10ème Congrès Français d'Acoustique
Lyon, 12-16 Avril 2010

Flow Field Measurements in a Self-Oscillating *in vitro* Model of the Vocal Folds

Adam G. Apostoli, D. Murray Campbell, and Clive A. Greated
School of Physics and Astronomy, University of Edinburgh, Edinburgh, EH9 3JZ, {adam.apostoli,d.m.campbell,c.a.greated}@ed.ac.uk

Within the larynx, complex soft tissue structures are caused to oscillate periodically by an airflow generated by an overpressure in the lungs. One of the difficulties encountered when studying the oscillation of the vocal folds is the inaccessibility of the human larynx. This paper describes a study using an *in-vitro* model of the vocal folds constructed from latex and water, which replicates basic features of the fluid-structure interactions that take place in the human larynx. Particle Image Velocimetry (PIV) is used to gather full flow-field measurements downstream of the model vocal folds at defined phase points in the phonatory cycle. An important development of this work is the use of an optically transparent *in vitro* model, which allows for measurements of the speeds and vortical structures of the jet emerging from the vocal folds.

1 Introduction

The glottal jet, as it emerges from the vocal folds, and the oscillatory behaviour of the vocal folds have been the focus of many studies for a number of years. Indeed, an understanding of these two components is crucial to any attempt at modelling the speaking or singing voice[1]. Due to difficulties posed by the inaccessibility of the vocal folds and the well-known difficulties involved in attempting to solve the Navier-Stokes equations numerically, one of the most convenient ways of investigating the glottal jet is through the use of a self-oscillating *in vitro* model. Through the use of Particle Image Velocimetry (PIV), it is possible to get full flow-field measurements of the flow at positions in the oscillatory cycle. Coupled with the use of a high speed camera, it is possible to then investigate the relationship between the acoustic field and open area of the model.

Due to the nature of a self-oscillating system, it is inherently difficult to synchronise PIV measurements where the phase of oscillation is defined by the system. In work undertaken by Newton[2], the way in which PIV image pair acquisitions were taken relied on a technique not too dissimilar to stroboscopy. Image pairs were taken at 0.5 second intervals over a 10 second period, thereby producing 20 image pairs. The acoustic field, close to the vocal folds, and the signal used for triggering the first PIV laser flash were also simultaneously sampled and used to calculate where in the acoustic cycle the image pairs in each run were taken. Using the open area/pressure relationship, it is then also possible to correlate the image pair acquisitions to the open area of the model.

The technique applied by Newton for identifying where in the oscillatory cycle PIV image pair acquisitions were taken relied on the idea of splitting up the acoustic cycle of the model into either 10 or 20 time windows (called 'phase windows') and then gathering the continuous distribution of measurements into these phase windows. As Newton identifies[2], grouping the measurements together into phase windows and averaging the maps within these windows, thereby producing a single average map for each window, allows the data set to become more manageable and has the effect of reducing some of the signal noise. A negative impact of this technique is that small-scale jet features, for instance small vortical structures, become lost in the averaging process. This paper outlines a technique by which it is possible to move from using phase windows to acquiring PIV image pair acquisitions at more precisely defined points in the oscillatory cycle, called 'phase steps'. In addition, using a model with greater optical access, it has now been possible to acquire PIV image pairs which extend to the glottal exit. Where before it was only possible to acquire PIV image pairs from 8mm downstream, being able to see the entire jet now will allow a more detailed investigation into the glottal jet behaviour to take place.

2 Experimental Design

An *in vitro* model of the trachea, vocal folds, and a short vocal tract, up-scaled to three times life size was used. As is shown in Figure 1, the perspex/glass trachea and glass vocal tract had square cross-sections, so that no distortion was introduced by any lensing effects caused by curved optical surfaces. Each vocal fold was created from sheet latex glued to a metal block with a cavity extruded. Once the latex sheet had been glued in place, the metal vocal fold blocks were then connected to a head of water and then sealed within a perspex case. This then allowed water to fill the cavity in each vocal fold block and hence cause the latex to stretch and the vocal folds to assume their shape. Careful adjustment of the height of the head of water was used to determine the pressure of the water within the cavity. This then altered the stiffness of the vocal folds and hence allowed for fine control of the frequency at which the vocal folds oscillate. The vocal folds and perspex case were then mounted onto the trachea forming an airtight seal.

