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HPIV Study of the Interaction of a Vortex Ring with a Solid Wall

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HPIV STUDY OF THE INTERACTION OF A VORTEX RING WITH A SOLID WALL

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Abstract

The interaction of a vortex ring with a wall at inclined incidence was investigated using Holographic Particle Image Velocimetry (HPIV) and flow visualization. The flow interaction was captured in HPIV holograms which were processed to obtain velocity vector plots of the three-dimensional flow field and of selected cross sections. These data as well as the flow visualization results confirm the observations by Kachman *et al.*[1] of vortex core reconnection near the wall and illustrate the capabilities and limitations of HPIV for the study of complex vortical flows.

Introduction

The interaction of a vortex ring with a solid wall at inclined incidence has been investigated using HPIV. The goal of the research is the development of HPIV for measurement of three-dimensional velocity fields in a volume. These measurements are needed for the study of the structure of turbulent flows and other vortical flows in Hydro- and Aerodynamics. These flow fields are characterized by nonlinear three-dimensional interactions of the vortical fluid with other vortical regions of the flow and with the walls. These interactions can result in topological changes of the vorticity field. Quantitative data on these flow processes are essential to gain a better understanding of these flows as well as to validate computational models. Another important feature of the vortical flows is their sensitivity to probe interference. HPIV is being developed in our laboratory to measure these flow fields nonintrusively.

Kachman *et al.*[1] investigated the interaction of vortex rings with clean and contaminated water surfaces, and with a solid wall. They considered a vortex ring colliding with the interface at inclined incidence and found that in all these cases the interaction of the region of the vortex ring core closer to the interface followed the type of evolution first described by Bernal and Kwon.[2] Bernal and Kwon reported that when a vortex ringmoves parallel and closed to a free surface vortex lines in the core opened and attached to the free surface. In this case the presence of normal vorticity was readily detected on shadowgraph visualizations of the water surface. In the case of a solid wall the normal vorticity at the surface must by zero. Kachman *et al.* argued that for a solid wall, vortex lines originally in the vortex ring core also rotated normal to the wall after breaking but the vortex lines attached to vorticity in a boundary layer at the wall. This scenario could not be proved because of lack of evidence of the presence of normal vorticity near the solid wall. To clarify this issue velocity field measurements are necessary to detect the presence of normal vorticity near the wall. HPIV is one technique that can be used to obtain such data.

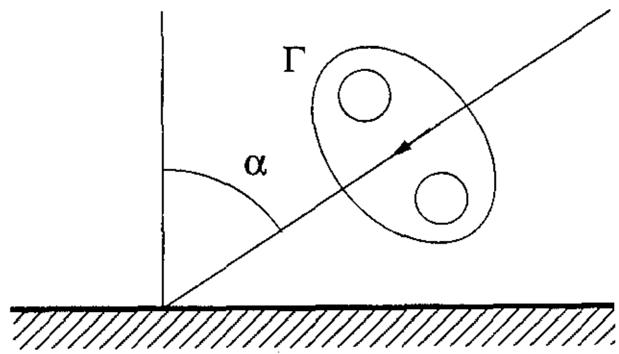

Figure 1. Schematic diagram of the interaction of a vortex ring with a wall. Γ vortex ring circulation. α incidence angle.

The resolution characteristics and spatial dynamic range of HPIV were documented by Scherer and Bernal.[3] The resolution is determined by the size of the particles used to seed the flow. It is of the order of $\pm 2\ d^2/\lambda$, where d is the diameter of the particles and λ is the laser wavelength. The test volume size is also limited by the particle size as $300\ d^2/\lambda$. An HPIV system was demonstrated with a resolution of about 2 *mm* in a test volume with linear dimension of 150 *mm* or less.[3] These specifications were obtained with relatively low particle concentration in an open field. The effect of seed particle concentration on these values has not been determined.

