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Investigation of Wave Formation using 3D3C measurement technique

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Abstract

The present effort utilized the volumetric three-component velocimetry (V3V) technique to capture instantaneous velocity volumes in wave generation water flume tunnel. The measurements were taken for the volume from the bottom of the flume to the water surface. In this case structures of the vortices generated by the Spilling wave and the Plunging wave could be measured. The goal of these measurements was to understand the mechanism of such vortex generation. Since air was entrained by the wave, a large amount of bubbles existed in the liquid. This posed a challenge for the measurements. One solution to remove the bubble image for the velocity measurements was to use fluorescent seed particles to allow only the seed particles to be seen.

The water flow was seeded with fluorescent seed particles of 107μm. The volume of 140 mm by 140 mm by 80 mm was illuminated with a 200 mJ/pulse, dual-cavity Nd:YAG laser. Particle images were captured by the volumetric 3-component velocimetry (V3V) camera system. Three high pass filters of 560 nm were used for the camera to allow the fluorescent signal generated by the particles to be captured. Velocity fields of the waves with more than 100,000 vectors were generated to give the 3D3C information.

Introduction

Wave energy is a large, widespread renewable resource that is environmentally benign and readily scalable. Understanding of wave formation can help to manipulate devices, such as turbines and power generator, to harvest the wave energy to its full scale. At the same time, wave formation is three-dimensinal in nature, hence it is important to study the flow phenonena with the 3-D measurement system in a volume.

Particle Image Velocimetry (PIV) has matured over the past decade and is becoming a very popular tool for quantitative flow visualization. However, traditional PIV techniques only capture 2D slices of the flow fields, thereby cannot reveal the complete topology of 3D flow structures. Scanning PIV extends the PIV technique to the volumetric domain, but lacks an important capability for quantitative flow visualization: capturing dynamic flow structures. A true volumetric technique (V3V) to allow the measurement of the 3D3C for the wave is discussed in this paper.

V3V is based on the second-generation Defocusing Digital PIV (DDPIV) technique, which was originally developed by Pereira and Gharib [1]. In principle V3V is a 3D particle tracking technique. The key innovation in V3V/DDPIV is a single-body 3D camera that records tracer particle images from three different views simultaneously. The three sensors inside the camera are arranged in a coplanar triangle pattern, so that a pattern search algorithm can be applied to extract particle 3D positions directly from the images. This approach enables fast and reliable flow measurements at much higher particle number densities than what has been achieved by conventional 3D PTV systems.

The first part of the paper briefly describes the V3V system setup, the principle and the data processing algorithms. Second part of the paper discusses the experiment of the wave measurement and the results captured by the V3V system.

System Description

Figure 1 shows a schematic overview of the V3V system. The V3V system consists of the 3D camera probe, a Nd:YAG laser with optics to generate the volumetric illumination, a synchronizer as timing control, and a computer system with the Insight V3V software (not shown in the figure). Laser pulses emitted from a double-pulsed laser is expanded by two cylindrical lenses, perpendicularly aligned to each other, to form a large cone for volume illumination. The 3D camera is mounted view the volumetric illumination cone. The intersection between the camera viewing region and the illumination beam defines the size, shape, and location of the measurement volume. Typically it is a region of 140 x 140 x 100 mm^3 at a distance of about 670 mm from the camera. The arrangement given in the figure is just one of the many arrangements commonly used. Focusing is not required since the 3D camera is designed to have large enough depth of field to cover the entire measurement volume.

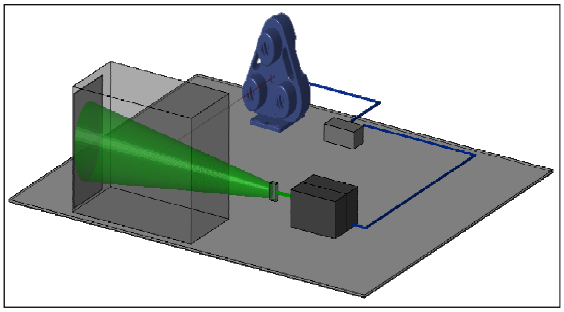

Figure 1: Schematic overview of V3V system.

The operation of V3V system is very similar to that of a PIV system. The camera is synchronized with the pulsed laser and images of tracer particles are captured during two successive laser pulses separated by a known time interval. Figure 2 shows the timing control of the laser pulses with respect to image capture. The laser pulses from each laser (green line) were timed to straddle neighbouring camera frames (red line) in order to produce images suitable for 3D particle tracking.

By recording particles images from three different views simultaneously, the 3D particle positions can be determined. Typically 100,000 to 140,000 particles can be measured simultaneously. Figure 3 shows a 128×128 pixels portion of sample raw image. The particle image looks identical to regular PIV images, although these images records particles in a large cubical volume instead of a thin light sheet.

