The Journal of Undergraduate Research

Volume 11 *Journal of Undergraduate Research, Volume 11: 2013*

Article 3

2013

Measurements of Three-Dimensional Velocity Fields Under Breaking Waves

Matthew Auch
South Dakota State University

Measurements of Three-Dimensional Velocity Fields Under Breaking Waves

Author: Matthew Auch

Faculty Sponsor: Francis Ting, Ph.D.

Department: Civil and Environmental Engineering

ABSTRACT

The three-dimensional (3D) velocity fields under breaking waves were measured using a Volumetric Three-Component Velocimetry (V3V) system. The V3V instrumentation determines the 3D positions and velocities of seed particles within a 3D measurement volume by using a synchronized laser-camera system and image processing algorithms. Measured velocity fields showed 3D vortex structures descending to the bottom and quickly dissipating as breaking waves propagated onshore.

INTRODUCTION

As waves break on the coast, intense turbulence is generated and a large amount of energy is dissipated in the surf zone. Large vortex-like structures are also observed, but their form, evolution, kinematics and dynamics are not well understood. Breaking-wave-generated vortices are hypothesized to contribute to the suspension and transport of sediment and therefore could have a major impact on beach erosion. Improved understanding of the turbulent velocity fields under breaking waves could lead to improved numerical models of surf-zone hydrodynamics and enable better coastal structure design and shoreline protection.

The V3V system uses image processing techniques to determine the three-component fluid velocities within a 3D flow volume. Images of seed particles suspended in the flow are captured using a three-aperture camera. The images are then processed to determine the 3D particle positions and displacement of the particles over a known time increment, thus allowing the velocities of the particles to be resolved in three dimensions within the measurement volume as a function of time.

V3V is a state-of-the-art technique in fluid mechanics measurement. It has the potential to significantly advance our understanding of the complex 3D flow patterns under breaking waves. This paper describes the V3V system, its principle of operation, and presents preliminary measurements of 3D vortex structures under breaking waves.

METHODS

Experiments were conducted in the Fluid Mechanics and Irrigation Laboratory in the Agricultural Engineering Building on the South Dakota State University campus. The laboratory is equipped with a 25-m-long, 0.90-m-wide, and 0.75-m-deep Plexiglas titling flume and programmable wave generator (Figure 1). The flume slope was set to 2.5% and a wave height of 0.12 m and wave period of 4.0 s were set by the wave generator where the still water depth was 0.3 m. The incident waves produced plunging breaker conditions within the measurement area where the still water depth was around 0.11 m.

Figure 1. Experimental setup with open-channel flume and wave generator

The V3V system was manufactured by TSI Incorporated in St. Paul, Minnesota. The complete system consists of a three-aperture camera probe, a Dual Nd: YAG laser (200 mJ/pulse, dual 15 Hz pulse rate), synchronizer, calibration target and traverse, and INSIGHT V3V^{TM} software (2012). The individual components of the system are described below (Figure 2).

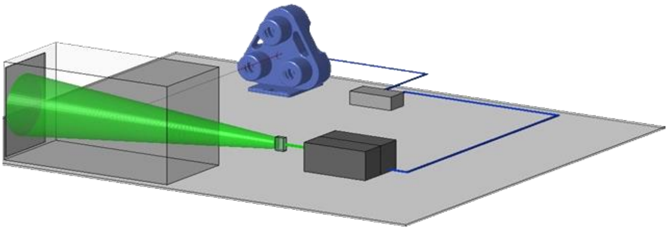

Figure 2. Schematic of V3V system with camera probe, lasers, synchronizer, and illuminated measurement volume (image courtesy of TSI Inc.)

Camera

The camera contains three sensors (top, right, and left) whose fields of view overlap and focal points converge to a single point approximately 670 mm from the camera, defining the reference plane. The illuminated region where the camera views overlap defines the measurement volume with dimensions of approximately 140 × 140 × 100 mm^3. In the present study, the measurement volume extended from the bottom of the flume to just below the wave trough level. Each camera views the measurement volume from a different angle and captures a slightly different image creating a distinct triangular pattern called a triplet (Figure 3). The size of the triplet corresponds to the particle's depth and the triplet centroid marks the in-plane position, thus locating the position of the particle in the 3D space.

