Sound Generation in a Flow-Induced Vibrating Human Vocal Folds Model

S. Becker[1], S. Kniesburges[1,2], S. Müller[1], A. Delgado[1]
[1] *Institute of Fluid Mechanics, University of Erlangen-Nuremberg, Germany*
[2] *Erlangen Graduate School in Advanced Optical Technologies (SAOT), University of Erlangen-Nuremberg, Germany*
Email: stefan.becker@lstm.uni-erlangen.de

Introduction

During human evolution a very effective device for sound generation has been developed, the larynx. Inside the two vocal folds (VFs) are located which close the airway into the lungs at the beginning of phonation. The airstream coming from the lungs excites the VFs to a vibration with a frequency between 80 Hz and up to almost 800 Hz of sopran singers depending on age and gender. Thereby the oscillation states a fluid-structure interaction that is a myoelastic-aerodynamic process. The frequency can be varied by the elongation or shortening and the accompanying stretching or thickening of the VFs [1]. The vibration produces the basic tone of the human voice with the frequency of the oscillation of the VFs. This basic tone is further modulated in the vocal tract which consists of the upper airways.

A disturbance of the efficient system of sound production leads to a restrained or the total loss of human communication. Identifying and analyzing the basic physical mechanisms of sound production are of great interest for improving medical treatment and for developing artificial vocal fold implants in the future. On this account, many international groups are engaged in experimental and theoretical approaches in voice research, with the common objective of identifying the leading processes for the production of the basic tone in human phonation. Therefore it is essential to understand the behavior of the individual parts in this multifarious physic problem.

There are three mechanisms of sound generation, the flow rate-induced sound, the structure-induced sound and the turbulence induced sound. The aim of the present work is to identify the physical parameters controlling the whole process and to determine their influence on the three mechanisms of sound production. Therefore an experimental model was designed which showed flow-induced vibrations of synthetic VFs and produced a detectable tonal sound in the acoustic fare field. The flow field of the fluid-structure-acoustic coupled problem was measured by Becker et al. [2]. The results showed the existence of the Coanda-effect which is responsible for the asymmetric flow field in the superglottal region. This asymmetry and the observed turbulence are assumed to be the leading mechanisms for the sound production.

Therefore, the authors are convinced that for investigation of the acoustic production a model has to be build which reproduce the full fluid-structure-acoustic process similar to human phonation. The synthetic VFs are based on those of Thomson et al. [5] who developed models which show human-like oscillation with a characteristic frequency of about 120 Hz. However, they didn't investigate the longitudinal tension within the VFs. Accordingly the models of the present work were adjusted to investigate the influence of this parameter additionally to the stiffness of the applied material.

Methods

In this work the vibrations of the VFs and the sound production was investigated depending on the tension within the the VFs. For this aim models were designed which satisfied the requirements of the measurements. The whole test rig was designed in human length scale under compliance with the physical parameters displayed in table 1.

Diameter of the larynx	$D = 18 - 22\,\mathrm{mm}$
Maximal glottis opening	$w_{\mathrm{G,max}} = 1 - 3\,\mathrm{mm}$
Pressure diff. across glottis	$\Delta p = 500 - 2000\,\mathrm{Pa}$
Mean velocity	$U_{\mathrm{mean}} = 20 - 40\,\frac{\mathrm{m}}{\mathrm{s}}$
Frequency	$f = 100 - 200\,\mathrm{Hz}$
Reynolds number	$Re = \frac{U_{\mathrm{mean}}\, w_{\mathrm{G,max}}}{\nu} = O(10^3)$
Mach number	$Ma = \frac{U_{\mathrm{mean}}}{c} = O(10^{-1})$
Strouhal number	$St = \frac{f\, w_{\mathrm{G,max}}}{U_{\mathrm{mean}}} = O(10^{-2})$
Young's modulus	$E = 5 - 10\,\mathrm{kPa}$

Table 1: Physical parameters of the human phonation.

Vocal fold models

The homogeneous VF model consisted of a three-component silicone rubber (fig. 1 left). The stiffness was set by choosing a certain mixing ratio. Therewith models with three different Young's moduli of 3.3 , 6.85 and 13.2 kPa were produced. The geometry of the oscillating part was similar to the models of Thomson et al. [5]. For setting a prestress within the synthetic VFs the transversal ends of the oscillating part were extended. These additional parts of the VFs were glued on mounting plates which were fixed outside of the test channel. Besides the free-length models two different prestresses were applied by stretching the synthetic VFs of about 6.8 mm and 10.8 mm.

