results of the flow through the glottis. Here the main focus lies on the Coanda-effect ([5], [6], [7], [8]), (attachment of the flow to one vocal fold and separation from the other) and the fluctuating separation-lines on the vocal fold ([9], [10]). In Hofmans et al. [5], who use rigid models of vocal folds, the movement is included in the investigations by different geometries of the vocal folds combined with a time-dependent incoming flow rate.

Research which involves the dynamic of the vocal folds movement displays an improvement of the methodology. Externally impressed vocal fold movement are used in [11], [12], [13]. Triep et al. [14] went a similar way. They used water as fluid, from which a better spatial and temporal resolution arises. In all investigations with external driven oscillations of the vocal folds there is the familiar problem of the exactly modulating modi of vibration. So far these modi are only approximetly describable because no measurement methodology exists for recording the areal and temporal movements of oscillation with a satisfying accuracy. Currently the basis constitutes a model by Hirono et al. [15]. The cycle of the vocal fold vibration begins with a convergent form of the cross-section of the vocal folds and gives way to a divergent cross-section during the closure process of the glottis. The schematic cycle is shown in figure 2. The improvement of that model for the healthy and diseased process of phonation is the topic of current research.

The investigations of the present work concentrate on a self-excited model of vocal folds. The flow impresses self-excited oscillations on the synthetic vocal folds within a fluid-structure interaction.

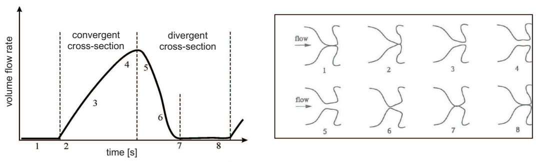

Figure 2: One cycle of the movement of the glottis in [12]

That methodology constitutes a obvious improvement of reproducing the human phonation in comparison to the externally driven models. Herein the ambition is to copy the whole process of the flow-induced vocal fold oscillations with the aid of capable materials close to reality and thus to preserve the energy balance of the whole process of the vocal fold movements. Concerning this matter observations were made by Thomson et al. [16].

The literature shows, that the research with flow-induced vocal folds is just at the beginning. There are first attempts for capable materials which leads to flow-induced vocal fold movements. However, the whole physical process of the fluid-structure-acoustic interaction which causes the human phonation has been not understood yet completely.

EXPERIMENTAL SETUP

To get a better understanding of the physically mechanism of the voice production a special test facility has been constructed. Figure 3 shows the design of the self-oscillating model of the vocal folds. It was cast into an idealized shape of the vocal folds on a 1:1 length scale with human vocal folds.

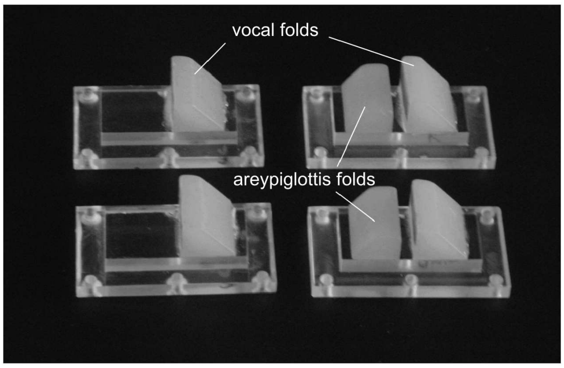

Figure 3: Vocal folds design

The vocal fold models (figure 3) were constructed using a three part polyurethane rubber compound. The stiffness of the cured rubber could be varied by adjusting the mixing ratios or the different compounds. Tensile tests on the different rubbers used in the experiments yielded youngs moduli from about 30kPa to 6.5kPa. These moduli are in the range of that found in vocal fold tissues.

