APPLICATION OF DDPIV TO BUBBLY FLOW MEASUREMENT

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ABSTRACT

Application of the Caltech-VioSense Defocusing DPIV Camera (DDPIV) to bubbly flow will be presented. The wake of a specially designed hydrofoil (loaned to us by Prof. Lasheras of UCSD), which generated a large quantity of small air bubbles in water, was studied. The camera was used to measure both the bubble velocity field and the bubble size distribution and several locations and freestream velocities.

The DDPIV system is designed to measure fully three-dimensional fields in a time-resolved manner. The third dimension is measured using the defocusing principle: in effect, the distance from the focal plane can be inferred from the degree to which an image is out-of-focus. (See Pereira, et al, 2000, EF 29: S78-S84.) Since standard DPIV video equipment is used, this volumetric three-component data can be captured in realtime. Furthermore, the light intensity and three-dimensional location are used to infer the particle size information. For bubbly flows, this means that the three-dimensional bubble field can be measured – with simultaneous measurement of the velocity and size distribution.

For this experiment, several hundred velocity/bubble fields were measured for each case, resulting in bubble statistics from as many as one million bubbles per run. The camera was able to interrogate a volume approximately five centimeters cubed, and measurements were taken with the volume centered at three downstream stations: one, eight, and ten chords. Freestream velocities of 0.75 and 1.5 meters per second were used, resulting in a chord Reynolds number of 57,000 and 110,000, respectively. The velocity of the bubbles was measured, showing the change in the velocity defect with downstream distance. The velocity fields appeared nearly identical, once scaled by the freestream velocities. Bubble size distributions were measured at the same conditions. These measurements show that the two velocities did not result in the same bubble population. In particular, at the higher speed, a lack of larger bubbles was found, shifting the distribution to smaller size.

The DDPIV camera was shown to be a useful tool in studying three-dimensional bubbly flow fields. It can simultaneously measure both the velocity field and the sizing information of such bubbles. Further studies are currently underway to understand the interaction between bubbles (singly and in groups) within boundary layers.

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1 INTRODUCTION

Bubbly flows are common around surface piercing bodies, but the detailed nature of this flow has escaped full understanding. Indeed even the origin of the bubbles in such flows remains a controversy, much less how such flows evolve downstream. Since bubble generation usually requires nearly full-scale Reynolds and Froude numbers, it is difficult to simulate them at laboratory scale. Towards this end, we tested a bubble generator (designed by Professor Lashera's group at UCSD), which injects a large quantity of small bubbles into the freestream. Although this sidesteps the issue of bubble generation, at least the evolution of bubbly flows can be studied in the lab.

To measure the resultant bubble laden flow field, we applied the DDPIV technique (Pereira and Gharib, 2002) to this flow. Although there are existing single point (Naqwi, et al, 1994) and planar techniques (Prasad and Adrian, 1993), neither are really suitable to the intrinsically three-dimensional flows that are of interest. Three-dimensional techniques like holographic PIV (Barnhart, et al, 1994) or NMR (Gatenby and Gore, 1996) are available, but such techniques are plagued by complexity, poor spatial or temporal resolution, and/or inability to simultaneously measure sizing and velocity information. DDPIV allows us to measure the full three-dimensional bubble velocity field (using the bubbles as tracers) in a time resolved manner. Hence we can measure the statistically mean and fluctuating flow field, which provides a useful data set from those wishing to pursue Reynolds averaged Navier-Stokes computations.

At the same time, the bubble size distribution is itself quite useful to measure. This provides information not only about the sizes of bubbles involved, but also if the population of bubbles is changing as the flow evolves. By correlating the apparent brightness of the bubbles to their actual size, we can use the DDPIV system to simultaneously measure the bubble sizes while we measure their velocities.

2 THEORY

2.1 DDPIV

Defocusing DPIV (DDPIV) is a time-resolved, three-component volumetric flow measurement technique. Details of the technique are available in Pereira, et al., 2000, so only an overview will be presented here. The essence of the technique is to use the difference between the focal plane of an imaged particle and the plane of the imager to infer the distance to the particle (figure 1). For example, if an imaging system is setup to focus on a plane at a distance L (reference plane) from the lens-aperture onto an imager (located at the image plane), then an object closer than the focus plane will be imaged onto a plane behind the image plane. By using multiple lens-aperture sets, the discrepancy between the image plane and the focus point results in multiple images forming on the imager. The distance between the multiple images can then be used to measure the distance to the object (figure 2). Furthermore, if one tracks which image came from which lens-aperture, then one can also uniquely determine on which side of the reference plane the object is located. In our case, we place independent cameras behind each of three lens-apertures (arranged in an equilateral triangle). Measuring the distance to the object reduces to measuring the displacement of the object image on each of the three images.