Figure 3. Triplet pattern

Laser

Cylindrical lenses mounted on the laser head refract the light beam into a cone to illuminate the measurement volume. Two pulsing lasers, each with a frequency of 7.25 Hz, flash at slightly offset times separated by a short time interval, Δt. The camera is synchronized to capture still images of the seed particles in the measurement volume with each laser flash

(Frame A and Frame B), thus allowing the system to determine the displacement of the particles during the Δt interval.

Calibration

Calibration establishes a correlation between the triplet signature and the particle depth and is performed before flow measurement. During calibration, the 3D camera captures images of a backlit target with a rectangular grid of dots as it is traversed through the measurement volume in increments of 2 to 5 mm. These images are processed to determine a signature triplet pattern at each depth position as well as dewarping polynomials which describe how the grid pattern changes across the field of view due to perspective distortions and other systematic errors.

Image Processing

INSIGHT V3V™ software runs a series of processing steps (Figure 4) on the raw images to determine the velocity vector field. The processing steps are summarized below.

1. Image Capture – a capture set comprises six images (Frame A and Frame B for Left, Right, and Top cameras)
2. Particle Processing – identifies particles in each image as peaks in grayscale intensity (six .p2d files output)
3. Triplet Processing – identifies triplets between the left, right, and top images using the calibration signature to create a 3D particle field (two .p3d files output)
4. Velocity Processing – matches particles between Frames A and B to determine the vector magnitude and direction of each particle based on displacement. The result is a 3D particle vector field (one .pv3d file output). Processor uses the relaxation method algorithm which tracks particle motion between successive images by identifying the most probable match for a set of potential matches. The algorithm considers a limited radius of displacement and assumes that adjacent particles will have similar trajectories (Pereria et al., 2006).
5. Velocity Interpolation – interpolates particle vectors onto a cubic 3D rectangular grid to create a gridded velocity vector field (one .gv3d file output)

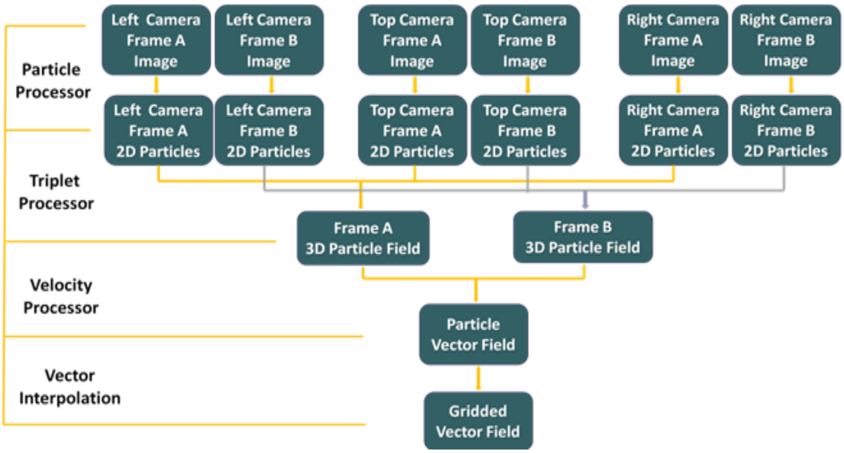

Figure 4. Image processing steps

Challenges

Much of the work was devoted to solving various problems that arose in applying the V3V system to breaking wave measurements. The goal was to achieve optimum data quality so flow structures could be properly identified. Some of these challenges included:

Equipment:

- Camera Mount - designed camera to minimize vibration interference from wave generator and be adjustable to flume slope.
- Laser Δt - set to produce a mean particle displacement of approximately 8 pixels at a typical wave velocity for optimum velocity pairing.

Data Processing settings

- Particle Identification - set particle intensity threshold and radius limits for maximum particle count and identification accuracy.
- Triplet Identification - set search tolerances for maximum triplet yield and position accuracy.
- Particle Tracking - the relaxation method algorithm was determined to be the most accurate and robust tracking option.

