EXPERIMENTAL STUDY ON INTERACTION OF ROUND JET WITH FREE SURFACE

Gentaro Tanaka, Takafumi Ishitsu, Yasuhiko Sugii, Koji Okamoto
Nuclear Engineering Research Laboratory, University of Tokyo
2-22 Sirakata-Sirane Tokai-mura Nakagun, Ibaraki-ken, Japan 319-1188
gentaro@tokai.t.u-tokyo.ac.jp

ABSTRACT

In this study, interaction of horizontal jet and free surface was evaluated by the experiment. Since the non-linear phenomena caused by turbulence at the free surface are fully three dimensional, three dimensional free surface shape and three-dimensional velocity distribution just beneath the surface should be simultaneously measured. Here, Stereoscopic Particle Image Velocimetry (stereo-PIV) and Specklegram Method (Tanaka et al.,2000) was combined to visualize free surface and underlying turbulence simultaneously.

The test section was a rectangular tank having a free surface. A circular nozzle was set horizontally beneath the free surface to form a jet. The jet interacted with the free surface, causing the wavy free surface condition. Three progressive CCD cameras (HITACHI KPF-110, 1024x1024[pixel], 10bit) were used in the experiment. Two cameras were set beneath the test tank to take the stereoscopic view of the turbulent jet. Three dimensional velocity distribution beneath the surface was obtained on the certain plane. Another camera was used for Specklegram Method which visualizes the three-dimensional surface shape. This optical technique enabled to measured the free surface wave quantitatively in a high accuracy. Using this quantitative surface information and velocity distribution measured by stereo-PIV, correlation between free surface fluctuation and flow field was obtained.

INTRODUCTION

Free surface and its underlying flow field may cause non-linear interaction resulting to phenomena such as self-induced sloshing. Fluctuations by the turbulence affect on free surface, causing the surface shape to be varied. Walker et al. (1995) measured the turbulence near a wavy-free surface using a three-dimensional Laser Doppler Velocimeter (LDV), showing the detailed characteristics of the free surface turbulence. However, their study just measured the averaged liquid velocity perturbation distribution. Since the free surface is a movable boundary condition, the surface response to the disturbance of the liquid is very important. In order to evaluate the interaction between free surface and turbulence, three-dimensional free surface shapes and the three-dimensional velocity distributions beneath the free surface should be simultaneously measured. Several techniques were proposed to measure the free surface shapes using the visualization technique. Suzuki et al. (1995) proposed a photometric stereo technique to visualize the surface gradient. It uses the distorted white light to illuminate the surface. The light was reflected at the surface and was projected to the screen above the surface. Then the intensity distribution on the screen was taken stereoscopic by CCD cameras to be converted to the surface height. Dabiri et al. (2000), applied free surface gradient detector (FSGD) and Digital Particle Image Velocimetry (DPIV) to obtain the correration between free surface elevation and shear layer. They observed the three-dimensional free surface shape using the FSGD technique, and also simultaneously took the velocity distribution beneath the surface using two-dimensional DPIV. Their result showed the strong correlation between the vorticity distribution and the free surface wave hight. There was an highest peak of the wave and the large voricity at the same point.

In this study, improved Specklegram Method(Tanaka et al.,2000) was applied to visualize the 3-dimensional free surface shape. Specklegram Method uses laser specklegram refraction at the free surface, resulting to a simple measurement setup. Stereoscopic Particle Image Velocimetry (Stereo-PIV) was combined with this Specklegram Method. Using this system, three dimensional free surface shape and three velocity components beneath the free surface was simultaneously measured.

EXPERIMENTAL SETUP

In order to evaluate the interaction between the free surface and turbulence, the jet was injected horizontally under the free surface. The interaction between the jet and free surface was measured experimentally. Figure 1 shows the schematic of the experimental setup. The test section was a rectangular tank having a free surface. A circular nozzle was set horizontally beneath the free surface to form a jet. The nozzle's inner diameter (D) was 5[mm]. The center of the nozzle was set 10[mm] (z=2D) under the free surface. The nozzle axial direction was defined as x-axis. The depth and spanwise direction was defined as z-axis and y-axis respectively. The injected water jet interacted with the free surface, causing the wavy free surface condition. The jet inside the nozzle was fully developed when it reached the end of the nozzle. The head tank was used to supply the constant flow rate. The velocity of the injected jet was set to 1.0[m/s]. The Reynolds number in the nozzle was about 5000 (Re=$V_{in}D/\nu$). The water level was kept constant using the overflow at the downstream of the jet. The Froude number based on the nozzle depth (2D) was more than 3, showing the wavy surface condition (Fr=$V_{in}/\sqrt{gH}$).

