Whole-Field 3D Characterization of a Pulsating Jet Using Synthetic Aperture Particle Image Velocimetry

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***Abstract*— In this study synthetic aperture particle image velocimetry is used on an excised human vocal fold model to study the airflow over the vocal folds during voice production. For the first time, a whole-field, time-resolved, 3D description of the flow is presented over one cycle of vocal fold oscillation. Complex, unsteady, 3D flow behavior is observed as the jet evolves.**

***Index Terms*—synthetic aperture imaging, particle image velocimetry, three-dimensional, vocal folds, glottal jet**

I. Introduction

Sound is produced as air passes from the lungs, through the trachea, and between the vocal folds. The air induces vibration of the vocal folds and an orifice-modulated jet is formed. This jet, known as the glottal jet, has been the focus of many studies because it is the primary source of sound during speech. A better understanding of the glottal jet and its interactions with the vocal folds will yield a better understanding of voice production. A full characterization of the fluid structure interactions of vocal fold vibration can benefit the development of computational and analytical vocal fold models. The end goal is the improvement of treatment and prevention of vocal fold related voice disorders [1].

In order to characterize the flow dynamics important for speech production, voice researchers have sought a better understanding of the glottal jet. Many have used particle image velocimetry (PIV) as a method for visualizing the glottal jet dynamics. Two-dimensional PIV has been used extensively with various synthetic and excised vocal fold models. Valuable information about glottal jet dynamics has been gained from these 2D studies and confirmed results from computational models, including: jet axis switching, flow separation, vortices, jet flapping, and vena contracta [1] [2] [3].

Due to the highly three-dimensional nature of the glottal jet, recent studies have focused on resolving the flow field in three dimensions. Triep et al. [4] used traditional 2D PIV at various slices of a 3D volume downstream of the vocal folds. A cam driven synthetic vocal fold model was used with water as the working fluid. The time resolved flow field was reconstructed with each 2D slice phase averaged. This study highlighted the 3D and unsteady nature of the glottal jet and stressed the need for a fully 3D study of the jet. Krebs et al. [5] used stereoscopic PIV, to resolve a third component in each slice of the 3D volume. Again, each slice was phase averaged to reconstruct the 3D volume. The study examined, in more detail, the 3D nature of axis switching and noted that the switching does not occur at a fixed distance from the vocal folds and is connected to the flow separation. Despite these recent studies of the 3D flow field there do not appear to be any whole-field, time-resolved, 3D glottal jet descriptions in the voice research literature.

In the present study synthetic aperture particle image velocimetry (SAPIV) was used with excised human vocal folds to characterize the whole-field, time-resolved, 3D glottal jet. SAPIV is a new technique to visualize flow fields in three dimensions. An array of synchronized CCD cameras is used to image the particle field of interest. The images are digitally refocused using synthetic aperture algorithms. The result is a complete focal stack of the region of interest. For a given plane in the focal stack, particles in that plane will appear sharply in focus (high intensity) and particles out of plane will appear out of focus (low intensity). These images are thresholded so that only particles in a given plane are visible. From this point traditional 3D PIV algorithms can be used to calculate the velocity field of the flow. Having multiple camera viewpoints allows for high seeding densities and partial occlusions [6]. These advantages open many new possibilities for understanding fluid flow phenomena. For a detailed description of the methodology of SAPIV see [6].

II. Methods

A. Experimental Setup

The experiments were performed at the University Hospital Erlangen Medical School in Erlangen, Germany. An excised human vocal fold from a 50 year old female was prepared by removing excess cartilage and tissue surrounding the vocal folds and mounted on a 16 mm diameter stainless steel pipe (trachea tube) and clamped to ensure a tight seal (see Figure 1). The vocal folds were symmetrically tensioned by hanging

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a 20 g and a 10 g weight from a string sutured to the front and back respectively. The trachea tube was connected to a compressed air reservoir and the flowrate was adjusted to the minimum needed to induce vibration in the vocal folds (4 L/min), controlled by a custom LabVIEW program.

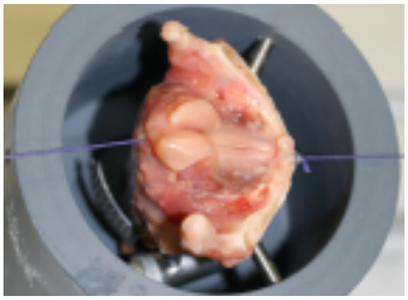

Figure 1: Excised human vocal fold model from a deceased 50 year old female, mounted on a 16 mm diameter steel pipe. The string is connected to the folds via suture and used to tension the folds.

The airstream was seeded with hollow polymer microspheres with a mean diameter of 40 μm (Expancel, 461 DET 40 d25). Flow measurements of the particle field were taken downstream of the excised vocal fold model. The SAPIV measurements utilized eight FASTCAM SA3 high-speed cameras (Photron, 2000 fps, 640 x 640 pixels) in combination with a double-pulsed Darwin-Duo laser system (Quantronix, Nd:YLF, 1000 Hz). A ninth camera was mounted above the vocal folds to track the surface motion of the vocal folds. Figure 2 shows the experimental setup. The pressure at a point upstream of the vocal folds was measured with a pressure probe in the trachea tube. Eventually, these three measurements will be combined to give more detailed, time resolved information.