Test facilities

The main test rig contains an unsteady mass flow device with a valve, a settling chamber and the rectangular test

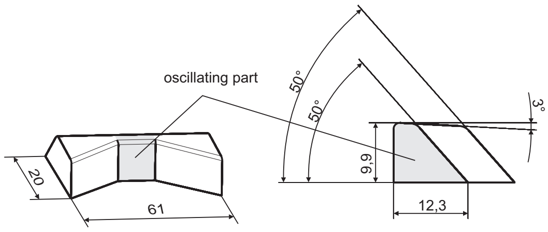
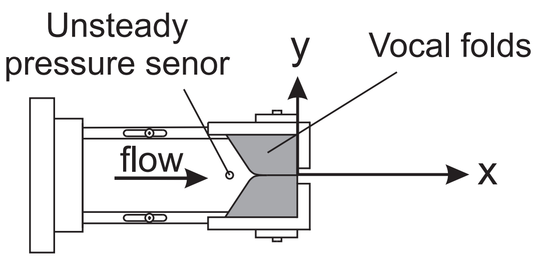


Figure 1: Geometry and photo of the synthetic VFs

channel at whose end the synthetic VFs were mounted (fig. 2). The cross section of the channel amounted 17.8×18 mm. The models were fixed on four mounting plates outside of the flow region. The plates could be moved in transversal direction to stretch the synthetic VFs.



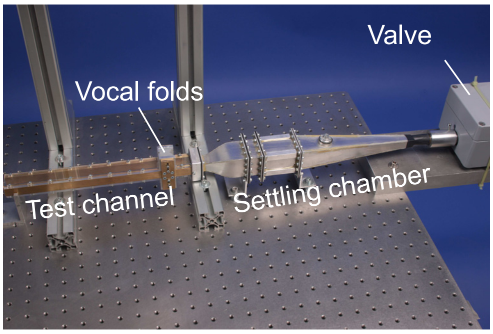


Figure 2: Test channel containing the models of the VFs. **Bottom right:** Photo of the main test rig including mass flow controller and settling chamber.

Several measurement techniques were applied investigating the whole problem. Firstly the oscillating models were visualized by using an high-speed camera with a frame rate of 5000 Hz. The recordings were triggered by an unsteady pressure sensor in subglottal region upstream of the glottal duct.

Secondly for the investigation of the sound production synchronous measurements of the unsteady pressure upstream of the glottis, the unsteady flow velocity downstream of the glottis and the acoustic pressure in the fare field were performed. The unsteady pressure was measured by a pressure sensor of *Kulite*. The flow velocity was determined with a hot-wire probe. The acoustic signal was detected by a microphone (*Type BK 2669*) with spherical characteristics. All signals were recorded synchronously controlled by a LabView program.

Results

The models of the VFs were used for the investigation of the influence of the stiffness and the prestress on the fluid-structure-acoustic coupled process. Figure 3 shows the determined oscillation frequency of models for three different Young's moduli and three prestressed states. The diagram indicates that the frequency strongly depends on the stiffness of the material. Furhtermore an increasing prestress within the VFs results in a higher frequency of the vibration of the VFs up to 96 Hz which is consistent to the range in human phonation.

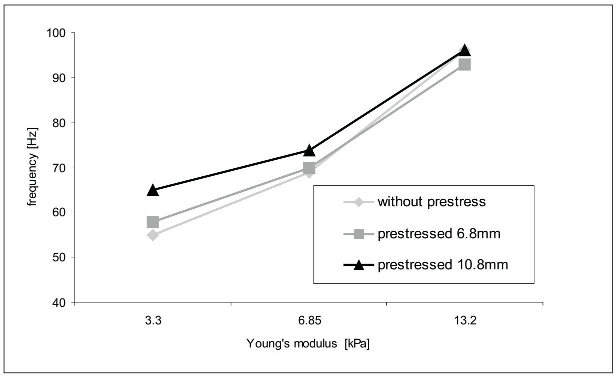


Figure 3: Oscillation frequency depending on the stiffness and prestress state of the vocal folds

The glottal width was measured between 0.7 and 2 mm by evaluating the high-speed visualisation measurements of the glottal movement. Figure 4 shows the VFs during one oscillation cycle in reference to the subglottal pressure. A phase shift of about $3/8\,\pi$ is recognizable considering the maximum pressure at $\alpha = \pi/2$ and the maximum glottal width at $\alpha = 7/8\,\pi$. The glottal opens at the increasing slope of the pressure distribution which reaches its maximum during the opening process. The accelerated fluid as well as the decreasing pressure starts the closing process which is finished with full glottal closure at $3/2\,\pi$.