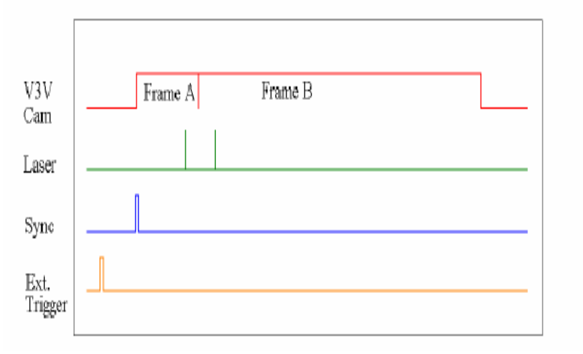

Figure 2 : Timing diagram for V3V captures

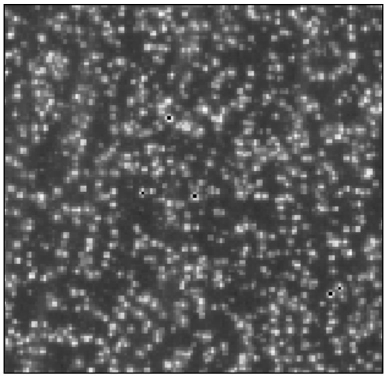

Figure 3 : Raw particles image

Principle of Operation

The operation of the V3V system is straightforward due to the fact that the 3D camera probe requires no alignment on its own. The camera is pre-aligned to view a volumetric domain of 140 by 140 by 100 mm^3. Detailed descriptions of the various steps are given in the following sections.

V3V in principle is a multi-view photogrammetric technique. The camera has three image sensors arranged in a coplanar triangle pattern and assembled into a common faceplate. The fields of view of the three sensors intersect to form the camera's mapping region, as shown in Figure 4. Each particle inside the mapping region is recorded by all three sensors, creating the basis for multi-view stereo vision. The coplanar sensor arrangement and its single-body design, the camera is able to measure particle 3D positions through quick search of triangle patterns. Particle images captured by V3V camera are focused images around 3 to 5 pixels in diameter.

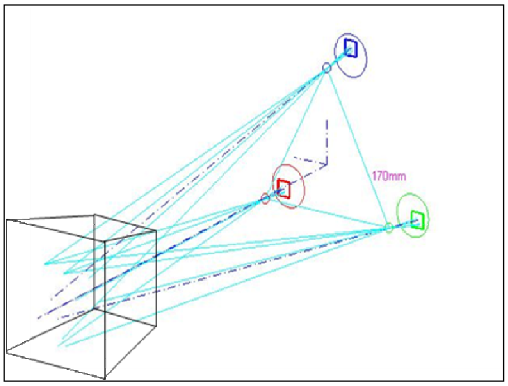

Figure 4: Overlapped region from the cameras

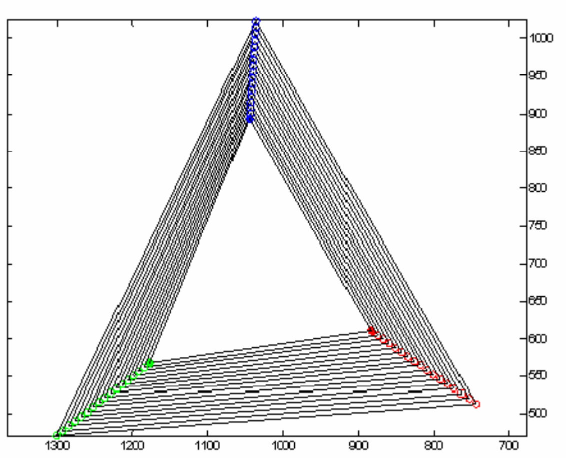

Figure 5: Triplet triangles from calibration

Since V3V uses triangle-pattern search based on pinhole optics to find particle 3D positions, it is critical to quantify the deviation of a real camera from a perfect pinhole camera. A real camera uses complex lens to minimize aberrations, so there is obvious deviation from pinhole optics particularly due to the unknown location of lens apertures. Although the use of photographic objectives minimizes the lens distortion, the flow facility usually introduces additional optical distortions that are very difficult and often impossible to eliminate. Moreover, there are errors in the manufacturing of camera parts and the misalignment of image sensors, which further distorts the triangle patterns.

