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A time-resolved PIV-based methodology to analyse the acoustics of human phonation

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Abstract

In the present paper, we aim to characterize the mechanisms of sound generation during voiced human speech, which is referred to as phonation. This has been achieved in a combined experimental-numerical approach, which applies a PIV-based flow field to numerically compute the acoustic source field and simulate the radiation of the resulting sound field. By adapting state-of-the-art formulations, the acoustic source is fully separated from non-acoustic fluid-mechanical pressure fluctuations. The most intense source was found directly at the vocal folds. In addition, slightly less intense sources were found along the shear layers of the glottal jet. The resulting spectrum of the radiated sound shows similar characteristics as the validating experimental microphone measurement below 1 kHz.

1 Introduction

The mechanisms of basic sound generation for healthy and disordered voice production is of scientific and clinical interest. In recent years, advances in the field of aeroacoustics enabled further insight into sound generation during this so-called phonatory process. Howe and McGowan (2007) showed in an analytical model that sound is mainly generated by aeroacoustic sources immediately downstream of the glottis. In an experimental approach, Lodermeyer et al. (2018) found that highly intense tonal pressure fluctuations are generated at the glottal exit, while broadband sound is evoked along the full length of the glottal jet. These approaches were based on Lighthill's acoustic analogy or Vortex Sound theory, which are derived from the basic equations of fluid mechanics. These classic analogies describe sound generation as a combination of fluid-mechanical and acoustic pressure fluctuations within the flow region. While the sound radiated into the far field is valid, the flow region shows no separation of fluid-mechanical and acoustic pressure fluctuations. Hence, these studies have limitations regarding the analysis of the acoustic sources within the flow region. To overcome this drawback in aeroacoustic analyses, a perturbation approach has been assessed, e.g. by applying the Acoustic Perturbation Equations (APE) by Ewert and Schröder (2003). This has been further optimized for high-performance computing (HPC) by Hüppe et al. (2014), who proposed a Perturbed Convective Wave Equation (PCWE). By neglecting the convective flow, the modified formulation referred to as the Aeroacoustic Wave Equation (AWE) as derived by Kaltenbacher (2017) may be derived as

$$\frac{1}{c_0^2}\frac{\partial^2 p_a}{\partial t^2}-\frac{\partial^2 p_a}{\partial x_i^2}=-\frac{1}{c_0^2}\frac{\partial^2 p_{ic}}{\partial t^2} \tag{1}$$

with the speed of sound c_0, the sound pressure p_a, the time t, and the incompressible fluid-mechanical portion of the fluctuating pressure p_{ic}. In studies by Haigermoser (2009) and Koschatzky et al. (2011), Curle's acoustic analogy which is based on Lighthill's source formulation was applied to flow data acquired

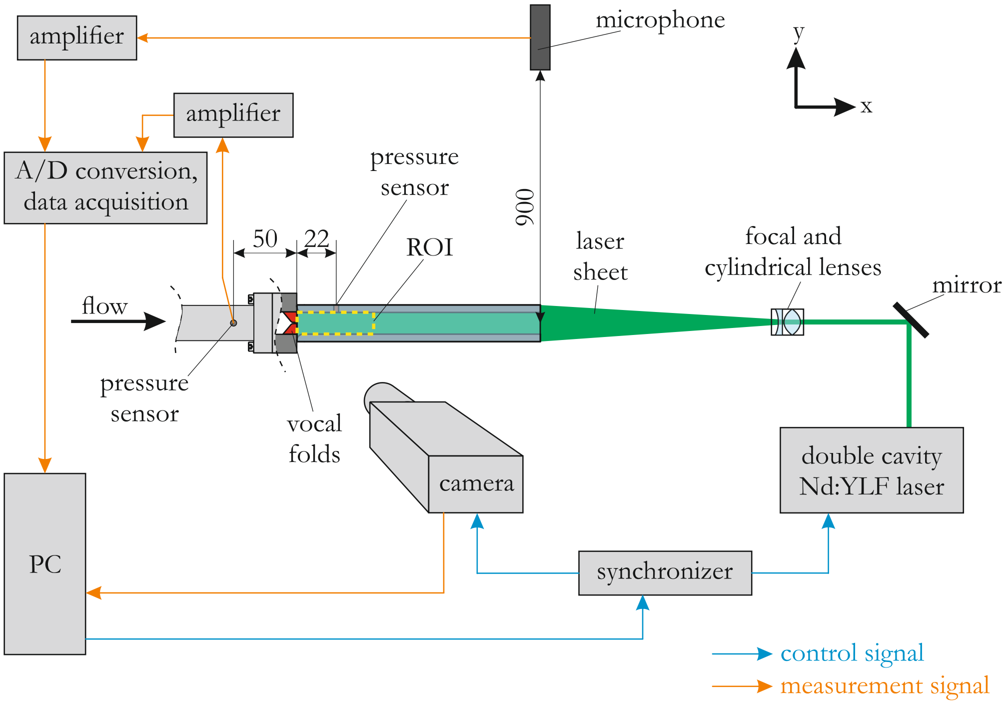


Figure 1: Experimental setup as applied in the HAcouPIV measurements.