In this paper we report HPIV measurements of a vortex ring colliding with a wall at inclined incidence. The flow configuration is shown schematically in figure 1. The main objective of the experiments is to demonstrate this measurement technique in a flow field where topological changes of the vorticity field occur. Several issues concerning flow seeding and data processing are also investigated. In addition this flow field provides an interesting example of the complex near-wall dynamics of vortical flows even in simple geometrical configurations. The experiment provides a nontrivial validation of the measurement technique.

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Flow Apparatus and HPIV Instrumentation

Flow Apparatus

The experiments were conducted in air using vortex ring generator driven by a loudspeaker. The vortex ring generator was mounted at an angle relative to a flat wall to produce the vortex ring at the desired incidence angle relative to the wall. In addition, a fixed reference frame was attached to the wall for calibration of the holographic imaging system.

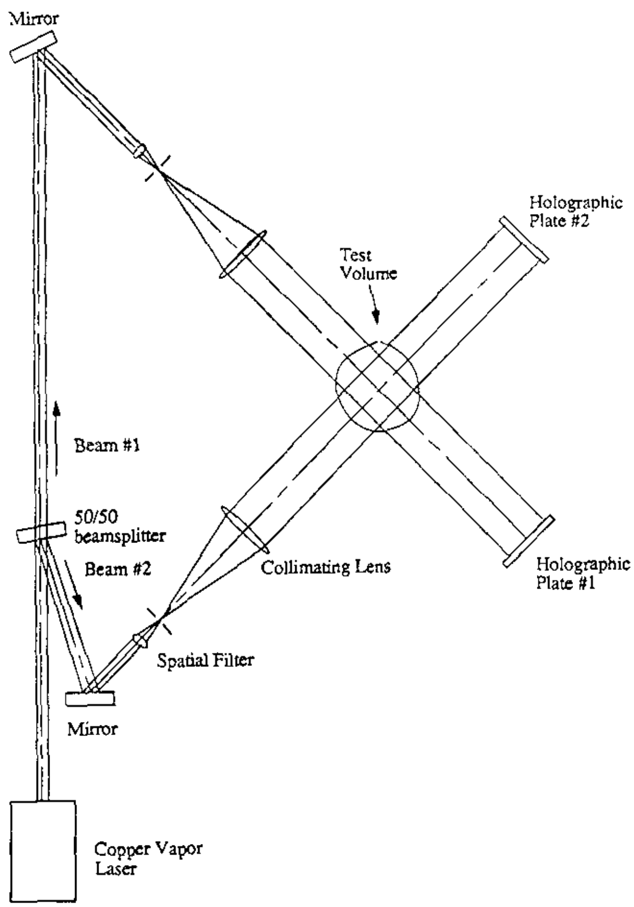


Figure 2. Holographic recording system

The vortex ring generator was based on the design of Roberts.[4] It consists of a wooden enclosure with one side formed by a thin steel plate having a 51 *mm* diameter orifice. The loudspeaker was mounted to the plate concentric with the orifice. The enclosure was vented on the back to maintain atmospheric pressure behind the speaker cone. The vortex rings were produced by applying a ramped voltage to the loudspeaker, which displaced the cone towards the plate and forced a slug of air through the orifice. When the cone reached its maximum deflection and stopped, the slug of air formed a vortex ring propagating away from the generator on a path perpendicular to the plate surface. The strength of the vortex ring could be controlled by adjusting the maximum voltage applied to the loudspeaker and the ramp duration. These parameters varied the maximum displacement and velocity of the speaker cone respectively. The vortex ring generator was also equipped with a remotely controlled rotating cover plate.

The vortex ring generator was operated in two modes. One mode was used for seeding the air inside the generator. In this case the cover was rotated over the orifice and the speaker cone was driven by a sine wave causing it to mix the seed particles in the generator. In the second mode, the generator was connected to the vortex ring driver circuit which actually caused the generation of the vortex ring flow. Typical operation of the system involved switching into vibrating/seeding mode for two or three seconds. After a brief elapsed time to settle the internal flows within the generator, it was switched to the vortex driver circuit mode and a vortex ring was fired seeded with small particles. The seed particles used in these experiments were glass microballoons 15-30 μm diameter.