Furthermore the phase shift is strongly influenced by the stiffness of the VFs and the prestress. As can be seen in fig. 5 left the phase shift increases with decreasing stiffness as well as with decreasing prestress. The changing of the phase shift is the result of the larger elastic forces which were caused by the higher stiffness and prestress. The elastic forces are the reaction of the structure to the driving forces of the fluid. Due to different inertias of the fluid and the structure a complex interaction between the two physical regions generates the self-sustained vibration of the VFs.

This dynamic process causes the basic tone of the human voice. To determine the influence of the different sound generating mechanism synchronous measurements of the subglottal pressure, the flow velocity in supraglottal region and the acoustic pressure in the fare field were performed. Figure 6 shows the amplitude spectra of the time signals. The major peak in all spectra is located at the vibration frequency of the synthetic VFs at about 69 Hz. Furthermore peaks of the higher harmonics are

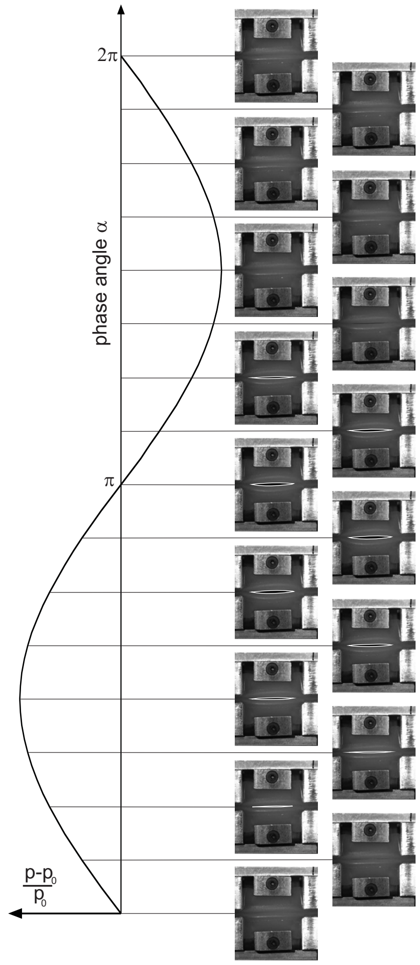


Figure 4: Pictures of the synthetic vocal folds depending on the subglottal pressure recorded with a digital high-speed camera

also clearly recognizable. It shows that the pulsating flow rate is the main acoustic source in human sound generation. Additionally a broadband sound could be detected during the measurements which is present in the spectra of the acoustic and the subglottal pressure at frequencies greater than 1000 Hz. Considering the acoustic analogy of Lighthill [6][7] the turbulent sound generation is related to turbulent fluctuations of the flow velocity. The fact, that there is no broadband behaviour in the spectrum of the flow velocity indicates that the turbulent vortex structures produced in the shear layers of the jet did not make a dominant contribution to the noise generation in the phonation process. Furthermore the maximum velocity obtained in the PIV measurements of 22.5 m/s (Ma $<$ 0.1 within the jet, see Becker et al.[2]) was to low to create a determinative acoustic source term in the shear layer. Therefore it tends to the conclusion that in healthy human sound production the turbulence-induced sound does not make a reasonable contribution to the human sound production. The detected broadband noise could be the result of an oscillating pressure gradient on the back faces of the synthetic VFs similar to the trailing edge noise at the wings of aeroplanes [8]. However to validate this theory further measurements has to be done.