by high-speed PIV. By that, the investigation of sound generation in an experimental approach is enabled. In the present study, we apply the aeroacoustic PCWE formulation in a PIV-based experimental approach to detect sound generating mechanisms relevant for voiced speech. Thereby, we analyze the fully separated sound field generated within the supraglottal region based on the PCWE formulation.

2 Methdology

The experimental setup is shown in figure 1. In our Hybrid Acoustic PIV (HAcouPIV) approach, we acquire the instantaneous flow field using time-resolved PIV at a sample rate of $f_s = 10\,\text{kHz}$. The ROI (marked with a yellow frame in figure 1) is located immediately downstream of the vocal folds (marked in red). The light sheet that illuminates the particle-seeded flow in the mid plane is guided through the channel outlet. The flow field data is then used to assess the pressure field as proposed by de Kat and van Oudheusden (2012). In a subsequent step, the aeroacoustic sources within the so-called supraglottal region, i.e. the channel downstream of the vocal folds, are computed. After that, the acoustic radiation is simulated to assess the resulting sound radiation. Since this HAcouPIV procedure applies both experimentally measured flow field data and simulated sound radiation, it is a hybrid approach. Instead of applying Curle's analogy, as already shown by Haigermoser (2009) and Koschatzky et al. (2011), we adopt an FEM-based approach using the code package of CFS++ as developed at the TU Vienna and FAU Erlangen-Nürnberg. Thereby, resonator modes are reproducible, which would not be possible for a Curle-based approach. A more detailed description of that approach is published in Lodermeyer et al. (2018). As an enhancement to that approach, we implemented the AWE and PCWE approaches as part of this paper to assess an acoustic pressure field that is fully separated from the fluid-mechanical pressure fluctuations. Hence, a direct analysis of the sound sources and its radiation is feasible.

3 Results and discussion

Figure 2 shows the flow field during the open phase (upper row) and closed phase (lower row) of the vocal fold oscillation. Thereby, the contour plots in the left column depict the velocity magnitude, while the right column shows the relative static pressure computed by a Poisson solver as proposed by Liu and Katz