The ambient air was also seeded. This was accomplished by gently tapping on a fine mesh sieve containing seed particles to form a cloud. The sieve was located above the region of interaction of the vortex ring with the wall. The location of the sieve was sufficiently far from the wall not to influence the flow. The cloud of seed particles was allowed to reach the wall before starting the vortex ring motion. The entire facility was enclosed to minimize the onset of air currents which tended to disturb the ambient flow. The particles used to seed the ambient fluid were of the same type as those used for the vortex ring fluid.

Holographic Recording System

An schematic diagram of the holographic recording system is shown in figure 2. It consists of two orthogonal in-line holographic recording systems formed using the 511 *nm* line of a Copper Vapor Laser (CVL). This system is essentially the same as the one used in reference 3 except for the use of a 50/50 beam splitter to form the two probe beams. Each system incorporates a 100 μm pinhole and a 150*mm*-diameter 450*mm*-focal-length lens to collimate the probe beam. For each flow condition two holograms were recorded in high resolution holographic plates positioned on the opposite side of the test section as indicated in figure 2. The use of the 50/50 beam splitter allowed a more balanced exposure of the two holograms

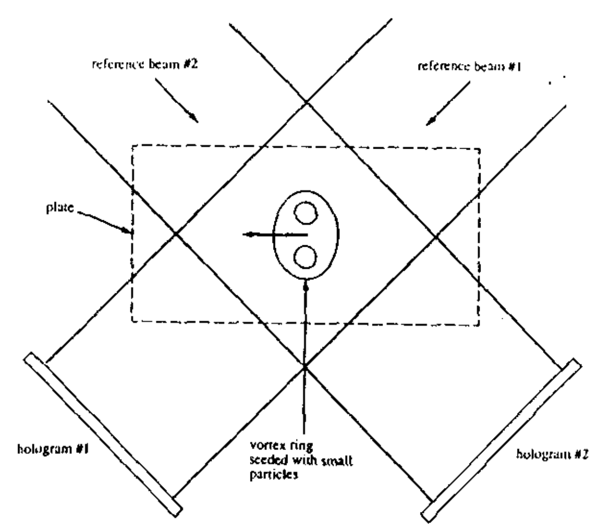


Figure 3. Diagram showing the relation between the vortex ring motion and the holographic recording system.

Figure 3 shows the direction of propagation of the vortex ring relative to the holographic recording system. The vortex ring propagated between the beam forming optics and the holographic plates, along a direction forming 45° with respect to both beams. This configuration was chosen because it minimizes interference between the flow and the holographic plates.

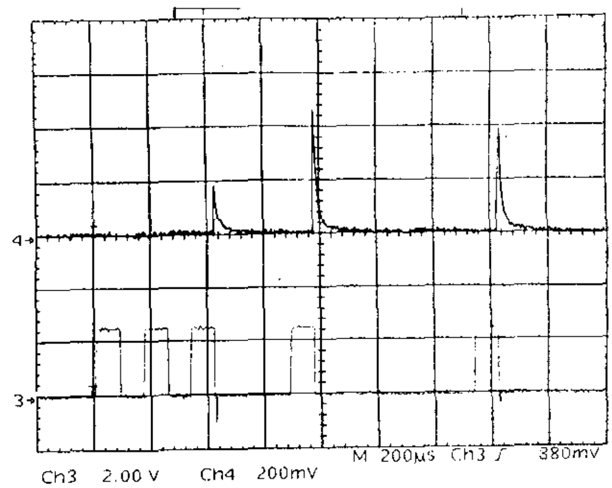


Figure 4. Oscilloscope trace showing the pulse train input to the CVL, trace 3, and the laser output, trace 4.

In these measurements three exposures of the particle field were recorded on each holographic plate to determine the magnitude and direction of the velocity vector. The pulse program input to the CVL was used to control the time between the three exposures. A typical oscilloscope trace showing the input pulse sequence to the CVL and the resulting laser output measured with a photodiode are shown in figure 4. The input pulse train consists of five pulses. The first three pulses are spaced 0.167 *ms*, which corresponds to the operating frequency of the CVL. They are followed by one pulse at 0.334 *ms* and by a fifth pulse 0.668 *ms* after the forth pulse. The light output trace shows only three pulses which correspond to the last three pulses into the CVL.