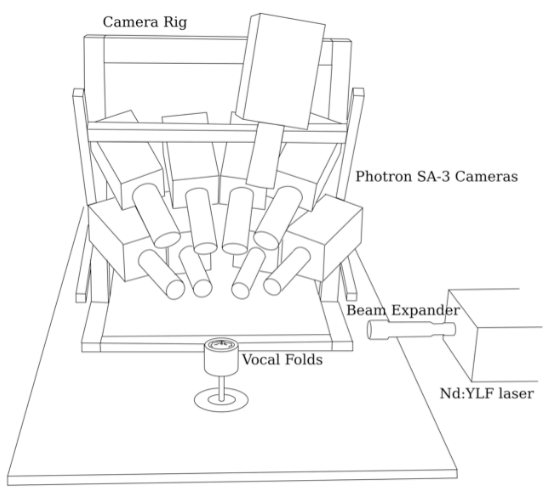

Figure 2: Diagram of the SAPIV setup. Eight high-speed Photron SA-3 cameras are focused on the volume above the vocal fold model. Another camera is mounted above for motion tracking. A high-speed Nd:YLF laser is used to illuminate the particles in the glottal jet.

B. Data Processing

The cameras were calibrated using a process based on the multi-camera self-calibration method presented in [7]. A checkerboard target was placed within the view of all eight cameras and images were taken at 4 different planes throughout the volume of interest. The checkerboard intersection points were found using an auto-correlation method. Using these points, the cameras were then self-calibrated using epipolar geometry relationships. The result of the calibration was a camera projection matrix with intrinsic and extrinsic parameters for each camera. For a more detailed description of the multi-camera self-calibration see [7].

The synthetic aperture refocusing algorithms utilized the calibrated camera projection matrix to combine the images from all eight cameras into a focal stack. The focal stack images were thresholded to remove the out of focus particles. The result was a focal stack containing only the particles sharply in focus for a given plane.

The focal stack was then processed using a 3D version of the matPIV algorithms [1] [8]. The 3D matPIV algorithms determined the 3D velocity fields.

III. Results & Discussion

The three-dimensional vector fields were plotted using MATLAB. The whole-field 3D evolution of the glottal jet over one cycle of oscillation can be seen in Figure 3. Frames (a) through (d) are each separated by 1 ms and approximately correspond to phases of fully closed (a), opening (b), fully open (c), and closing (d). These results indicate that the vocal folds are oscillating at ~250 Hz. The flow fields demonstrate the unsteady 3D nature of the glottal jet, consistent with results reported by Triep et al. [4]. Figure 4 shows a 2D slice of the glottal jet in a frontal plane located 3 mm inferior to the front of the vocal folds.

From these figures, the pulsatile nature of the jet is evident. At (a) the vocal folds are closed and there is no jet present. When the vocal folds are opening, in (b), a jet is just beginning to form. The jet is well established in (c), when the vocal folds are fully open. There is an area of high velocity right at the vocal fold exit. Finally in (d), when the vocal folds are closing, the jet has grown to fill the height of the region of interest. As the jet evolves it remains closely aligned with the downstream axis. Further data processing is needed to observe the glottal jet evolution of several cycles of oscillation.

Algorithms are currently being developed for automatically tracking the surface motion of the vocal folds from the gathered data. The data was gathered at the same moment in time as the SAPIV flow data and will be able to be directly correlated together. This will provide an increased understanding of the fluid structure interactions of vocal fold vibration.