Optical setup for the visualization was shown in figure2. Camera 1,2 was used for stereo-PIV and viewed the jet through the mirror which was set beneath the test tank. Camera 3 was used for the specklegram measurement. All three camera was the same type of camera, HITACHI KPF-110 (1024 × 1024pixel,10bit). Parabolic mirror ($\phi = 200[mm]$) was set beneath the test tank, and was used to reflect the cylindrical laser light for specklegram method to be projected to the screen above the free surface.

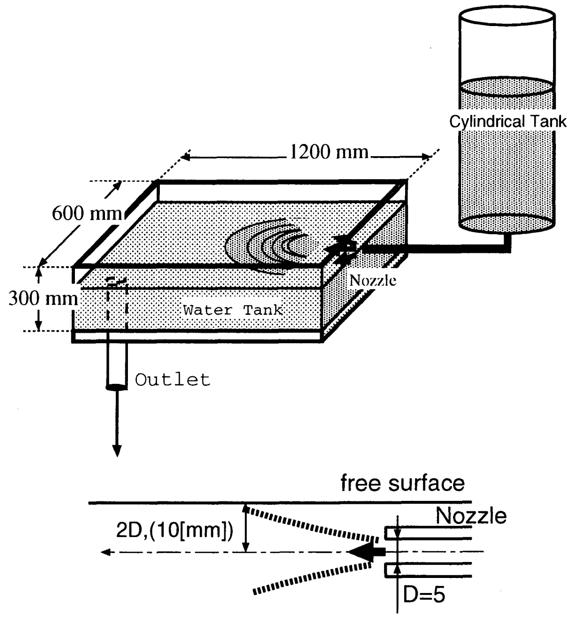

Figure 1: Experimental Setup

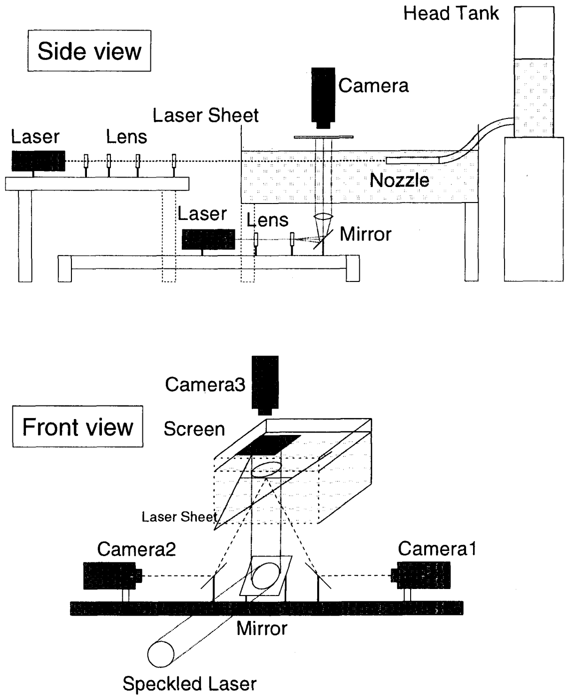

Figure 2: Camera Setup

Specklegram Method

In order to measure the three dimensional surface shape, Specklegram Method (Tanaka et al., 2000) was applied. Figure 3 shows the schematic of the surface measurement. The laser light through the optical fiber system or diffuser contained a lot of speckle noises caused by the small defection and multi-reflection inside the fiber or diffuser. The speckle noises through the optical fiber or diffuser were applied to the speckle pattern for the surface measurement. From the figure on the left, local surface gradient θ could be written as below:

$$\theta = \frac{\delta}{(n-1)L}.$$

where δ was the local displacement vector, n was the refractive index, L was the distance between the surface and the screen. The diameter of the visualized surface area was about 60[mm]. The speckle pattern projected on the screen was recorded by progressive CCD camera (HITACHI KPF-110,1024 × 1024pixel,10bit). An example of the speckle pattern displacement is shown in the right side of figure3. Cross-correlation technique used in Particle Image Velocimetry was applied to calculate the local pattern displacement of the test image from the reference image. In order to calculate the displacement with high accuracy, gradient method based sub-pixel analysis (Sugii et al., 2000) was applied. This method based on optical flow technique had an accuracy of 0.01 pixel for sub-pixel analysis of cross correlation PIV technique. Reconstructed surface shape was shown in figure4. The surface was reconstructed from the vectors shown in the right side of figure3. The wave height was less than 1[mm] and wave length was about 30[mm]. It can be clearly seen that the three dimensional surface shape was visualized quantitatively.