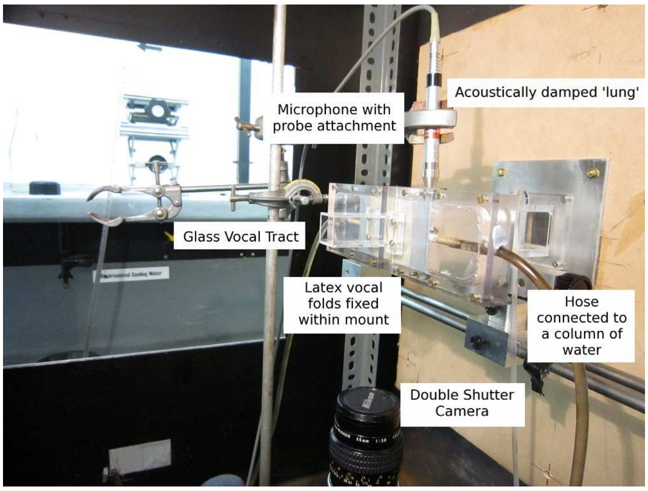

Figure 1: Image showing the experimental setup with key components labelled.

As can be seen in Figures 1 and 2, the trachea was mounted on a large wooden 'lung'. This wooden box, lined with acoustical absorbing foam, was used to maintain a constant overpressure and to reduce the effect of any resonances upstream of the vocal folds. A cuboidal glass vocal tract, 58mm in length with a 20mm x 20mm cross-section, was attached to the vocal fold casing once this had been fixed to the lung. A schematic diagram for the experimental setup used for providing seeding for PIV and air pressure to the model can be seen in Figure 2. The seeding for PIV was provided through the use of a SAFEX-NEBELGERÄT F2004 fog generator. The particles were a mixture of alcohol and water and were approximately 1μm in size[3]. The fog was collected in a wooden overflow box and then taken into an Air Control Industries Ltd. 8MS11 0.25kW air pump, which was then fed into the lung via a double-shanked inlet valve. An additional source of pressure from a centralised pressurised air supply was fed into the other side of the double-shanked inlet valve. The air pressure was modified at the source of the centralised compressed air supply within the laboratory. To measure the pressure upstream of the vocal folds a Digitron P200UL digital manometer was connected, via a thin length of Portex flexible tubing, to the upper wall of the vocal tract.

An Oxford Lasers LS20-50 copper vapour laser was used as the illumination source, delivering approximately 6-10 mJ per pulse. The laser beam was delivered via a fibreoptic cable and then expanded into a thin sheet, approximately 1-2mm thick, using an Oxford Lasers Fibresheet. Due to the LS20-50 being a class IV laser, the entire model and light sheet arrangement, once set up, was enclosed in a metal housing to protect the user. A PCO SensiCam Double Shutter digital camera, with a resolution of 1280 × 1024 pixels, was used to capture the PIV image pairs. The PIV images were all analysed in Dantec's DynamicStudio v2.3 software then exported to MATLAB for later analysis. The laser and

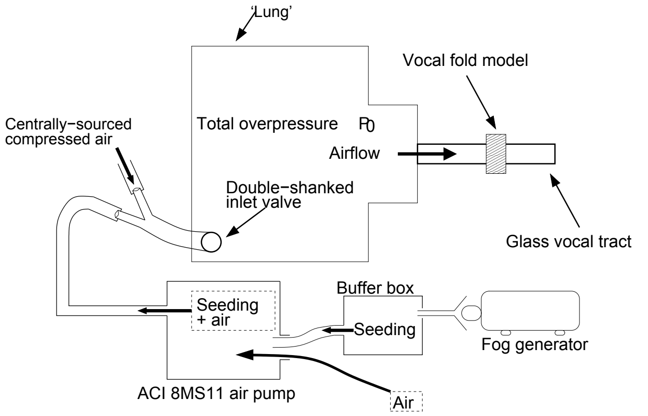

Figure 2: Schematic diagram of the experimental setup [2].

camera were both triggered externally using a Berkley Nucleonics Model 500A delay generator.