The geometric dimensions of the test channel were adapted to the human vocal tract. Figure 4 shows a

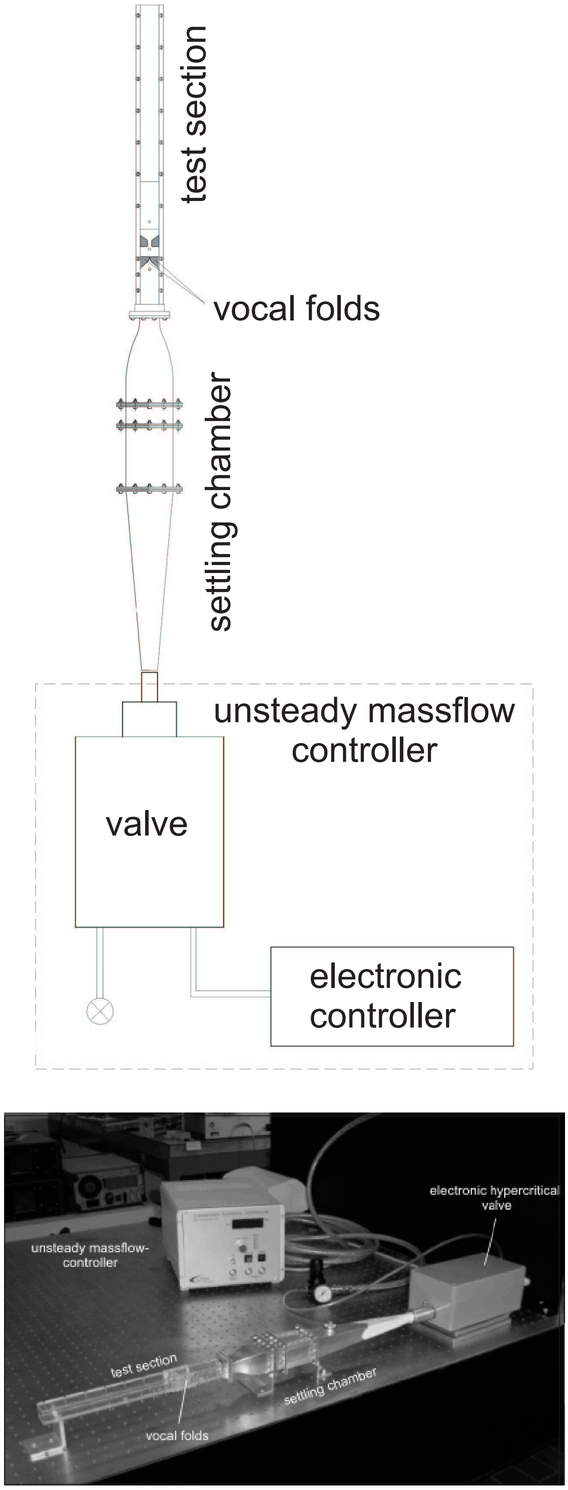

Figure 4: Schematic exposition and a photo of the basic test rig

schematic exposition of the test rig.

It consists of an unsteady mass flow controller which can deliver a constant as well as a pulsating mass flow rate comparable to the human breathing process. To the mass flow engine a settling chamber with a nozzle is connected which is screwed to the test section over a flange. The test section contains the vocal fold models.

For the experimental investigations different measurements techniques were used. At first the experiments started with visualization experiments. To get information about the complex fluid–structure–acoustic interaction in the glottis the instationary flow field and pressure field were correlated with structure movements and the acoustic sound signal.

The velocity measurements were done by phased resolved Particle–Image–Velocimetry (PIV) measurements and Constant–Temperature–Anemometry (CTA). For getting information about the structure oscillating a Laser scanning vibrometer was used (figure 5).

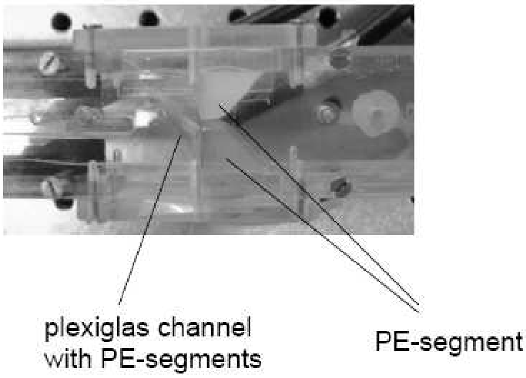

Figure 5: Measurements of vocal folds vibration by using Laser-Scanning-Vibrometer

RESULTS

To get flow induced oscillations of the vocal folds an additional mass body was integrated which causes a frequency in the range of 35 Hz. Thereby a clear hum could be heard in the acoustic far field. Figure 6 shows an open glottis of the testmodel (left) and one of a human being (right). A very good consistency of the oscillation form was found between the synthetic and the human vocal folds.