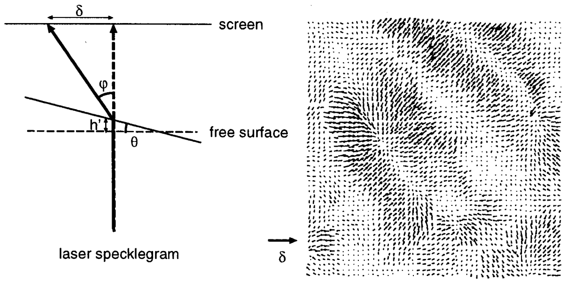

Figure 3: Specklegram Method

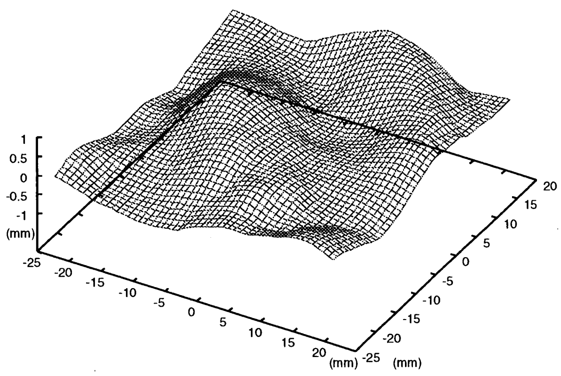

Figure 4: Reconstructed Free Surface

Stereo Particle Image Velocimetry

In order to obtain the three-dimensional velocity profile on the laser light sheet plane, stereo PIV system was applied. The camera setup is shown in figure2. These camera was set in scheimplug condition and had the lens that could tilt and shift (Micro-Nikkor 85mm). The camera was set beneath the test tank and the distance to the target area was about 1500[mm]. Laser light sheet was provided by double pulsed 25[mJ] Nd:YAG laser ($\lambda = 532[nm]$) horizontally beneath the free surface so that it could illuminate center of the nozzle ($z = 10[mm]$). Gridded stenless plate was used to calibrate the stereo camera. The calibration plate was $200[mm] \times 200[mm]$ and had 10000 grid points on the plate. The plate was set at the measuring region and on the laser light sheet plane. Calibration image was taken at three cross-section, at $z = -1, 0, 1[mm]$. Camera calibration was done using direct mapping method (Soloff et al.,1997) using about 6000 grid points taken from the calibration images. The displacement of a particle image on camera c, where $c = 1, 2$, is

$$\Delta X^{(c)} = F^{(c)}(x + \Delta x) - F^{(c)}(x)$$

and the estimate of the mapping function was set as

$$\begin{aligned}\hat{F}(x) &= a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_1^2 \\ &+a_5x_1x_2 + a_6x_2^2 + a_7x_1x_3 \\ &+a_8x_2x_3 + a_9x_3^2 + a_{10}x_1^3 \\ &+a_{11}x_1^2x_2 + a_{12}x_1x_2^2 + a_{13}x_2^3 \\ &+a_{14}x_1^2x_3 + a_{15}x_1x_2x_3 + a_{16}x_2^2x_3 \\ &+a_{17}x_1x_3^2 + a_{18}x_2x_3^2\end{aligned}$$

where a_i are vector-valued coefficients to be determined. A least-squares polynomial with cubic dependence in x_1 and x_2, but quadratic dependence in x_3 was adopted as the mapping function estimate. Mapping error analysis was done by remapping the two dimensional grid data which are known to the three dimensional coordinate. As a result, the mapping error was found out to be less than 0.1 pixel at each grid point on the calibration plate. During the PIV analysis, highly accurate sub-pixel analysis based on gradient method (Sugii et al., 2000) was applied for the cross correlation PIV. Also, recursive PIV technique with correlation based error correction (Hart et al.,1999) was applied in order to obtain the velocity vectors with high resolution.