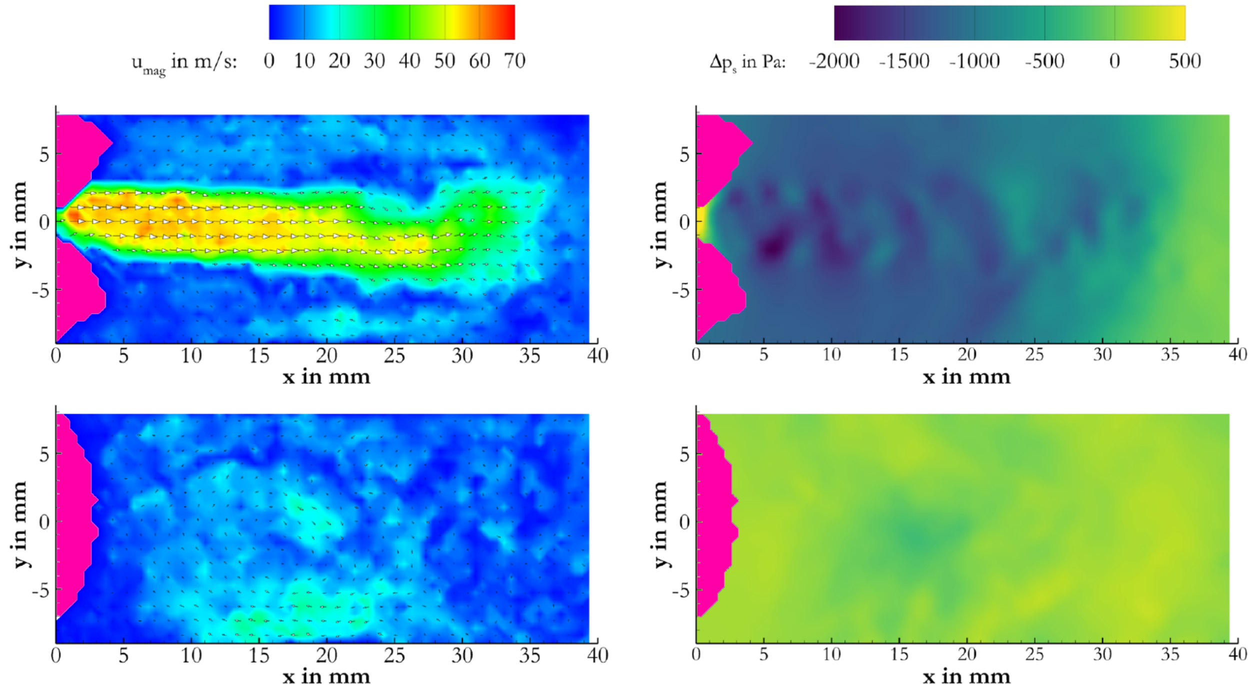
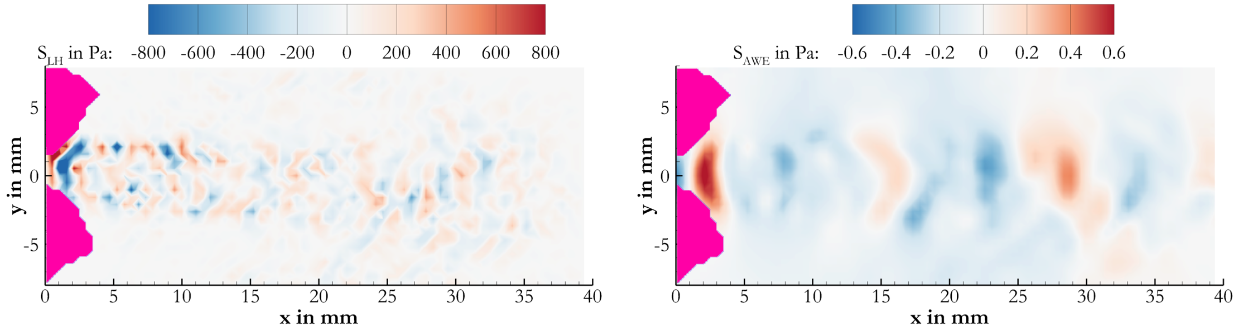


Figure 2: Resulting velocity field (left column) and static pressure field (right column).The upper row shows a time step with a fully developed glottal jet through the opened glottal duct and the lower row depicts a time step of closed vocal folds. The region that represents the vocal fold structure has been masked for the PIV algorithm; the masked cells are tinted in magenta.

(2006) and de Kat and van Oudheusden (2012). During the open phase, a glottal jet develops that measures 35 mm in downstream direction, amounting a maximum velocity just below 70 m/s in the core of the jet. The corresponding static pressure field shows a strong positive relative pressure between the vocal folds. Downstream thereof, the relative pressure is below 1 kPa and shows fluctuating components along the shear layer of the jet. Further downstream of the jet, the field approaches the ambient pressure. As the vocal folds close the glottal duct, a large recirculation vortex develops that rotates with a velocity between 15 m/s and 20 m/s. The corresponding relative static pressure field has a less negative overall level and only shows a slightly negative region in the center of the large recirculation vortex.

Figures 3(a) and 3(b) show the source term based on Lighthill and AWE, respectively, resulting from the flow field with the fully developed glottal jet. Both source fields have their global maximum intensity at the glottal exit. However, the Lighthill-based source formulation yields an intensity that is three orders of magnitude larger than the AWE counterpart. This is due to the superposed acoustic and fluid-mechanical pressure fluctuations inherent in Lighthill's analogy Lighthill (1952). The AWE formulation, in contrast, shows the acoustic pressure fluctuation that is fully separated from the fluid-mechanical fluctuations. This makes the evaluation of sound valid for the latter formulation even within the source region. When analyzing the sources along the glottal jet, the AWE formulation yields spatially more extended fluctuations when compared to Lighthill's analogy. This, again, may be explained with the superposed fluctuations in the latter.