During PIV measurements, the acoustic pressure was sampled using a Bruël and Kjær type 4192 condenser microphone with a probe attachment placed in the top of the vocal tract, 10mm upstream of the vocal folds. The microphone was attached to a Bruël and Kjær type 2691 conditioning amplifier, which was connected via BNC cable to a National Instruments PCI-6024E data acquisition card via a National Instruments SCB-68 connector block. Software written in LabVIEW was created and used to capture simultaneously the pressure signal sampled at the Bruël and Kjær probe microphone and the triggering signals. In the LabVIEW software the fundamental frequency of oscillation for the vocal folds (f0) was calculated for several seconds of the first run. This frequency was then used to calculate time delays, which were then transmitted to the Berkley Nucleonics delay generator via the RS232 protocol.

During PIV runs using the phase windowing technique, the delay generator was sent a 2Hz square wave signal (generated in LabVIEW), the rising edge of which was used to begin the PIV image pair acquisition sequence. The 2Hz square wave, acoustic pressure, and synchronisation sine wave signals were all recorded by the LabVIEW software and saved in text format for later analysis in MATLAB. The start of PIV runs using the phase windowing technique was not synchronised, as there was no method available through which the programme could be locked to the acoustic field. During PIV runs using the phase stepping technique, the PIV image pair acquisitions were locked to the acoustic field. Using a zero-crossing trigger, built in-house, it was possible to send a pulse to the delay generator once a positive-going zero-crossing in the acoustic signal had been detected.

Through the use of our zero-crossing triggering device, it was possible to then specify a time delay corresponding to a phase step in the acoustic cycle and transmit this to the delay generator. This then allowed an entire PIV run to be targeted to one particular phase step, allowing a high density of image pairs to be accumulated at this phase step should further runs be taken. As with most PIV experiments, one of the overriding difficulties encountered when undertaking PIV experiments close to a wall was glare. To counteract this, strategic parts of the apparatus were blacked out with matt black paint, although this did not remove all of the glare. In addition to the black paint, an image mean for each PIV run was removed from all images in the run, which helped improve the data. Various MATLAB analysis tools and scripts written in-house were used to process the data and synchronise the PIV image pairs to the acoustic signal.

3 Measurements

In the results which follow, 10 PIV runs of 19 images were taken using both the phase windowing technique and the phase stepping technique. For these runs, the camera was positioned at the glottal exit showing the entire width of the 20mm vocal tract and extending to just under 18mm downstream of the vocal folds.

Figure 3 shows the distribution of PIV image pairs across an acoustic cycle using the phase windowing technique. Each point on the graph corresponds to a PIV image pair acquisition in a run, with the time of the x-axis being the time of the acquisition relative to the nearest preceding positive-going zero crossing, and the pressure on the y-axis being the pressure at the point of acquisition recorded from the microphone arrangement, expressed as a voltage. It can be seen that the image pair acquisition points are spread throughout the acoustic cycle, with no particular group of image pairs being synchronised with any point in time. Fluctuations in the pressure measurement for acquisition points at the same time in the acoustic cycle are due to different pressures being recorded at the microphone at the point in the measurements during which that particular image pair was acquired.

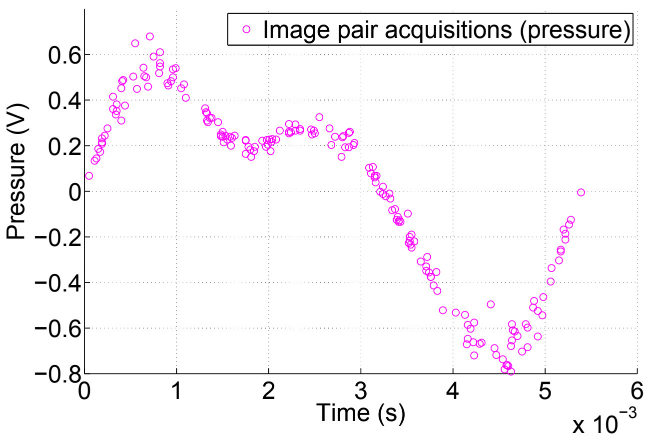

Figure 3: Distribution of PIV image pairs across an acoustic cycle using the *phase windowing* technique.