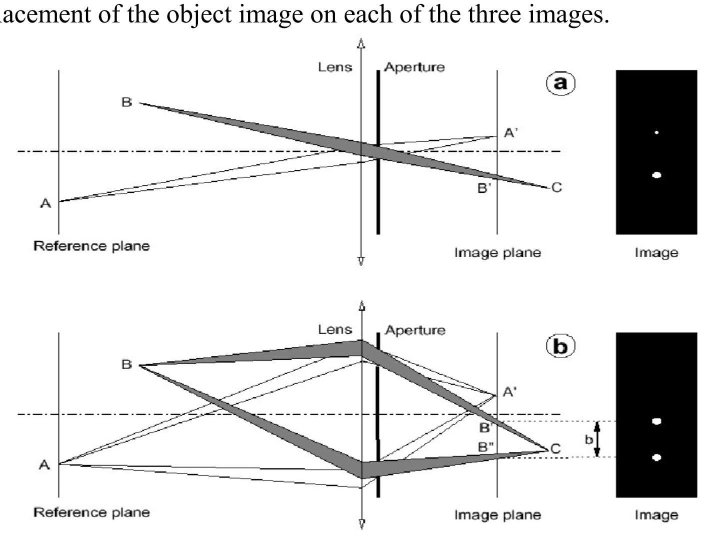

Figure 1 Concept of defocusing, the heart of the DDPIV technique. The degree to which a particle image is defocused is used to determine its distance from the camera.

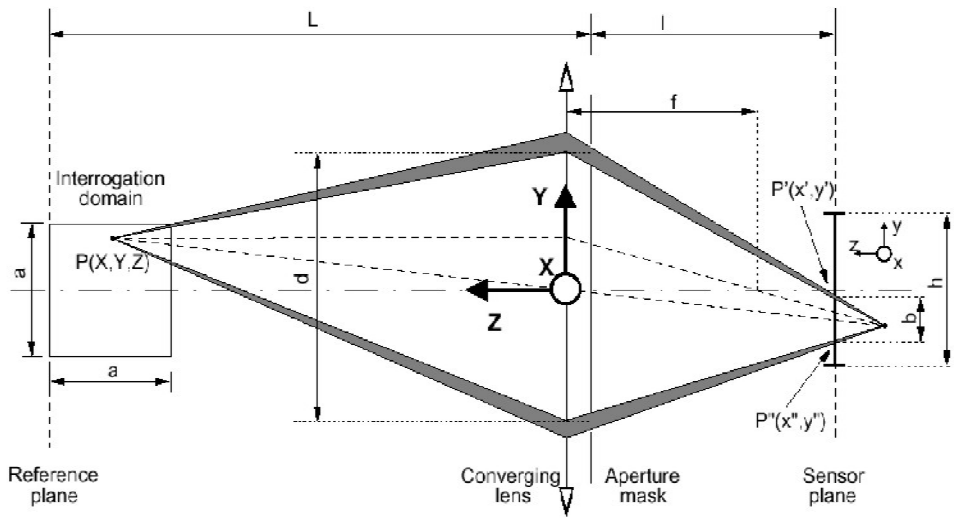

Figure 2 Converting the measured degree of defocusing into the real (x,y,z) coordinate of the particle.

2.2 Measuring bubble size.

The bubble size measurement technique is an adaptation of that described in Pereira, et al. To summarize, we infer the size of tiny air bubbles using the intensity of the scattered light. The relationship between intensity and size comes from the Lorenz-Mie theory of scattering from a sphere (Van De Hulst, 1957). The greatest complication when using this method is determining the intensity distribution of the light source. Towards this end, we moved a grid of uniformly sized glass spheres through the volume where the laser light intersects our interrogation volume. By measuring the apparent brightness of the scattered light, and knowing the size and relative index of refraction of our test particles, we can infer the source intensity distribution at that point in space. We then construct a three-dimensional intensity distribution of our source. Then we can infer the bubble size at any point in our interrogation volume by looking up the local source brightness and using the Lorenz-Mie relationship to back out the size of the scatterer.