Results of the radiated sound as generated during the phonatory process are depicted in figure 4. Since the flow data is only available within the plane of the PIV light sheet, it was assumed that the acoustic source intensity is homogeneous across the full width of the channel. This needs to be regarded as a limitation of the applied approach. As a validating reference, experimental microphone measurements were conducted during the PIV measurement. In the corresponding spectrum of the sound pressure level (SPL), a combination of harmonics, sub-harmonics, and broadband sound is visible. Additionally, resonator modes are present, significantly above $f = 1$ kHz, which are more clearly visible in a smoothed spectrum which is marked with a dotted line in the spectrum. These resonator modes are called formants in voice research and are indispensable for producing vowels. Both HAcouPIV solutions based on Lighthill's analogy or the PCWE approach show agreement as well as deviations from the experimental measurements. Since the



(a) Lighthill (b) AWE

Figure 3: Exemplary acoustic source fields responsible for aeroacoustic sound generation. The depicted time step is identical to the upper row of figure 2.

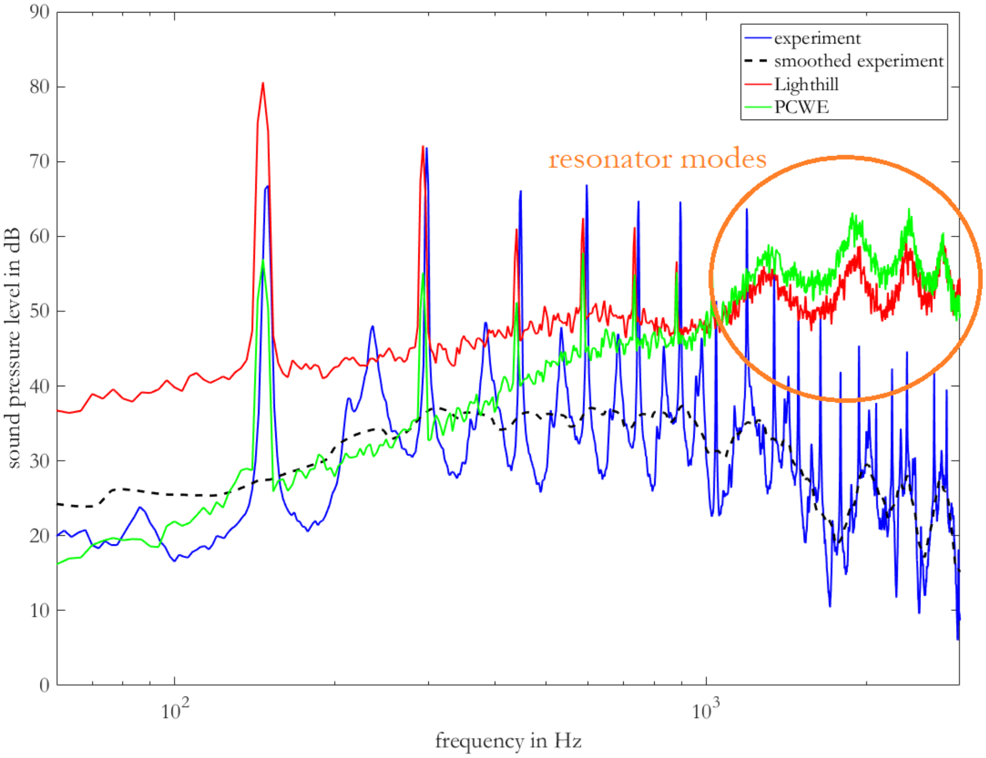


Figure 4: Resulting spectra of the HAcouPIV approach applied to the sound generation of the human voice. The experimental microphone measurement is additionally shown in a smoothed representation using a dotted line to better replicate the resonator modes. The resonator modes in the simulation are emphasized with an orange ellipse. The spectrum corresponding to the AWE formulation is not included since it deviates from the PCWE counterpart by less than 1 dB.

spectrum that is based on the AWE formulation deviates from the PCWE counterpart by less than 1 dB, it is not included in the figure. In general, the lower harmonics are well reproduced, as are the frequencies of the resonator modes. The PCWE approach replicates the SPL below $f = 400$ Hz remarkably well, but overestimates it above. The quality of the tonal behaviour is comparable to the Lighthill-based result. The latter, in contrast, overestimates the resulting sound pressure in the whole frequency range. However, its spectral slope better matches the experimental microphone measurement.

4 Conclusion

In conclusion, our experimental method to determine sound generation was further improved by the PCWE approach, as the sound field and the source field within the supraglottal region is directly accessible by that. While the resulting Lighthill-based spectra of the sound pressure level are overestimated in the whole frequency range, the PCWE formulation better replicates the spectral slope below 400 Hz. A strong pressure gradient that transitions from a high to a lower pressure at the glottal exit spatially correlates with a strong acoustic source at the glottal exit. In addition, slightly weaker acoustic sources were detected along the glottal jet with the PCWE approach.

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