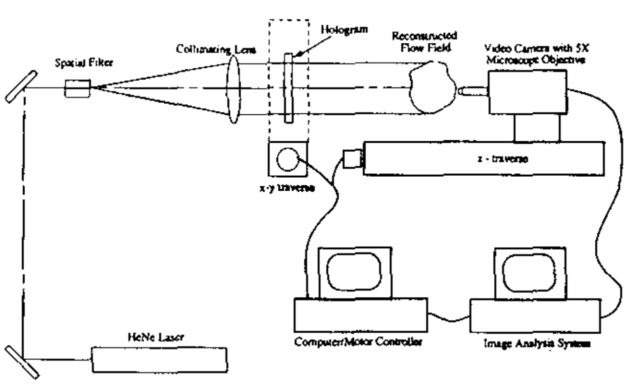


Figure 5. HPIV reconstruction and image analysis system.

Figure 6. Photograph of particle images.

Holographic Reconstruction and Data Analysis

In HPIV the velocity is obtained from measurements of the particle displacement in reconstructed images of the flow. An schematic diagram of the image analysis system used in this investigation is shown in figure 5. Computer controlled

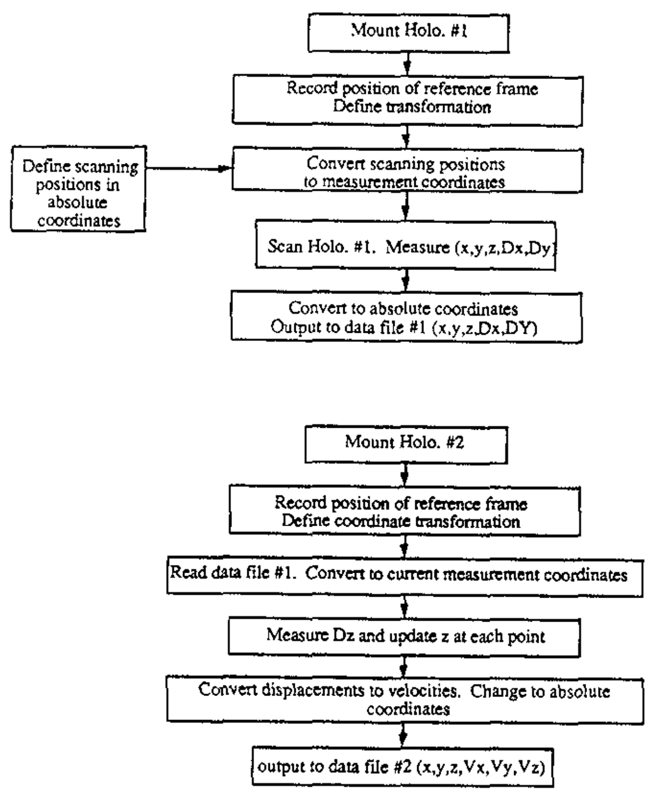
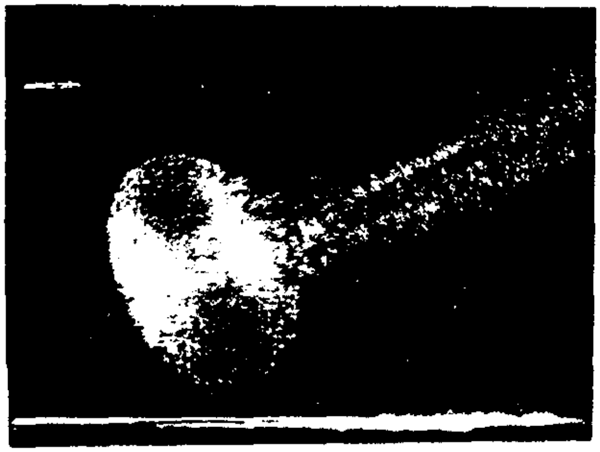
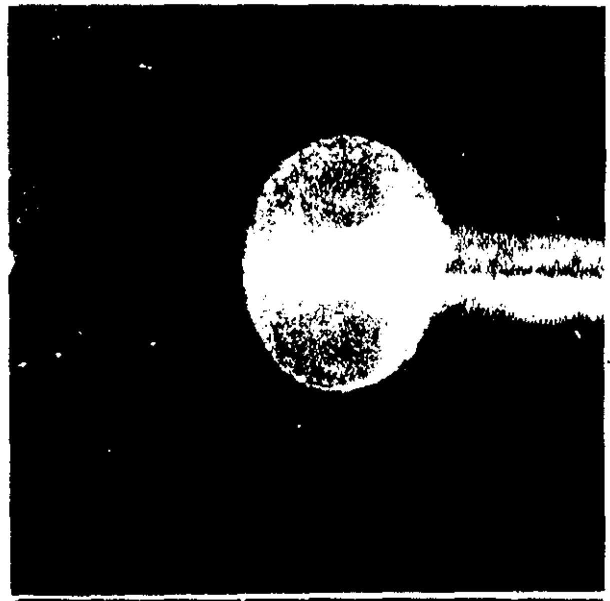
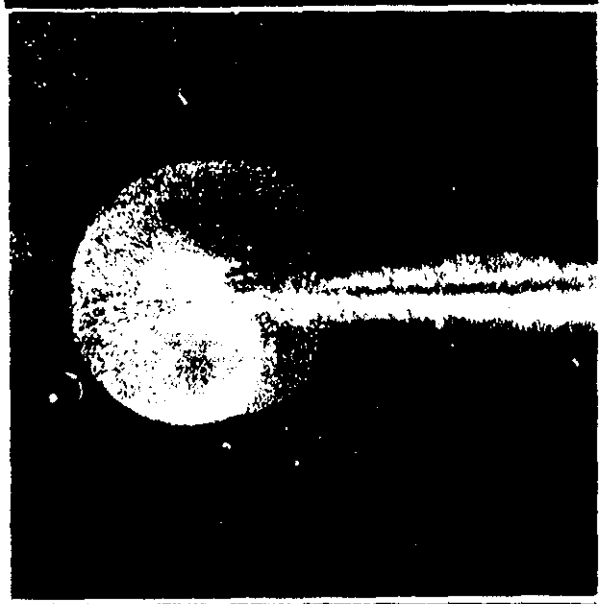