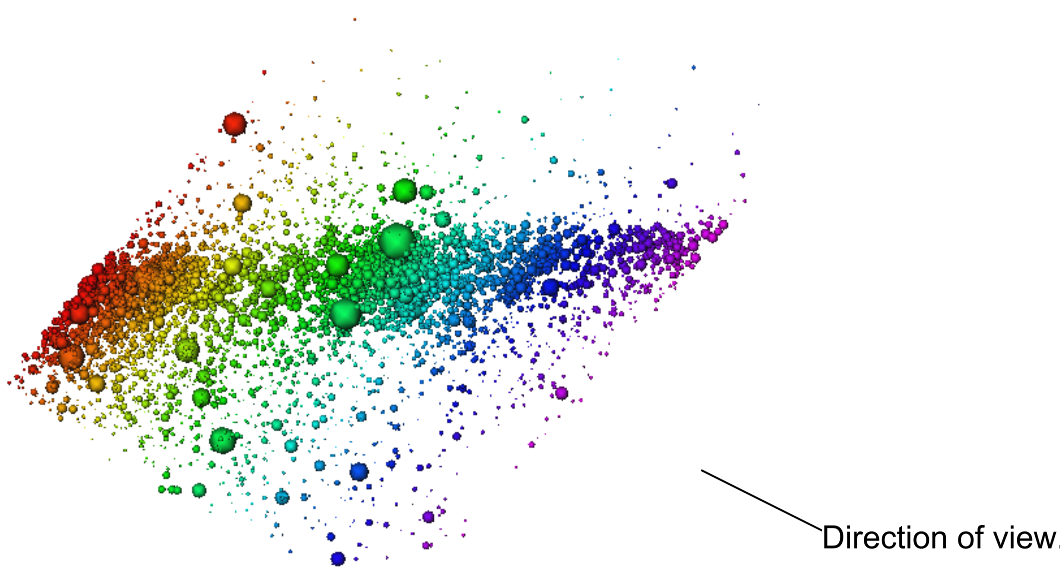

Figure 3 Overhead view of a sample intensity calibration field. The laser beam was spread into a thick sheet cutting diagonally across the field of view.

3 SETUP

3.1 Water tunnel.

The experiments were performed in the GALCIT free surface water tunnel. The facility features a test section of 20” wide by 21.5” deep, and is capable of speeds in excess of four m/s. For these experiments, a surface plate was used to minimize the effects of the free surface. The DDPIV camera was placed underneath the tunnel, looking upwards at the bubble stream. The laser illuminated the bubble stream at approximately 45 degrees forward scatter.

3.2 Description of bubbler.

The bubble generator consists of an airfoil with a porous metal plate near the leading edge, with a perforated cylinder ahead of it spraying alcohol onto the surface. (Professor Lasheras of UCSD, who performed a parallel set of measurements at his facility, loaned the generator to us.) Compressed air is pumped through the porous plate, producing bubbles on the surface of the airfoil. The alcohol injection serves to alter the surface tension at the bubble/fluid/wall interface, which results in much smaller bubbles being produced. The device served to inject a large quantity of bubbles into the freestream with minimal flow disturbance.

3.3 Run conditions.

Tests were performed with the bubble generator in the horizontal position, and data was taken at one, eight, and ten chord lengths downstream. The interrogation volume was approximately six inches (or two chord lengths) wide in the streamwise direction. We tested the bubble generator at two different freestream speeds of 0.75 and 1.5 m/s, which results in a chord Reynolds number of 57,000 and 110,000, respectively. The alcohol and compressed air settings were prescribed to us by Lasheras’ group, so we did not alter those.