Calibration

- Backlight - constructed light source to illuminate target grid while minimizing glare.
- Target step interval - decreased the distance the target moved between calibration captures to produce a finer resolution calibration signature.

Light Interference

- Laser mask - paper mask on flume wall constrained laser illumination area to the measurement volume only, which decreased illumination intensity of air bubbles.
- Fluorescent seeding - lens filters blocked light from air bubbles and captured only illuminated fluorescent particles.

Wave Conditions

- Regular (non-breaking waves) - initially studied because simpler velocity patterns could be predicted based on wave theory and compared to V3V results to evaluate measurement accuracy.
- Breaking conditions - wave period and height were adjusted to produce strong plunging waves within the measurement area; observed using video recording.

RESULTS

The wave breaking process generates a large amount of air bubbles which interfere with optical measurements. The water was seeded with fluorescent particles with a mean diameter of 100 μm. The particles absorb the green light emitted by the lasers and fluoresce red light. Three high pass filters of 650 nm wavelength were mounted on the camera lens to admit the red light but block green light scattered by air bubbles. Because of the small quantity of fluorescent particles (about 2 g) available, only between 6,000 and 8,000 fluorescent particles were identified in each of the six images. Between 50% and 80% of the 2D particles were identified as triplets between the left, right, and top cameras. Figure 5 shows a typical 3D particle field.

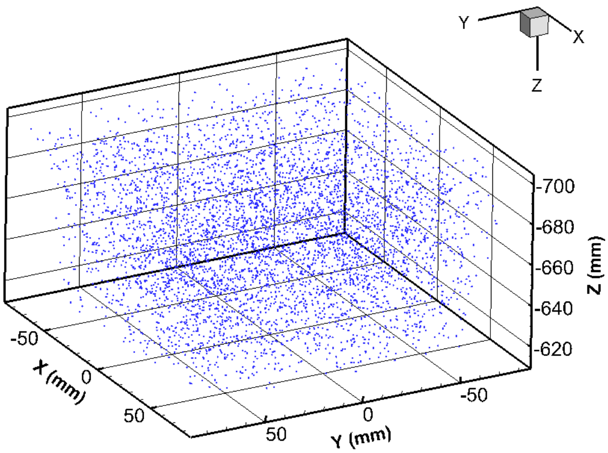

Figure 5. 3D particle field associated with a plunger vortex. The measurement volume is approximately 140 mm X 140 mm X 85 mm. *Y* direction is the direction of wave propagation; *X* direction is across the flume; and *Z* direction is positive downward. The bottom of the flume is located at *Z* = -611 mm.

Using the relaxation method algorithm, approximately 90% of the 3D particles identified were matched as vector pairs between Frames A and B. Maximum velocity magnitude was around 0.3 m/s and vectors with significantly larger magnitude were considered erroneous and filtered out of the data set. Figure 6 shows the 3D particle velocity vector field associated with a plunger vortex. The measured velocity field contains approximately 4,000 vectors randomly spaced within the measurement volume. The randomly spaced particle vectors were interpolated onto a cubic grid with 8-mm voxels and 50% overlap resulting in approximately 25,000 gridded velocity vectors at 4 mm vector spacing. This was the final processed data used for analysis of the flow patterns.

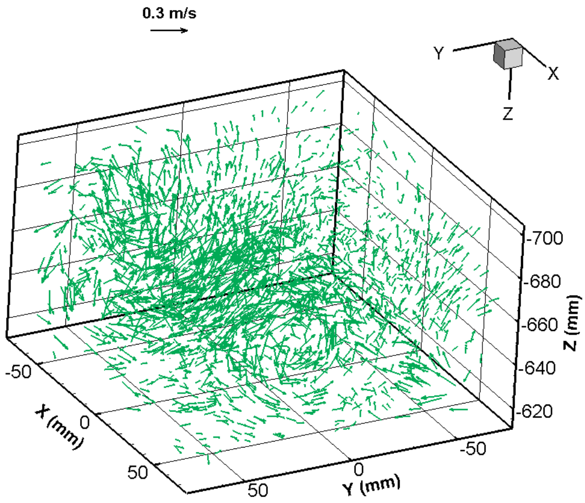

Figure 6. 3D particle velocity vector field showing the swirling fluid motion associated with a breaking-wave-generated vortex.