Figure 7. Block diagram of HPIV velocity data acquisition system.

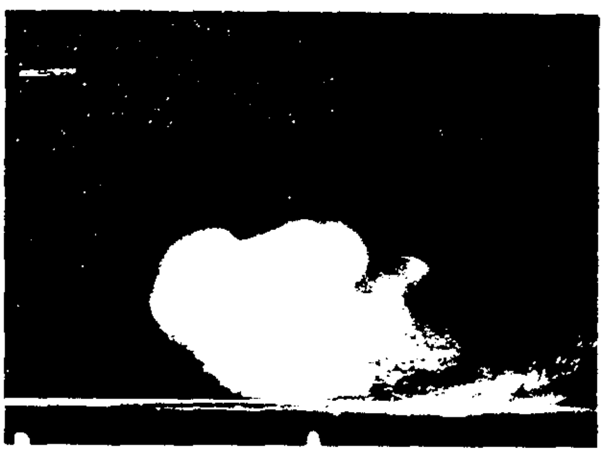


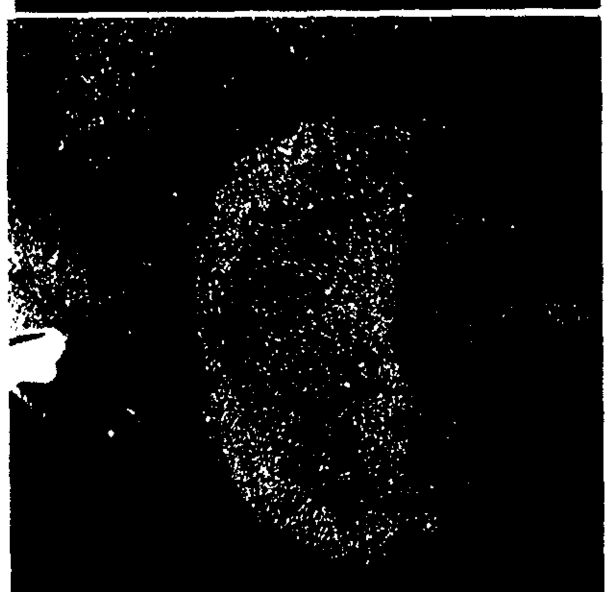


$t^{+} = 7.12$



$t^{+} = 8.06$





$t^{+} = 11.0$

Figure 8. Flow visualization pictures. Side view left column. Top view right column.

traverses were used to position the hologram relative to the video camera. The reconstructed real image of the particle field was analyzed using a real-time image analysis system equipped with a microscope objective. A typical photograph of the particle field obtained with this system is shown in figure 6. Because of the pulse program each particle in the field produces three images. The distance between the first two images is one half the distance between the second and third images. From these images the magnitude and direction of the displacement of the particle were easily measured. This photograph also illustrates the background noise present in these images. It was found that the background noise increased significantly when the ambient fluid was seeded compared to when only the vortex ring fluid was seeded.

The velocity is measured on a fixed grid defined with reference to the vortex ring flow using a partially automated technique. A block diagram of the hologram analysis technique is shown in figure 7. The two holograms obtained at each flow condition must be analyzed to determine the particle displacement since only the components normal to the optical axis can be measured accurately on each hologram. The reference frame recorded on each hologram is used to calibrate the position controllers. One hologram is scanned first to determine the location of particle images and two components of the particle displacement at the grid points. In the current implementation of the software the position of the hologram is computer controlled while the particle location and displacement is entered by the operator using the cursors. The second hologram is scanned only at the grid points where particle images where found in the first hologram. The remaining component of the particle displacement is then measured at those points by the operator using the cursors.

Results

Flow Visualization

Figure 8 are flow visualization pictures of the interaction of a vortex ring with a wall. The vortex ring Reynolds number was $\Gamma/\nu = 3{,}000$ and the incidence angle was 70°. The flow pictures were obtained using the CVL laser beam as the light source by seeding the vortex ring fluid only. The pictures were obtained with a 35 *mm* camera positioned normal to the wall for the top view pictures and normal to the plane of symmetry for the side view pictures. A single photograph was obtained on each realization of the flow. The photographs in figure 8 are typical of several realizations at the same stage in the interaction.

The sequence of photographs in figure 8 captures the main features of the interaction as a function of the nondimesional time $t^+ = \frac{U_r t}{a}$, where t is the elapsed time since the initiation of the flow, U_r is the measured propagation speed of the vortex ring and a is the vortex ring diameter. At $t^+ = 7.12$ the vortex ring has not reached the wall and the vortex ring core does not show a significant distortion. At $t^+ \geq 8.06$, the side view picture shows only the upper part of the vortex ring core which indicates that the vortex ring core has reconnected with the boundary layer vorticity as first proposed by Kachman *et al.*[1]

Also for $t^+ \geq 8.06$ the top view shows also significant lateral spreading of the vortical region which is consistent with the reconnection mechanism. In the last two pictures there appears to be an increase in smaller scale three-dimensional motions.