4 RESULTS AND DISCUSSION

4.1 Velocity measurements.

The measured bubble velocity fields are shown below in figure 4. Plotted are the average velocities of the bubbles, as measured with the DDPIV system, for the two velocities and three locations listed. To clarify the figure, two cuts through the velocity field are shown at each station. The contour levels are

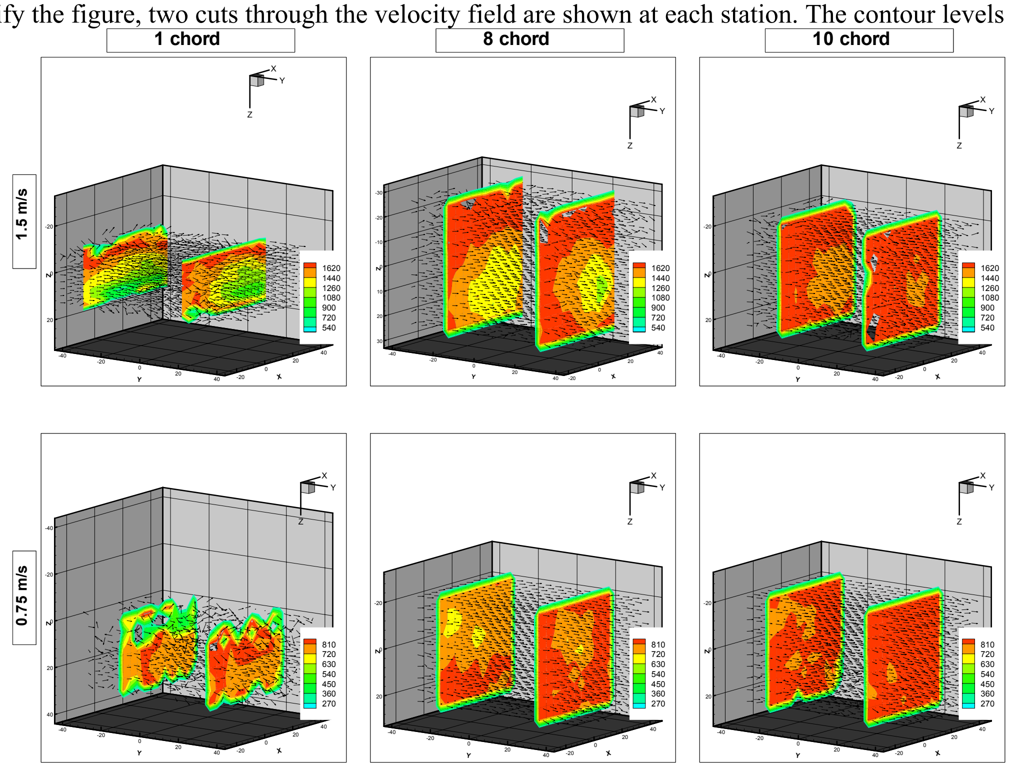

Figure 4. Three-dimension bubble velocity fields behind a bubble-generating hydrofoil. The upper row is with a freestream velocity of 1.5 m/s, the lower at 0.75 m/s. From left to right, the data were taken at one, eight, and ten chords from the trailing edge.

exactly twice as high in the 1.5 m/s case; hence the similarity of the contours implies that the overall velocity field is scaling with the freestream quite nicely.

A couple of observations are worth making about the above data. First, since the only flow markers we used are the bubbles, the effective interrogation volume grows with downstream distance. Hence the velocity field at 1 chord is noticeably “shorter” than at the farther downstream stations. Second, there is relatively little velocity deficit, especially at the furthest downstream stations. We believe this is due to enhanced momentum mixing caused by the presence of a high concentration of bubbles. And third, there does not appear to be a large difference between the two velocities, once the freestream is scaled out. This is somewhat surprising when one examines the bubble size distribution.

4.2 Bubble size distribution.

The corresponding bubble size distributions are plotted below. Shown are the probability distributions, i.e., integral under the curve is one. At the lower speed, the data compares quite well to that determined by Lasheras’ group. Furthermore, given the behavior of bubbles, the size range indicated seems quite appropriate. (Much larger bubbles would rise and not be visible, much smaller bubbles would be too small to image.) In each case, the distribution is constructed with approximately one million bubbles. This is another advantage of doing a study like this with DDPIV – large statistics are fairly easy to obtain.