Simultaneous Measurement

Simultaneous measurement of the free surface shape and the underlying flow field was done using these two optical method mentioned above. Three camera and two laser unit was driven by the pulse generator and the delay generator. The pulse generator had 4 output channels that can produce TTL signals up to 30[Hz]. The snnignals was then delayed inside the delay generator which had one input channel and 8 output channles. Timing chart of these equipment is shown in figure5. Frame of the PIV camera was opened and that of the specklegram camera was close when the double pulse laser was shot for the PIV. On the other hand, frame for the specklegram camera was just opened for 1[ms] when another pulse laser was shot to measure the free surface. Therefore, camera and laser for PIV measurement and for specklegram measurement never had interfered each other.

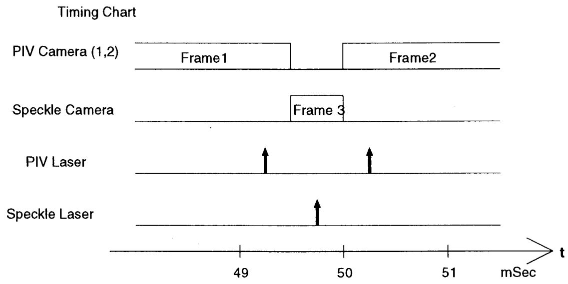

Figure 5: Laser and Camera Timing Chart

EXPERIMENTAL RESULTS

Mean velocity vector distribution is shown in figure6. Using the stereo PIV method, three componenet of the velocity was obtained at the laser light sheet plane. The mean velocity profile was an average of 144 instantaneous velocity distribution. Because of the calibration method mentioned above, the jet was not at the center of the image but was at $y = 10[mm]$. The jet had a symmmetric velocity distribution for the horizontal velocity component. The vertical componenet of the velocity profile was not symmetric to the laser light plane, and was slightly headed downward. This was because the horizontal jet close to the surface tends to shift toward the free surface (Nezu et al.,1986) and the laser light sheet at the center of the nozzle was not at the center but below the jet axis at the measuring point (x=20D). Figure7 shows an expamle of the instantaneous velocity vector with its free surface shape on the top. Three componets of the velocity field at the laser light sheet plane and also the surface shape in the same time was quantitatively visualized. It can be cleary seen the jet below generating the surface wave toward the jet's axial direction. The region measured by stereo-PIV was not fully covered by the surface measurement. This results from the optical setup chosen in this experiment. This problem could be easyly evaded by choosing a larger lens for the specklegram surface measurement. Since the vertical component was hard to view on the figure above, figure8 shows its vertical velocity componet. From the figure meandering of the jet in its horizontal and vertical direction can be clearly seen. For example, the vertical velocity was negatively large at $x = -20[mm]$ and $x = 10[mm]$. The cycle for meandering was about 30[mm] for both direction. Instantanous vorticity distribution (figure9) was calculated from the velocity distribution in figure7. According to the coordinates, the jet had positive vorticity on the left and negative vorticity on the right, naturally. Figure10(and fig.4) shows the water level, taken simultaneously with the velocity profiles. The peak of the wave can be seen at $x = -10, y = 0[mm]$ and also at $x = 20, y = 10[mm]$. From this figure, the wavelength was estimated to be about 30[mm] and it agreed well with the observation during the experiment. And it also agrees with the meandering cycle of the jet which was about 30[mm]. However, peak of the surface wave did not match the peak of the vertical velocity components ($x = 0, y = 0[mm]$ on figure 8). The highest peak of the wave was observe at $x = 8[mm]$ on figure10, but the upwelling velocity of the jet was high at the point of $x = 0[mm]$ on figure8. It can be seen from these figures that there were some phase-lag about 90 degrees between the surface wave and the vertical component of the jet. This value quite agrees with the theoritical value which should be also 90 degrees. On the other hand, only a few correlation was found between the vorticity (figure9 and the surface waves (figure9). Figure9 showed negatively strong vorticity at $x = -8[mm], y = 0[mm]$. This was the exact place where the highest peak of the wave was observed. However, this was not so conspicuous in the other area. This was because the laser light sheet plane was not close enough to the free surface. As mentioned above, the laser light sheet plane was set at the center of the nozzle, but that was not the center of the jet itself, and so the vortices beneath the jet was seen in figure9.