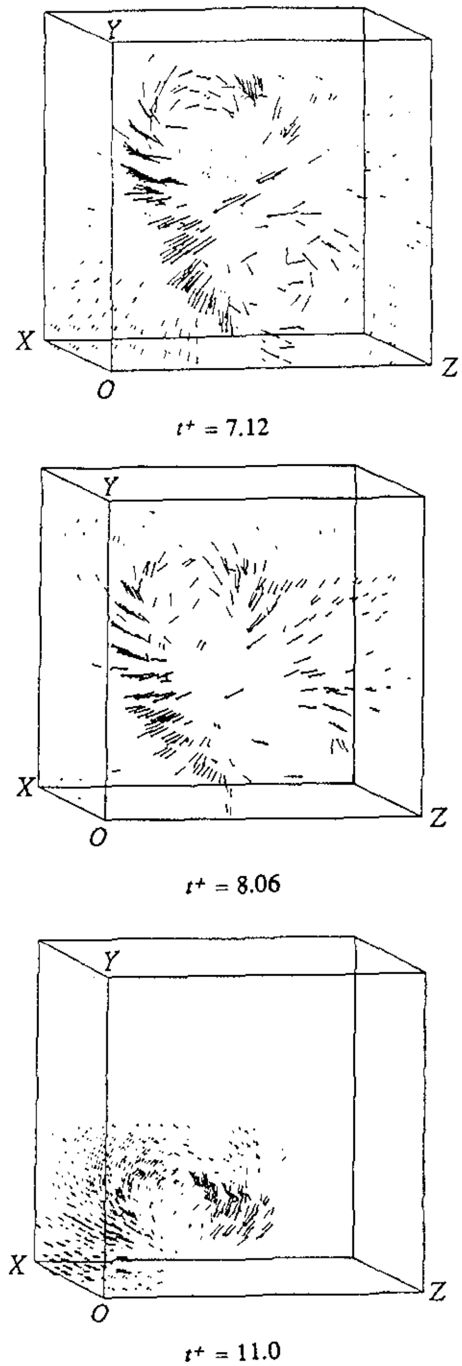
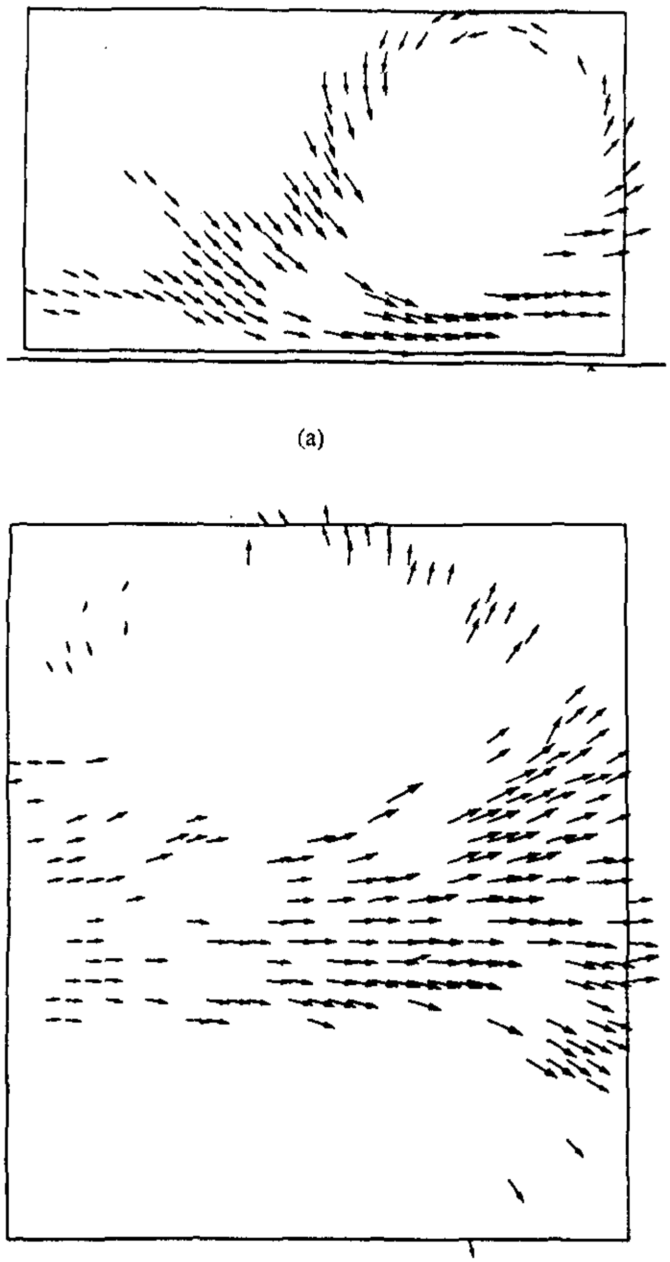