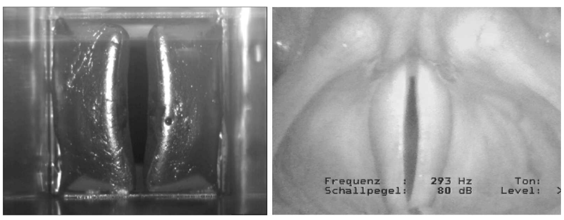

Figure 6: Glottis of the test model and of a human being

The whole oscillation process is shown in figure 7. The single pictures were made by a digital high-speed-camera. As reference value the pressure fluctuation upstream the glottis was used.

Thereby a phase shift between the maximal pressure upstream the glottis and the complete closure of the glottis could be seen in the whole process.

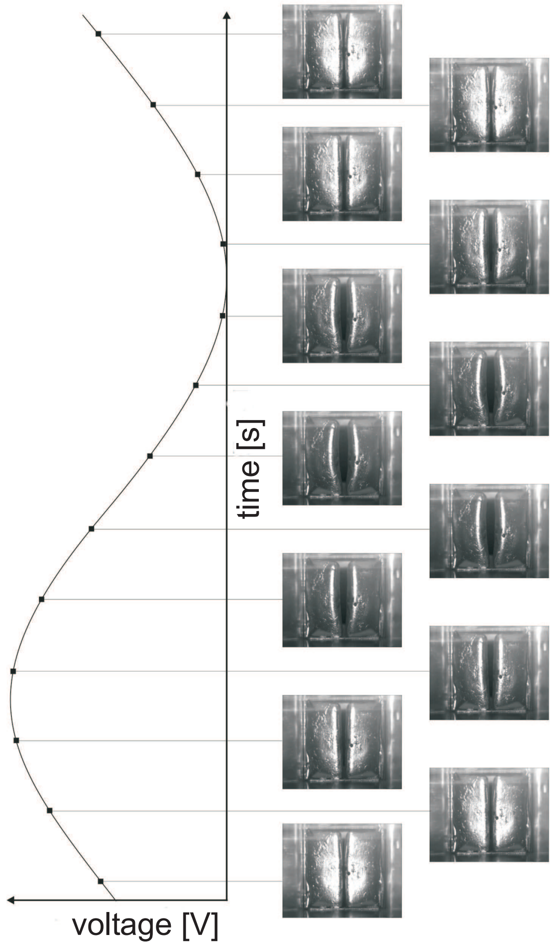

Figure 7: Form of the glottis during a whole oscillation cycle in reference to the pressure signal upstream the glottis

The figure 8 shows the vortex distribution behind the vocal folds. The flow separated the one vocal fold just passed the minimum glottal cross section and remained attached to the glottal wall of the other vocal fold until reaching the glottal exit expansion.

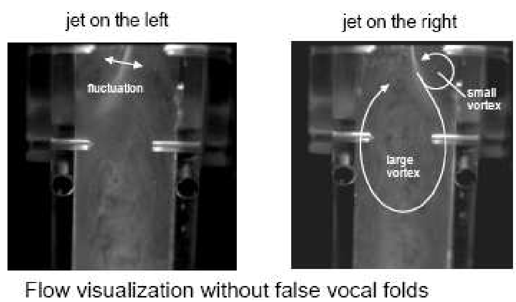

Figure 8: Visualization of the flow field

To get information about the complex fluid–structure–acoustic interaction in the glottis the unsteady velocity field and pressure field were correlated with structure movements and the acoustic sound signals.

Figure 9 represents the velocity field at a single time step during the opening phase of the vocal folds.