Figure 4 shows the distribution of PIV image pairs across an acoustic cycle using the phase stepping technique. When comparing this with Figure 3, it is immediately apparent that the image pair acquisitions using this technique are not spread throughout the acoustic cycle, but are gathered together in definite groups. As stated previously, any fluctuation in the pressure measurement for acquisition points taken at the same time in the acoustic cycle is due to fluctuations of the model over time.

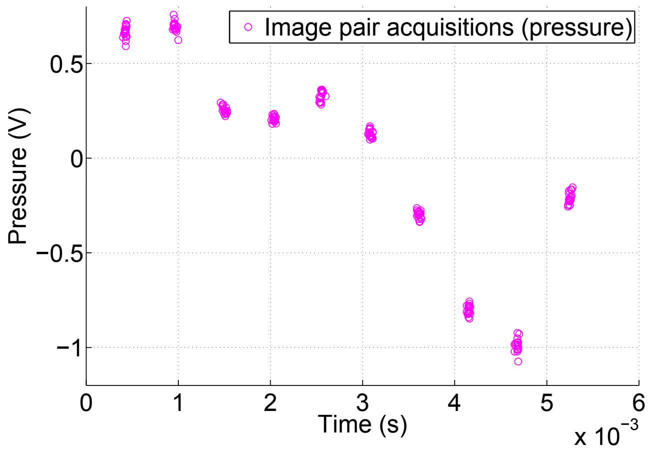

Figure 4: Distribution of PIV image pairs across an acoustic cycle using the *phase stepping* technique.

	N	μ (s)	σ (s)
Phase Window 4/10	19	1.902×10^{-3}	1.381×10^{-4}
Phase Step 4/10	19	1.502×10^{-3}	1.83×10^{-5}

Table 1: Table showing the differences in the mean and standard deviation of image pair acquisition times in a run, where N is the number of image pair acquisitions, μ is the mean time of the image pair acquisition times in the phase window/step, and σ is the standard deviation.

Considering the contents of Table 1, although there are the same number of image pair acquisitions in the phase window as there are in a phase step, it took 10 PIV runs to achieve this using the phase windowing technique. In addition, due to the technique applied, the number of image pair acquisitions per phase window is not constant across all phase windows. When considering the mean time and standard deviation, it is also clear to see that by using phase steps over phase windows, the standard deviation of image pair acquisition times is reduced by an order of magnitude. This is an important result, as the standard deviation of the velocity magnitude of PIV maps within a phase window is used to assess the general stability and consistency of the flow and provides a quantifiable representation of the quality of the data[2]. In terms of computational modelling, this fundamental piece of information regarding the jet behaviour is crucial. Using the phase stepping technique reduces the error introduced in the averaging process, thereby providing more reliable measures by which it is possible to characterise the behaviour of the glottal jet.

A further development has been the use of a model with greater optical access. Figure 5 shows one image from an image pair acquisition overlaid with the result of its corresponding PIV analysis, with the magnitude and direction of the flow in a interrogation area represented with a green arrow. Some glare can be seen at the top of the image along with the outlines of the vocal folds (appearing as bright white). These patches of glare are for the most part removed when the mean of the image run is removed from each image. Figure 6 shows the

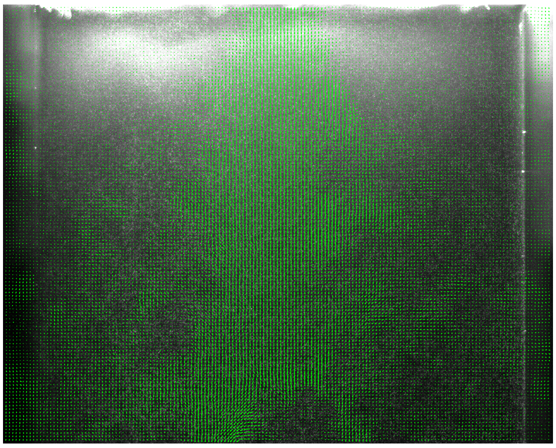

Figure 5: PIV image showing the glottal jet emerging from the *in vitro* vocal fold model. The green arrows, overlaid on one of the original images used for the cross-correlation, are the results of the PIV analysis and represent the velocity magnitude and direction for each interrogation area.