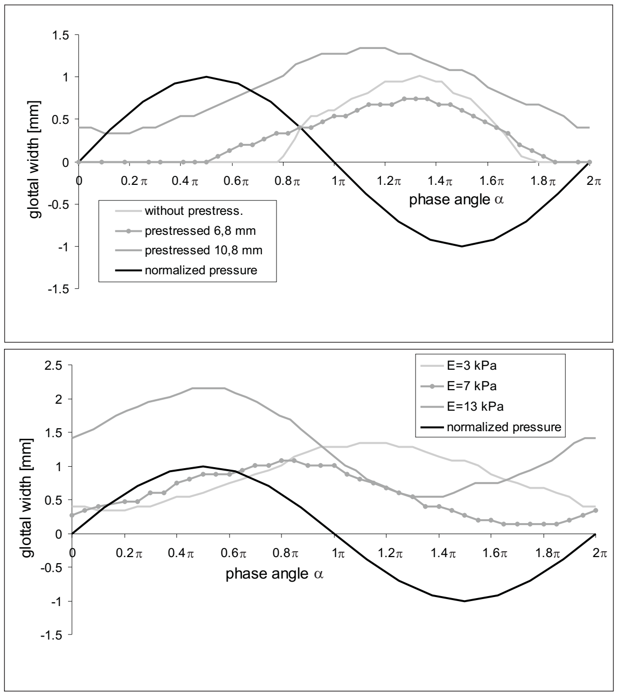


Figure 5: Opening of the glottis depending on prestress (upper diagram) and Young's modulus (lower diagram) during an oscillation cycle in reference to the subglottal pressure.

Conclusion

In the present work experimental investigations of the fully coupled fluid-structure-acoustic process in a human larynx model were reported. Therefore the most important conditions were first the generation of self-sustained oscillations of the synthetic VFs and second the production of a tonal sound. Therefore a model of the human vocal folds was designed satisfying these conditions.

A strong influence of the oscillation frequency of the VFs on the stiffness of the material and on the prestress was determined. Varying these two parameters oscillation frequencies up to 96 Hz were obtained which is consistent with frequencies in human sound production. Furthermore a phase shift between the periodic movement of the VFs and the subglottal pressure distribution was observed which also strongly depended on the stiffness and the prestress. The synchronous measurement of the subglottal pressure, the flow velocity downstream of the VFs and the acoustic pressure in the fare field identified the pulsating flow rate as main acoustic source. Analyzing the amplitude spectrum of the flow velocity the turbulence-induced sound is assumed to give no contribution to the detected broadband noise. The broadband sound is rather produced by the oscillating pressure gradient on the back faces of the synthetic VFs.

Acknowledgement

The authors gratefully acknowledge funding of the researcher group DFG FOR 894: "Strömungsphysikalische Grundlagen der menschlichen Stimmgebung" and the Er-

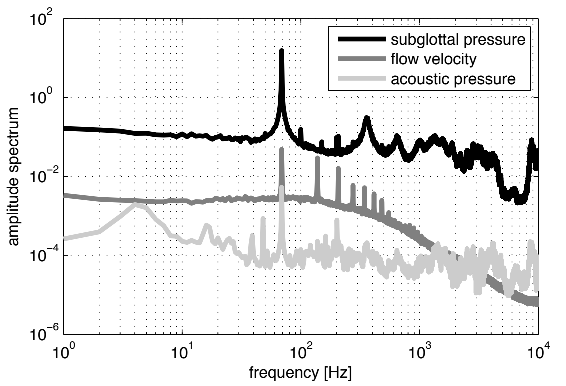


Figure 6: Amplitude spectra of the subglottal pressure, the unsteady flow velocity and the acoustic pressure for prestressed models with $E = 6.85\,\mathrm{kPa}$

langen Graduate School in Advanced Optical Technologies (SAOT) by the German National Science Foundation (DFG) in the framework of the excellence initiative.

References

[1] S. McCoy: "Your voice: an inside view", Inside View press, ISBN 0-9755307-2-0, 2004.

[2] S. Becker, S. Kniesburges, S. Müller, A. Delgado, G. Link, M. Kaltenbacher, M. Döllinger: "Flow-structure-acoustic interaction in a human voice model", J. Acoust. Soc. Am., vol. 125(3), pp. 1351-1361, 2009.

[3] H. Coanda: "Device for deflecting a stream of elastic fluid projected into an elastic elastic fluid", US-patent, 2,052,869, 1935.

[4] G.C.J. Hofmans, G. Groot, M. Ranucci, G. Graziani, A. Hirschberg: "Unsteady flow through in-vitro models of the glottis", J. Acoust. Soc. Am., vol. 113(3), 2003.

[5] S.L. Thomson, L. Mongeau, S.H. Frankel: "Physical and Numerical Flow-Excited Vocal Fold Models", 3rd International Workshop MAVEBA, ISBN 88-8453-154-3, 2003.

[6] M.J. Lighthill: "On sound generated aerodynamincally I. General theory", Proc. R. Soc. London, A 211, pp. 564-587, 1952.

[7] M.J. Lighthill: "On Sound generated aerodynamically II. Turbulence as a source of sound", Proc. R. Soc. London, A 222, pp. 1-32, 1954.

[8] T.F. Brooks, T.H. Hodgson: "Trailing edge noise prediction from measured surface pressures", Journal of Sound and Vibration, vol. 78,pp. 69-117, 1981.