The multi-plane calibration which is employed to quantify the deviation is essentially a 2D-to-2D mapping between real images and perfect images in multiple planes across the entire measurement volume. In multi-plane dewarping, a calibration target, with a precise grid of dots, is traversed through the entire measurement volume one plane at time. The 2D calibration images from multiple planes are analysed, and a 2D Gaussian fit is used to find the dot locations that are then related to the known geometries and fixed alignment of the apertures within the camera probe, to determine the 3D dot locations. Figure 5 shows the result of a typical calibration, where the camera signature graph, showing the triangles formed by the centres of the target in each calibration plane, indicates the importance of correcting mechanical misalignment error. In most cases the RMS error of particle image positions after dewarping is less than 0.1 pixels.

Since the V3V camera has large depth of field, the images look identical to regular PIV images although these images records particles in a large cubical volume instead of a thin planar sheet. The goal of image processing is to obtain particle 3D positions from raw images captured by a calibrated system. The data processing consists of four steps. They are (1) 2D Particle Identification, (2) 3D Particle Identification (Triplet Search), (3) 3D Particle tracking, and (4) Grid Interpolation.

The first stage of data processing is searching for particles in the raw images, each of which consists of six images of 2K by 2K pixels. A 2D Gaussian fit algorithm is used to fit the particle image to a 2D Gaussian function for better accuracy and it also has the ability to separate overlapped particles, which is important due to the fact that an entire volume is illuminated. Local peaks with intensity greater than their neighbours are first identified. Each group of pixels is then processed by a 2D Gaussian fit algorithm, based on the observation that particle intensity distribution can be approximated by a Gaussian function. The 2D Gaussian fit algorithm returns particle centroid position and other particle parameters such as radius and peak intensity. The algorithm also acts as a filter to reject invalid pixel groups whose intensity distribution does not resemble a Gaussian function.

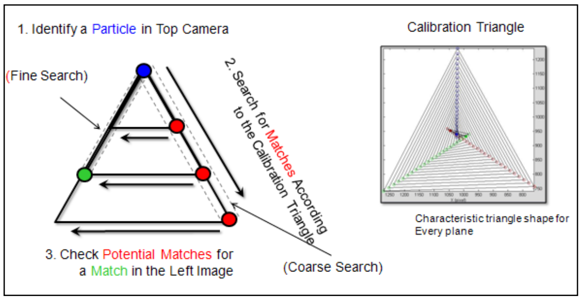

Figure 6: Triplet search based in the calibration signature graphs

Images from each of the apertures are effectively combined in order to determine the 3D location of each particle. Each 'triplet' represents a single particle in the flow. Figure 6 shows the triplet search process to identify the location of the particles in the 3D space. The search starts with any particle in the image from the Top camera. Based on the calibration signature graph, the search extends to the particle images captured by the Right camera. If a particle image is identified, then the search continues with the particle image capture by the Left camera. The process repeats until the Triplet is found. Subsequently the particle location is defined once the triplet is located.

The third stage of data processing is searching for particle pairs in two successive images to obtain 3D velocity vectors. Particle tracking method is a natural choice because particle positions are readily available. Three algorithms have been implemented for 3D particle tracking: the nearest neighbour method, the relaxation method by Baek and Lee [2], and the particle matching method by Stellmacher and Obermayer [3]. Our test results show that the relaxation method proposed by Pereira et al [4] is the most robust and efficient, while the particle matching method has similar performance but is a little slower. Note that particle tracking is performed without local flow estimation, as it was found that the flow estimate has imperceptible effect on the performance of 3D particle tracking.

After the 3D particle tracking step, the vectors lie on a randomly spaced grid, according to particle locations. In order to computer quantities such as vorticity, it is useful to have vectors on a rectangular grid. This was done through regular Gaussian-weighted interpolation.

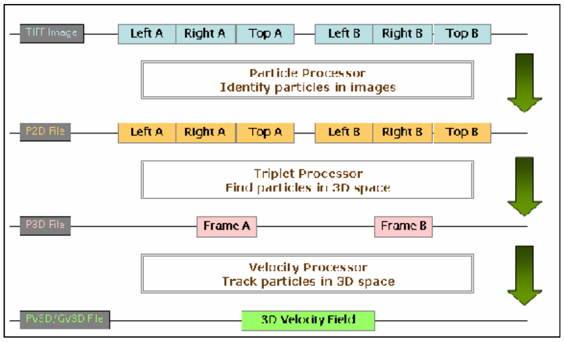

Figure 8 : Steps of Image Processing to obtain velocity vectors

Experimental Setup

The test section of the flume water channel is shown in Figure 9. The wave generator is located upstream, with the capability to generate various type of wave formation at different frequencies. The V3V camera was mounted at the bottom of the flume to allow the flow structure at the bottom to be captured more easily, as shown in Figure 10. Further image distortion due to the air-water interface and bubbles generated by the wave would be minimized with the camera probe in such location.