The obtained results document the existence of the Coanda effect. The flow attaches to one vocal fold while passing the glottis and creates a large scale vortex down-

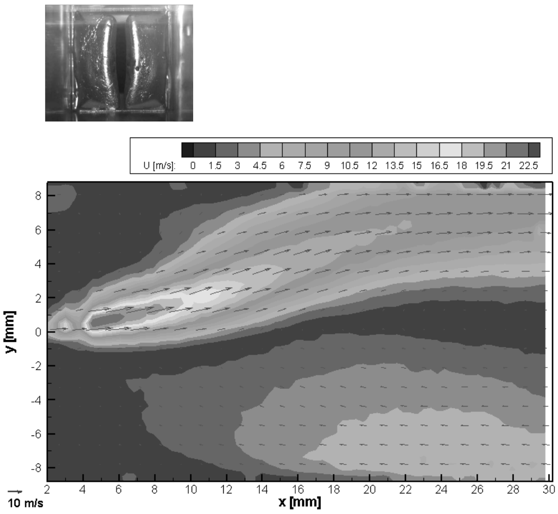

Figure 9: Vector plot and contour plot of the velocity downstream the vocal folds and the correspondent glottis opening

stream of the vocal folds. This process is not tied to one specific vocal fold. Instead the sides are changed in a stochastic manner.

In order to study further the process of sound production simultaneous measurements of two unsteady pressure transducers, a Constant–Temperature–Anemometer and a microphone were conducted at various flow rates.

Correlation analysis revealed that at a discrete frequency of 34 Hz and higher harmonics thereof significant coherence is present. The coherence among wall pressures upstream and downstream of the vocal folds and the coherence between velocity fluctuations in the flow and the recorded sound pressures give rise to the following assumption. The flow is assumed to impose deflections of the vocal folds causing them to oscillate at their resonance frequency which in turn causes pulsations of the flow and additionally leads to a pulsating jet and pressure fluctuations which can be observed in the acoustic far field.

Figure 10 displays local wall pressure spectrum, local velocity spectrum (obtained via HAD downstream of the glottis) and the recorded acoustic pressure spectrum.

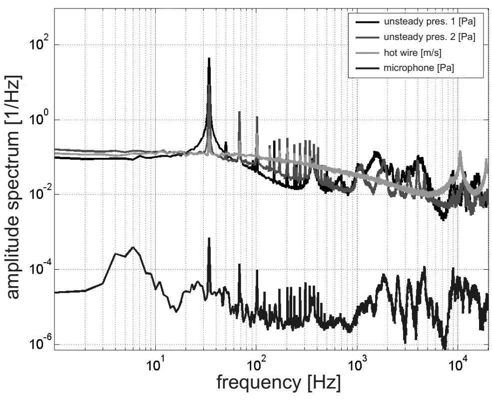

Figure 10: Amplitude spectrum of the unsteady pressure at two positions in the testsection, of the velocity measured by the Constant–Temperature–Anemometry and of the acoustic sound measured by the microphone

The lack of coherence between local velocity fluctuations observed via HAD which might be attributed to vortices in the shear layer and the microphone signal leads to the conclusion that turbulence induced sound plays a minor role in this case.

Via laser scanning vibrometer the direct relation between displacements of the vocal folds, pressure oscillations in the flow and radiated sound could be observed.

Oscillations of the vocal folds and local wall pressure are recorded for several flow rates. In a limited range of flow rates both oscillations rise steeply which leads to the assumption that humans are capable of increasing pressure fluctuations and thereby loudness of their speech by increasing the rate of flow coming from their lungs.

It was observed that the vocal folds are already oscillating according to their resonance frequency at low flow rates and low non audible frequencies. The resonance frequency is almost unaffected by increases of the flow rate.

This might be an indication that the major part of the sound production is due to pulsations of the jet and not due to turbulence.

This gives rise to the need of further investigations using PIV systems with higher spatial and temporal resolution which enables direct determination of vortex induced source terms in the experiment.

CONCLUSION

Recapitulating one can say that in this work the model of the vocal folds was optimized and a manlike phonation process could be reproduced. Furthermore detailed measurements of the velocity field with a flow-induced oscillating model of vocal folds could be done for the first time. These measurements are impossible to be done with human patients. The results allowed a good insight in the complex process of human sound production and was helpful in evaluating existing theories.

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