Figure 9. Three-dimensional vector plots of velocity field. $\Gamma/\nu = 3{,}000$, $\alpha = 70°$



(a)

(b)

Figure 10. Vector plots of the velocity field in selected cross-section planes. (a) Plane of symmetry. (b) Plane parallel to the wall. $\Gamma/\nu = 3{,}000$. $\alpha = 76^\circ$

Flow Field Velocity Measurements

HPIV velocity measurements were obtained at the same conditions as the flow visualization pictures. As for the flow visualization pictures the data for different values of t were obtained on different realizations of the flow. The hologram were analyzed to obtain the velocity field in a relatively coarse *three-dimensional grid*. Three-dimensional vector plots of the velocity field are shown in figure 9 for $t^+ = 7.12$, 8.06 and 11. Although the data is fairly sparse due to a lack of seed particles, the flow features are consistent with the flow visualization results. The velocity field data at $t^+ = 8.06$ shows a reduction of the cross section of the lower part of the vortex ring core. And at $t^+ = 11$ the velocity field data clearly shows the lateral spreading of the vortex ring core after reconnection. Also apparent in these data is the lack of seed particles in the core of the vortex and to some extent in the ambient fluid. The former was expected due to the relatively large size and density of the glass microballoons, the pressure field within the vortex core would necessarily force the seed particles out of the core. The lack of seed particles in the ambient fluid is attributed to the difficulty in seeding what is effectively a zero velocity stream.

In order to determine whether or not vortex reconnection had occurred, an HPIV hologram set was processed to obtain the velocity field in selected cross sections. The results are shown in figure 10. The measurements were conducted on the symmetry plane and on a plane parallel to the wall. A single vortex core is found on the symmetry plane. At the same time the data measured on a plane parallel to the wall shows a strong circulatory motion suggestive of the presence of vorticity normal to the wall.

Conclusion

HPIV measurements of the interaction of a vortex ring with a wall at inclined incidence were conducted to demonstrate the technique in complex vortical flows. The results show the break up and reconnection of the vortex ring core vorticity to vorticity in the wall boundary layer.

Seeding is a critical problem. A uniform particle distribution is essential to obtain well resolved velocity data. The particle size that must be used in HPIV is larger than for other nonintrusive techniques. In water flows this is not a difficult problem because particles are available with density within a few percent of the water density. In air, however, the particle density is significantly larger than the air density which results in large flow-induced nonuniformities of the particle distribution.

The particle image structure at high particle concentration contains significant background noise. This noise will have to be removed using image processing techniques for fully automated analysis of HPIV holograms.

Image analysis and velocity extraction of HPIV holographic records is very time consuming. Two approaches were developed in this work. (i) Full three-dimensional data sets were generated with reduced resolution. (ii) Selected cross-section were analyzed with higher spatial resolution. In both cases the data obtained with HPIV goes beyond what can be obtained with conventional PIV systems.

Acknowledgements

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References

1. Kachman, N.J., Koshimoto, E., and Bernal, L.P. "Vortex ring interaction with a contaminated surface at inclined incidence" **AMD- vol 119**, in "Dynamics of bubbles and vortices near a free surface." Ed: Sahin, I., Tryggvason, G. and Schreyer, H.L., ASME 1991.

2. Bernal, L.P. and Kwon, J.T. "vortex ring dynamics at a free surface," **Phys. Fluids A 1**, 3, pp 449-451, March 1989.

3. Scherer, J. and Bernal, L.P. "Resolution characteristics of Holographic particle image velocimetry" **AIAA paper 92-0009**.

4. Roberts, W.L. "A premixed laminar flame interacting with a vortex resulting in flame stretch and quenching," PhD Thesis, University of Michigan, 1992.