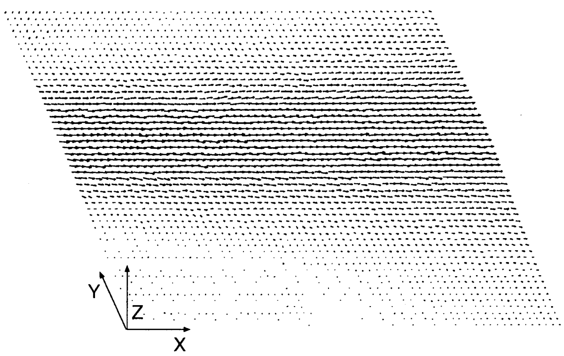

Figure 6: Mean Velocity Vectors

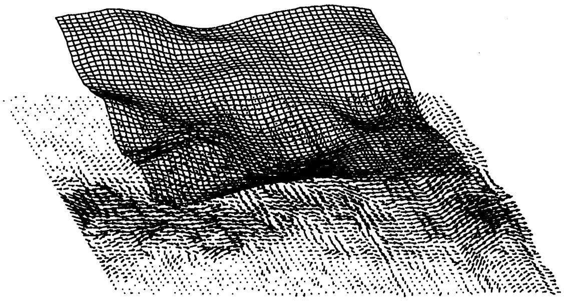

Figure 7: Instantaneous Velocity Vectors with free surface shape

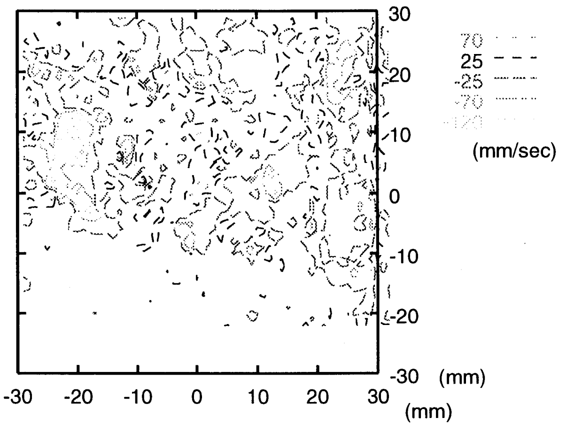

Figure 8: Vertical component of Velocity Distribution

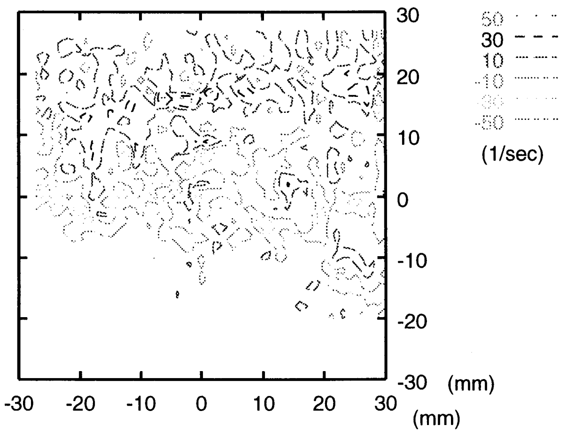

Figure 9: Vorticity Distribution

CONCLUSION

Optical technique was devoloped for the simultaneous measurement of the three-dimensional surface shape and velocity distribution beneath the free surface. Interference of the laser light sheet for stereo-PIV measurement and the volume illumination for Specklegram Method was avoided using the pulsed laser and controlling the trigger for CCD camera and the laser unit. Using the high resolution CCD camera and applying the high accuracy sub-pixel analysis enabled the free surface shape and the velocity distribution to be measured simultaneously with high resolution and

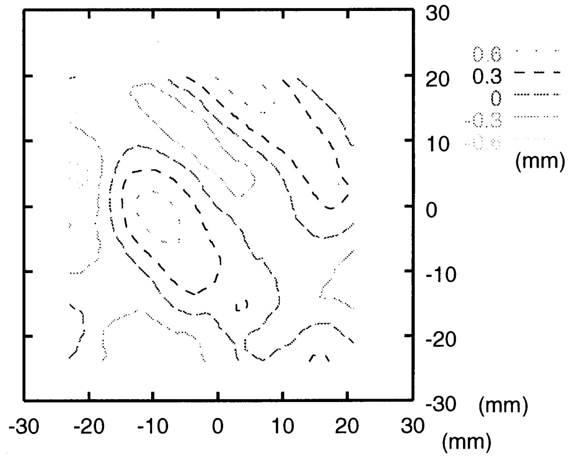

Figure 10: Free Surface Level

accuracy. As a result, vertical velocity componet of the jet had a strong effect on the free surface waves, which seems to be quite natural. However, it seemed to have small correlation between the vorticity distribution and the free surface waves. This results from the laser light sheet to be set at the center of the nozzle, and the velocity distribution slightly beneath the jet was visualized by stereo-PIV.

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