Figure 9 : Test section of the Flume channel

Figure 10: Location of the V3Vcamera probe looking from the bottom of the flume tunnel

The laser illumination came from the side of the channel, with the desired capture volume of 140 by 140 by 100 mm^3. The water flow is seeded with fluorescent seed particles of 107 microns to remove the image of bubbles entrained by the wave. The volume of 140 mm by 140 mm by 80 mm is illuminated with a 200 mJ/pulse, dual-cavity Nd:YAG laser.

Model of vortex generation from wave

Figure 11 shows of the conceptual model of the vortex generation due to the wave formed on the surface as proposed in Ting [5]. First, a span wise vortex is formation and evolution formed when the overturning wave front strikes the front face of the breaker. As a result of non-uniform wave breaking in the transverse direction, the falling water mass causes part of the vortex tube to descend through the water column before the rest of the vortex tube. Strong velocity gradient in the vertical direction then produces more stretching and bending to deform the primary vortex into a vortex loop with counter-rotating vorticity. As the broken wave propagates onshore, the vortex loop is left behind and becomes tilted in the wave direction. The two legs of the vortex loop are connected beneath water surface by a transverse vortex with the upper ends open at the free surface. One of the objectives for the 3D3C measurements is to see whether the vortex structures could be captured as suggested in the model.

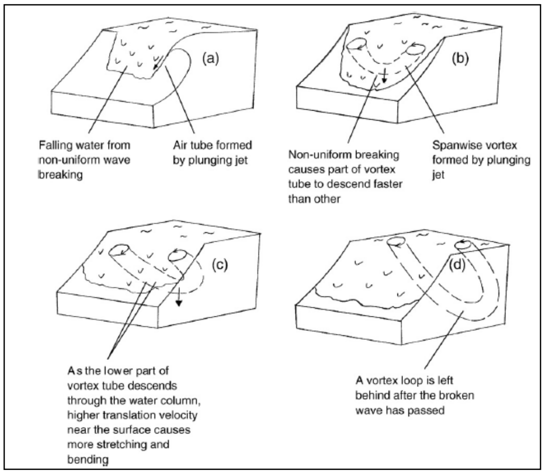

Figure 11: Conceptual model of the vortex generation from wave

Experimental Results

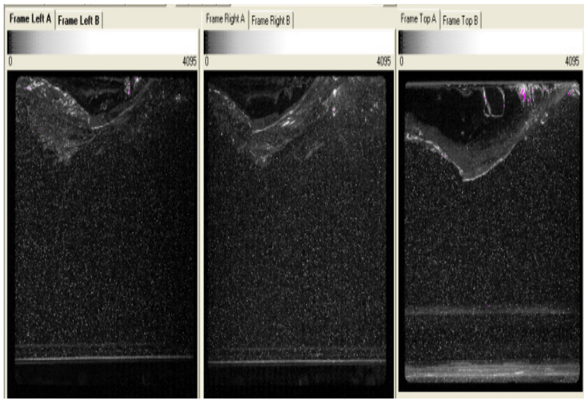

Figure 12 : Particle images captured by the 3-D camera

Figure 12 presents the three separate particles images captured by the three apertures from the 3-D camera. The images show the interaction between the water and air at one instance of time. The result of one capture, with velocity vector plot overlapped with iso-surfaces of vorticity, is given in Figure 13 as indicated from red to blue. It appears that there is a strong vortex formation at the surface of the water. The result does indicate sign of the vortex structure proposed in the earlier section.

Summary

In this paper the V3V technique was employed to investigate the vortex generator due to wave formation. Since the vortex structure is very three-dimensional in nature, the 3D3C capability of the V3V system was able to provide the entire flow structure. The large amount of bubbles generated during wave breaking were removed by using the fluorescent seed particles so that only the seed particles were captured by the cameras when high pass filters were used. The results showed the generation of the vortices by the wave from the water surface down to the bottom of the flume. Further work will be carried on to make further investigation of the vortex generation with different types of waves.

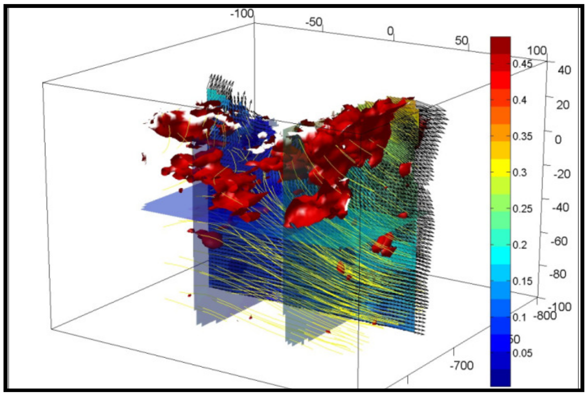

Figure 13 : Velocity and vorticity plots showing vortex formation close to the ware surface

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