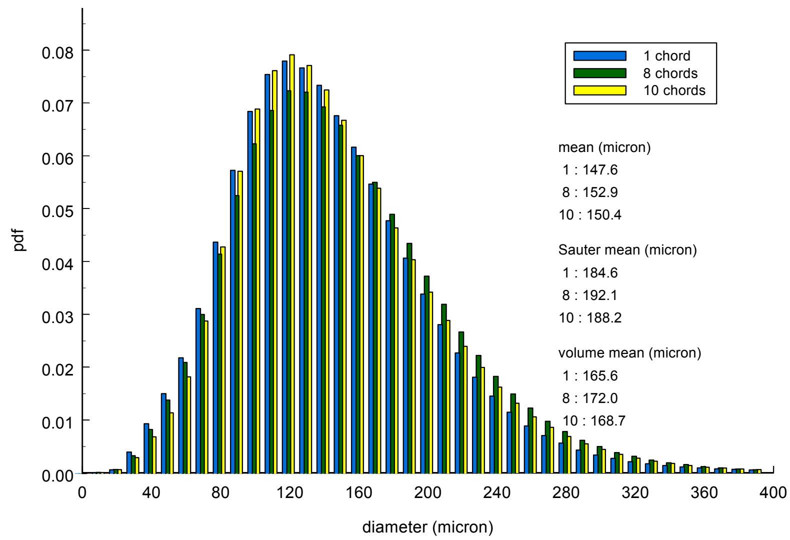

Figure 5. Bubble size distribution for freestream velocity of 0.75 m/s.

At the lower speed, the relative invariance of the distributions also agrees with what the Lasheras group found. However, this is not the case at the higher speed. Here we seem to see some kind of selection effect happening, such that the larger bubbles present near the trailing edge of the generator do not seem to be present at the farther downstream stations. This does not seem to be due to the mean velocity profiles, since they do not look fundamentally different at the two speeds. However, since bubbles are not the most faithful flow markers, we can not be certain of what the fluid flow is doing to the bubbles. Since the distributions are basically the same between the eight and ten chord stations, it can be assumed that the effect is occurring fairly close to the generator.

It is also possible that the bubbles for at the higher freestream case are actually smaller, but that the pressure field on the hydrofoil itself inflates the size of the bubble. Further downstream, the pressure would be expected to recover towards the freestream pressure, so the bubbles would return to smaller sizes. Since we do not have pressure data, we cannot determine by which mechanism the bubble size distribution has been altered.

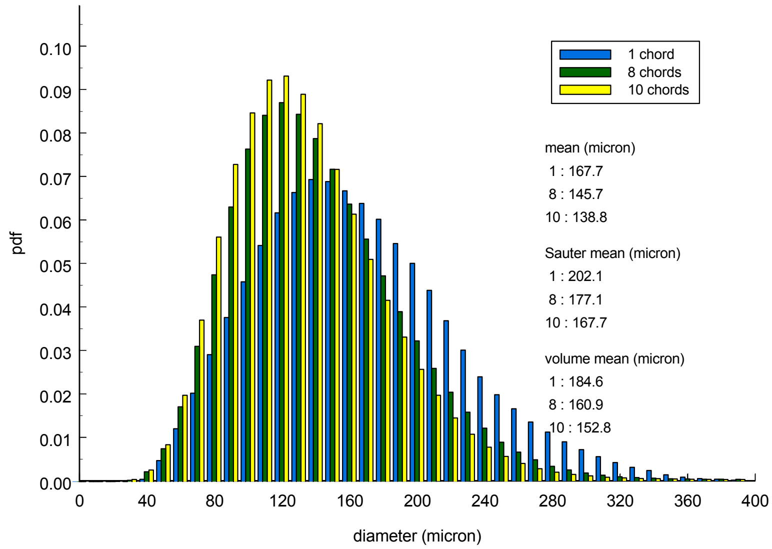

Figure 6. Bubble size distribution for freestream velocity of 1.5 m/s.

5 Conclusions

DDPIV was applied to a bubbly flow to track not only the velocity field, but also the bubble size distribution. The technique was able to compile both statistically mean velocity fields as well as size distributions for a large number of bubbles. A reasonable method for calibrating the intensity of the illumination field was found, and seemed fairly successful. For the same bubble generation system at the same conditions, good agreement was found with the measurements by Professor Lasheras' group. A separate measurement of only the fluid flow field would need to be performed to better understand why a change in freestream speed caused such a large change in the bubble distribution downstream from the generator. Nevertheless, DDPIV was demonstrated on a three-dimensional flow laden with bubbles, simultaneously measuring the statistical bubble velocity field and bubble size information.

6 Acknowledgments

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7 References

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