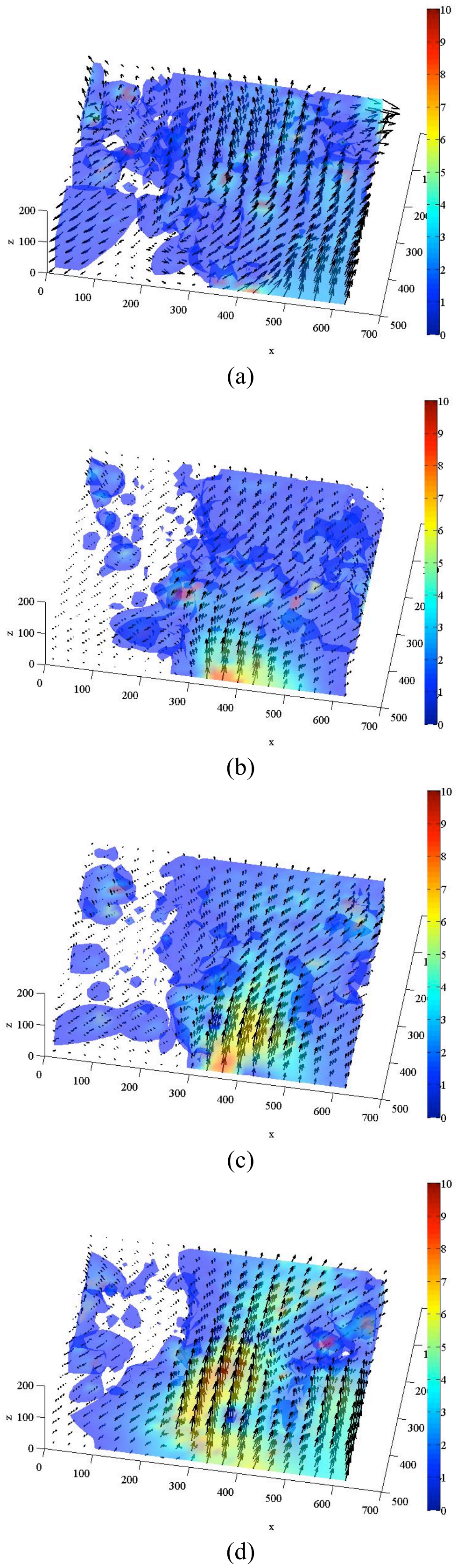

Figure 3: Four time steps of the reconstructed velocity field from excised human vocal folds. Vectors indicate direction of flow while the colorbars represent the magnitude, scaled the same in each image [voxels/second]. The vocal folds are closed at (a) opening at (b), fully open at (c), and closing at (d) with 1ms spacing between each image.

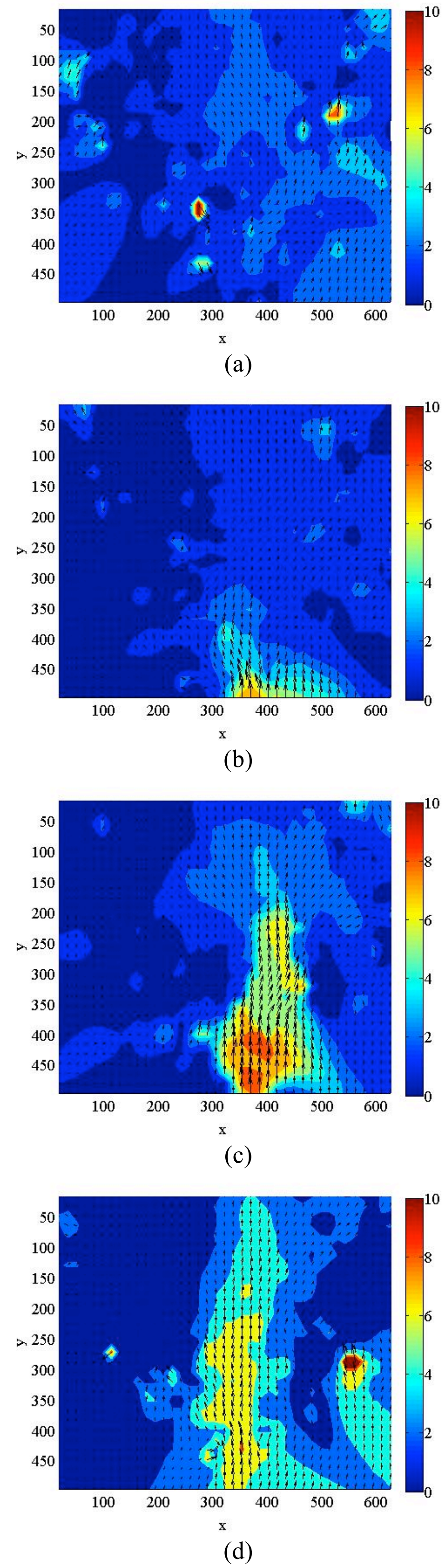

Figure 4: The same four time steps of the reconstructed velocity field shown in Figure 3 representing a 2D slice of the velocity field at z = 3 mm. Vectors indicate direction of the flow while the colorbars represent the magnitude, scaled the same in each image [voxels/second].

IV. Conclusions

Using SAPIV on excised human vocal folds, the whole field, time-resolved, 3D glottal jet was reconstructed. The unsteady 3D nature of the glottal jet that was observed is consistent with current voice research literature findings. SAPIV is a useful technique in obtaining a whole field, time-resolved characterization of the glottal jet.

This study used a pair of healthy human vocal folds. Future studies will use SAPIV to characterize the 3D flow for various vocal fold conditions: vocal folds with abnormalities (polyps, scar tissue, etc.), asymmetric tensioning, and variable flow rates.

The flow fields were also correlated with the motion of the vocal folds and the upstream flow pressures (too be shown). Coupling the motion of vocal folds with the glottal flow could help improve the understanding of these complicated interactions. Visualizing these phenomena and their interactions will help researchers and clinicians better understand the physics of speech production, with the ultimate aim of helping improve the clinical approach to treating patients with voice disorders.

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