Visualization and analysis of the processed data was conducted in Tecplot software. 2D slices extracted from the 3D vector fields were viewed to identify swirling flow patterns which may indicate a vortex. Contours of vorticity magnitude were also drawn to reveal 3D flow structures. The velocity fields captured immediately after the wave crest passed were of particular interest because they contained the strongest turbulent motions and breaking-wave-generated vortices dissipated rapidly with time. Figure 7 shows an example of a plunger vortex, identified by iso-surfaces of vorticity magnitude, ω of 15 1/s. The 3D structure has the form of a vortex loop which consists of two counter-rotating vortices connected by a transverse vortex at the base. The vortex loop is obliquely stretched in the onshore direction. A 2D slice of the transverse vortex reveals the counter-clockwise fluid rotation that is often captured in 2D flow measurements.

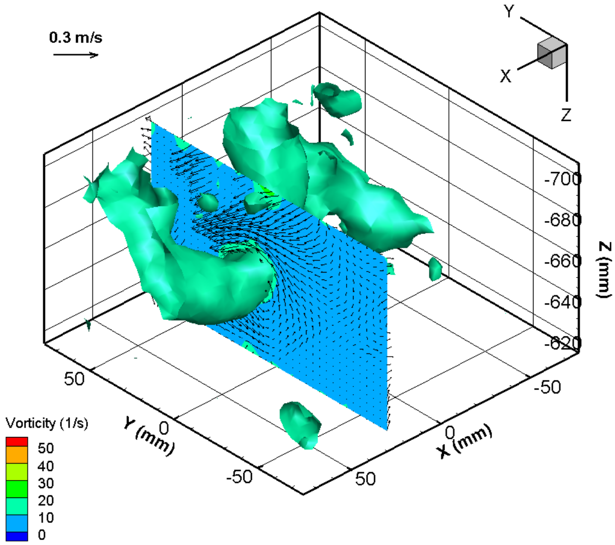

Figure 7. Iso-surfaces of vorticity magnitude of ω = 15 1/s associated with a plunger vortex. The corresponding particle and particle velocity vector fields are shown in Figures 5 and 6, respectively.

CONCLUSIONS

V3V measurements revealed complex vortex flow patterns in the fluid velocity fields under breaking waves. Iso-surfaces of fluid vorticity magnitude showed that the 3D flow structure generated by a breaking wave was a vortex loop extending obliquely upward toward the free surface. Counter-rotating vorticity was measured in the two braids of the vortex loop. The vortex descended quickly to the bottom and dissipated before the next breaker arrived. These 3D measurements are consistent with the velocity fields measured in a 2D plane using the stereoscopic Particle Image Velocimetry (PIV) technique. Ting (2008) suggested that these 3D vortex loops were developed from stretching and bending of the spanwise vortices generated in the wave breaking process. Future research will determine the kinematics (fluid velocities) and dynamics (fluid stresses) associated with these vortices and study their interactions with bottom sediment.

ACKNOWLEDGEMENTS

This study was sponsored by the National Science Foundation (NSF) through Grant OCE-1128754. Dr. Francis Ting was the principal investigator. Jedidiah Reimnitz was the graduate research assistant. Matthew Auch was supported by a Research Experience for Undergraduates (REU) supplement to the NSF grant. The support of NSF is gratefully acknowledged. The researchers also acknowledge the technical support provided by Dr. Wing Lai with TSI Incorporated.

REFERENCES

INSIGHT V3V TM 4G System (2012). Volumetric Three-Component Flow Measurement and Visualization User's Guide. TSI Incorporated, St. Paul, MN, USA.

Pereria, F., Stüer, H., Graff, E. C., Gharib, M. (2006). Two-Frame 3D Particle Tracking. Measurement Science and Technology 17, 1680-1692.

Ting, F. C. K. (2008). Large-scale turbulence under a solitary wave: Part 2 forms and evolution of coherent structures. Coastal Engineering 55 (6), 522-536.