same PIV image only this time as a colour contour map of the velocity magnitude. The first point to note about both of these figures is that the glottal jet, as it emerges from the vocal folds, is fully visible. In light of the need for researchers to have an understanding of the glottal jet and vocal fold behaviour in order to model voiced sound production, having the ability to see the glottal jet as it emerges from the vocal folds is a significant improvement. One of the most important aspects of the glottal jet is the point at which the bulk flow separates from the walls of the vocal folds. Through the use of the phase stepping technique, allowing many image pair acquisitions to be taken at well-defined steps through the acoustic cycle up to the vocal folds, the speed and shape of the glottal jet as it leaves the vocal folds should be visible, which should allow various theories regarding flow separation to be tested.

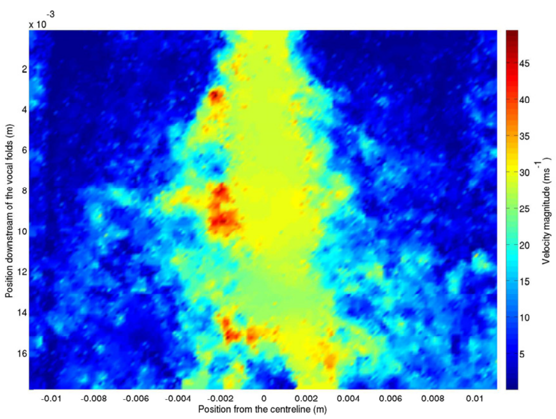

Figure 6: Colour contour map showing the velocity magnitude for an image pair acquisition.

4 Conclusions and Future Work

This paper has shown that using a technique which locks onto the acoustic field, such as phase stepping, the scattering of image pair acquisition times within the acoustic cycle can be reduced, typically by an order of magnitude. This has an impact on the way jet characteristics are determined, as the standard deviation of the velocity magnitude of PIV maps within a phase window or phase step is used to determine the stability of the glottal jet and is a measure of the quality of the data[2]. In terms of computational modelling, having detailed information on the characteristics of the glottal jet is important.

In addition, an improvement in the current *in vitro* model of the vocal folds, allowing greater optical access, was discussed. An image map and a PIV contour map of velocity magnitude were shown demonstrating that the full glottal jet, as it emerges from the vocal folds, could be seen. The impact of this allows for a fuller understanding of the glottal jet behaviour to be acquired, thereby assisting with the production and validation of speaking and singing voice models.

Further work will entail more measurements using the improvements outlined in this paper allowing comparisons to then be made between the results. Further optical access is possible upstream of the glottal exit on the current model. This additional optical access, exposing the vocal folds when viewed from the side, makes it possible to see the shape of the vocal folds as they oscillate. It is hoped that filming with a high speed camera using this additional optical access will allow for us to better synchronise our image pair acquisitions with the actual shape of the vocal folds at that moment in time.

Acknowledgments

The authors gratefully acknowledge the financial support of the Engineering and Physical Sciences Research Council (EPSRC). They would also like to thank Dantec Dynamics A/S for the use of their DynamicStudio software, used for the processing and preparation of the PIV data presented in this paper.

References

[1] Pelorson, X., Hirschberg, A., van Hassel, R. R., Wijnands, A. P. J., and Auregan, Y., "Theoretical and experimental study of quasistedy-flow separation within the glottis during phonation. Application to a modified two-mass model", *J. Acoust. Soc. Am.*, Volume 96, Number 6, (1994).

[2] Newton, M. J., "Experimental mechanical and fluid mechanical investigations of the brass instrument lip-reed and the human vocal Folds", *PhD thesis*, The University of Edinburgh, (2009).

[3] Dantec, "Safex fog generator", Technical Report, Dantec Measurement Technology A/S, (1998).